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Research paper

Enhancing PV modules efficiency and power output using multi-concept cooling technique

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HIGHLIGHTS

- PV module surface temperature reduced to 20 °C at the peak of sunlight.
- A multi-concept cooling of PV module is proposed.
- PV module efficiency/power output remains continuously enhanced.

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ABSTRACT

The efficiency and power output of a PV module decrease at the peak of sunlight due to energy loss as heat energy and this reduces the module power output. Multi-concept cooling technique, a concept that involves three types of passive cooling, namely conductive cooling, air passive cooling and water passive cooling has the potential to tackle this challenge. The experiment was set up using two solar panels of 250 watts each with both modules mounted at a height of 37 cm to create room for air-cooling, with the application of water-cooling at the surface of one of the PV modules to reduce the surface temperature to 20 °C. The rear of the same module attached to an aluminium, Al heat sink. The other module also mounted was without water-cooling and Al heat sink attachment. The Al heat sink comprises aluminium plate attached with aluminium fins to aid cooling, and water at a reduced temperature achieved with the introduction blocks of ice facilitated the module surface cooling. Analysis of the power output achieved, carried out with the help of the equation for PV array power output with a derating factor of 80%. The experiment recorded an increase in output power of 20.96 watts, and an increase in efficiency of not less than 3% achieved thus making the module more efficient and productive.

1. Introduction

Nigeria is a country, which experiences high Sunlight throughout the year, and as a result, every effort of Nigerian government focuses on taking advantage of the availability of intense sunlight to end the problem of shortage of power supply in the country. The idea is to reduce over-dependence on the hydroelectric energy power source, which is inadequate and requires huge capital every year. Due to the abundance of sunlight in Nigeria, electricity generation from solar energy resources appears more prominent than energy generation from wind.

Electricity generation from solar energy resources does not produce pollutants, and also fuelling is not required, as a result, it makes it a very favourable source of energy (Meral and Diner, 2011).

Generation of electricity from solar energy sources is a function of the efficiency of the PV module, and several factors as shown in Fig. 1 influence module efficiency.

Temperature among the numerous factors affecting the efficiency of PV module is the major factor affecting PV module efficiency and power output in Sokoto, Gusau, and other locations with similar weather condition. This is because the location experiences high temperature, long period of sunshine and setback from the use of PV power when the temperature is at its peak

With the exposure of PV module to sunlight, the amount of energy from the sun converted to useful energy is about 31%, a greater percentage change to heat energy, which tends to make the temperature of the module to rise, and this leads to a reduction in electricity produced by the module. An increase in the temperature of the module as a result of this energy wasted as heat can damage the material used to fabricate the PV module and hence reduce the cell lifespan as well as its conversion efficiency (Koteswararao et al., 2016).

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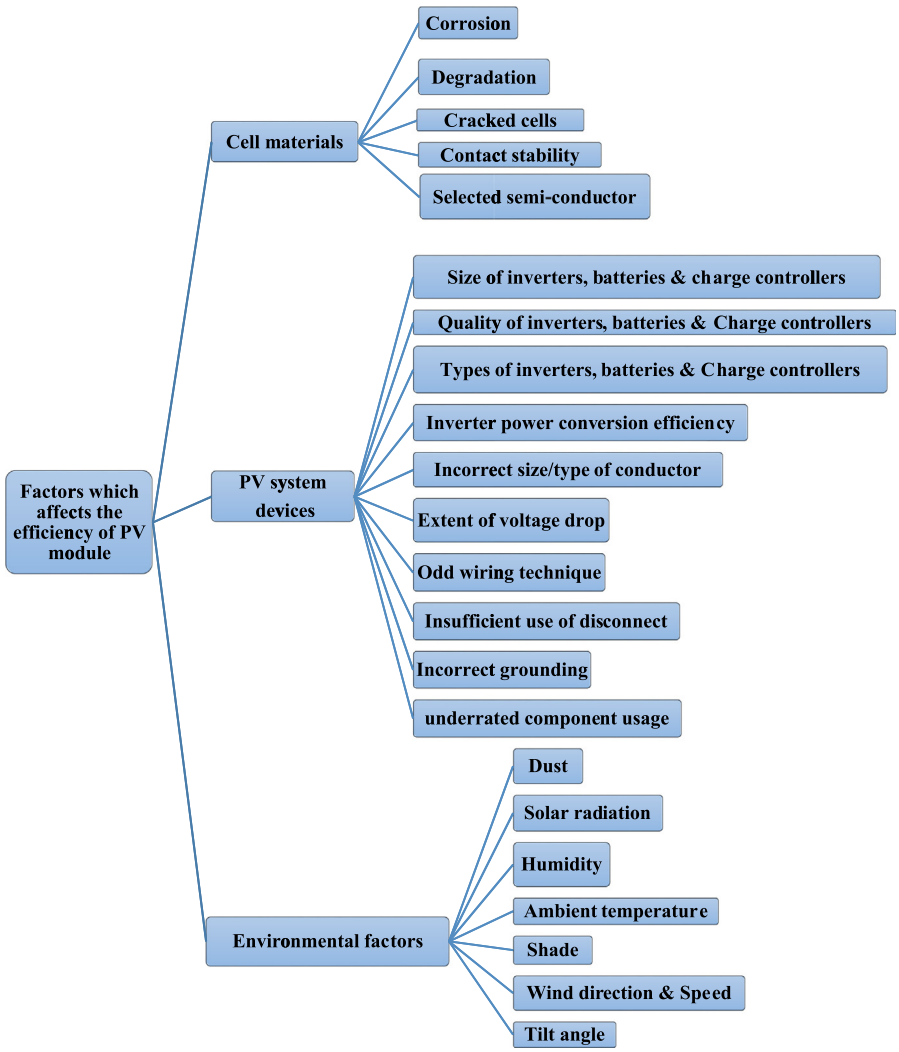


Fig. 1. Factors that affect the efficiency of Photovoltaic module.

A review of past research effort to identify a solution to the challenge of overheating of PV modules shows that a single concept cooling technique has been employed.

In Ceylan et al. (2014) an attempt was carried out to provide active cooling, a pipe whose role was to serve as a spiral exchanger was stationed on the module, the result indicates 13% increase in the efficiency of the module with this cooling approach. In a recent research, (Moharram et al., 2013) effort was made to cool the PV module using water spraying, effort was also made to ascertain how long it takes to reduce the temperature of the module to 35°C, the result indicates the module energy output was highest when cooling commenced at 45 °C. In order to reduce the temperature of the module from the rear, an attempt was made in Bahaidarah et al. (2013) where an efficiency of 9% was achieved, in this experiment an active cooling system was adopted where a heat exchanger was mounted at the back of the PV module and this helped to reduce the module temperature appreciably.

Conversely, another effort was also made to extract heat from the rear of the PV module in Alami (2014), here a sheet of clay was added to the rear of the module and a provision was made for an insubstantial amount of water to evaporate and in the process, the power output increased by 19.4%. Still on the rear of the panel, in Irwan et al. (2013) a cooling system was carried out with the help of a fan for air cooling and an appreciable amount of energy was achieved. A hybrid solar/thermal system was carried out in Teo et al. (2012) to reduce the temperature of PV modules, in this experiment, the rear of the PV module was fitted with an arrangement of air channel, an increase in efficiency of around 14% was achieved.

A past research, (Du et al., 2012) focuses on the use of active water cooling on concentrated CPV and the result shows that as the module temperature dropped below 60 °C, the power output improved. Several other efforts are ongoing to tackle the challenge posed by overheating of PV module. To achieve a more efficient use of the energy from the sun, an experiment was designed and performed in Hosseini et al. (2011) where the energy extracted through the use of a small arrangement of the water used in cooling is being channelled for another purpose so as to avoid wastage, the efficiency obtained in general was more than the regular arrangement.

Some years ago, an attempt was made in Kordzadeh (2010), to reduce the PV module temperature using an installed water pumped. In this experiment, the pump water serves as the source of cooling water to the module. The results show that the PV module and the overall efficiency improved substantially. Furthermore, the performance of PV module when immersed in water was carried out in Rosa-clot et al. (2010), an appreciable rise in the output power was achieved.

The surface cooling approach was adopted in Odeh and Behnia (2009), an effort was made here to lower the temperature at the

surface of the panel, a water arrangement was installed to provide water drizzling on the PV module surface, the experiment yielded 15% rise in output at the height of solar radiation. In Abdolzadeh and Ameri (2009), cooling of the PV module surface to reduce the temperature became the primary focus, a water pump was used for spraying the PV module as well as enhancing the operation of the pump framework. The experiment recorded a rise in the power of the cell, which causes the efficiency of the system as well as the rate at which the pump flows to increase. A cooling medium, which employs the use of siphonage was carried out in Furushima and Nawata (2006), the cooling medium was fastened to the solar module rear side of a number of PV modules connected together, cooling was achieved through the help of a number of small openings in the cooling medium at the rear of each panel through which water flows. The siphonage helped to channel water into the PV module. Cooling of the PV module improves the efficiency of the PV module, as well as the power output and, the experiment helped to generate hot water for use. In another research (Kluth, 2008) effort made to help improve the PV module efficiency using water as the cooling medium, with the spraying of the water facilitated by a fan. The results show that out of the two PV modules used in this experiment, the PV module sprayed with water facilitated with the help of a fan produced a higher power output. An observation worthy of note is that using the fan for spraying was not effective as some part of the PV module that cannot be reached were left out of the cooling process.

Furthermore, a researcher attempts to reduce the overheating of a concentrating PV module in Anderson et al. (2008), the experiment involves a concentrated solar energy obtained from the PV module and a heat pipe made of copper with water as the working fluid. Conversely, attached to the heat pipe are fins made of aluminium to aid cooling, the result shows that the heat pipe helped to channel the heat away from the PV module.

In a recent research (Dorobanţu et al., 2013) an effort was made to reduce overheating of PV cell by applying free running water at the surface of the panel. Asides cooling, the free running water washed away the dirt deposit on the surface of the panel. The experiment recorded 8.4% rise in its power output, but there was nothing to show the quantity of used pump water for cooling. Another research carried out recently, Rahimi et al. (2014) involves a wind collecting apparatus based cooling system built to reduce PV cell temperature in a hybrid Wind/PV system. The cooling system performs two functions: it reduces the PV cell temperature and generates power. The outcome of the experiment shows that both the wind and PV module recorded a 36% rise in power. A review of the possibility of using Nanofluids for cooling PV cells was carried out in Al-shamani et al. (2014), the result indicates that the temperature of the Solar thermal system can be reduced with the help of Nanofluids.

A Recent research work, Najafi and Woodbury (2013) employed the use of Peltier effect to reduce the temperature of PV modules, at the rear of the single PV cell was attached a thermoelectric unit with an assumption that the PV cell will provide the energy to operate the thermo-electric unit. A MATLAB model was developed to ascertain the system temperature, the experiment considered two techniques and the outcome shows that the temperature of a solar cell in a PV module can be kept low with the help of a thermoelectric cooling unit. Another research effort was made in Tang et al. (2010) to cool the temperature of the PV module with water or air using a micro-heat-pipe. The experimental setup is made of a PV module, which embraced air-cooling, and another PV module, which embraced water-cooling. The heat-pipe, which is attached to the rear of the module has two major parts namely the condenser part and the evaporator part. The experiment achieved cooling of the condenser part using water or air as the medium. The result of this setup attained a rise in the module efficiency by 2.6% with air, as the medium for cooling while a 3% rise in the efficiency of the PV module was achieved using water as the medium for cooling the module.

This research aims at using the multi-concept cooling technique to help reduce overheating of PV module. This is to increase the PV module efficiency and power output by cooling the module surface with water and attaching an Aluminium heat sink to the rear of the module for heat extraction. This research attempts to solve the following research questions:

- PV module efficiency/Power output reduces as the surface temperature of the PV module increases due to overheating; how do we solve the challenge of overheating?
- How can the PV module generate peak power continuously at the peak of sunlight?

1.1. PV module efficiency

Ambient temperature, as well as the temperature of the module, affects a PV module efficiency and this is because the module voltage and current depend on temperature. The PV module maximum power as expressed in Sethi et al. (2012) and Dubey et al. (2013) is

$$P_{mp} = V_{mp} \cdot I_{mp} = V_{oc} \cdot I_{sc} \cdot FF \tag{1}$$

Where P_{mp} stands for the PV module maximum power, V_{mp} stands for the maximum voltage, I_{mp} stands for maximum current, FF stands for fill factor while V_{oc} and I_{sc} stand for open circuit voltage and short circuit current respectively. As the module temperature increases, the I_{sc} rises a little bit while the fill factor and V_{oc} reduce in magnitude.

The efficiency of a PV cell as in Chikate and Sadawarte (2015) is the ratio of energy output obtained from the PV cell divided by the energy input provided by the sun as represented in Eq. (2).

$$\eta = E_{out}/E_{in} \tag{2}$$

The PV module efficiency can also take the form of Eq. (3)

$$\eta = P_{\max}/E \cdot A \tag{3}$$

Where $P_{\max}$ is the maximum power, E is the solar irradiance under STC (W/m^2) and A is the surface area of the module in m^2.

The efficiency of a solar cell can also be expressed using the relation in Kaldellis et al. (2014) as

$$\eta_{pv} = \eta_{rT}[1 - \beta(T_{pv} - T_{rT})] \tag{4}$$

Where η_{pv} represents the efficiency of the PV cell, η_{rT} is the PV module efficiency at the reference temperature, which is usually 25°C, T_{pv} is the temperature of the PV module cell, β represents the temperature coefficient of power and T_{rT} is the reference temperature of the PV module or module cell.

1.2. Temperature effect of PV module

The temperature effect of a PV module can be expressed using the equation for PV array power output as in Anon (2014) as

$$P_{pv} = Y_{pv} \cdot f_{pv}(G_T/G_{T,STC})[1 + \alpha_p(T_C - T_{C,STC})] \tag{5}$$

Where

Y_{pv} is the rated capacity of the PV array, which implies that its output power under standard test conditions (KW)

f_{pv} is the PV derating factor (%),

G_T is the solar radiation incident on the PV array in the current time step (KW/m^2)

$G_{T,STC}$ is the incident radiation at Standard Test Conditions (1 Km/m^2)
α_p is the temperature coefficient of power (%/°C)
T_c is the PV cell temperature in the current time step (°C)
$T_{C,STC}$ is the PV cell temperature under standard test conditions (25 °C)

The PV module temperature coefficient of power is essential as it helps in the determination of the deviation of power produced by the module from its values at STC (Hren, 2011), the temperature coefficient of power for this PV module is −0.44%/°C. Furthermore, the experiment considered the derating factor of PV module; this is because, PV modules, measurement in the field may indicate that the module powers obtained are different from that of the nameplate reading. Some environmental factors such as cloud, high dust concentration, shadow, etc. can reduce the efficiencies of the PV module (Yerli et al., 2010). Performing a PV module experiment with a derating factor of 0.95 implies that the test yielded power readings at STC, which are 5% lower than the nameplate rating of the PV manufacturer. The power output equation of the PV array uses this factor to account for factors like wiring losses, shading, soiling of the module etc.

This experiment used a derating factor of 0.8 to account for the losses and a derating factor of 1.0 for an installation done in an ideal situation.

The efficiency of the PV module can be expressed as in Anon (2014) as

$$\eta_{mp,STC} = Y_{pv}/(A_{pv} \cdot G_{T,STC}) \tag{6}$$

Where
$\eta_{mp,STC}$ is the PV module's efficiency under standard test condition (%).
Y_{pv} Represents the PV module's rated power output at STC (KW)
A_{pv} Is the PV module's surface area (m^2)
$G_{T,STC}$ Represents the radiation at STC (1 KW/m^2)

By substituting, for $A_{pv} \cdot \eta_{mp,STC} = Y_{pv}/(G_{T,STC})$, in Eq. (5), the efficiency of a PV module becomes

$$\eta_{mp} = P_{pv}/((A_{pv} \cdot f_{pv} \cdot G_T)[1 + \alpha_p(T_C - T_{C,STC})]) \tag{7}$$

1.3. Photovoltaic module temperature coefficient of power

For a PV module, this coefficient shows the extent to which the temperature of the PV cell affects the power generated from the module. This temperature coefficient is assigned a negative value and this is because as the temperature of the PV cell increases, the power output reduces (Anon, 2017a). The temperature coefficient of the model of 250 Watt PV module used in this experiment is −0.44%/°C (Anon, 2017b), this implies that for every degree rise in temperature above 25 °C, the module maximum power experiences −0.44% reduction. When the temperature increases above 25 °C, the power output reduces and when the temperature of the module surface reduces below 25 °C, power output increase above the module rated value is expected (Anon, 2017c).

1.4. Effect of heat on PV module

As the temperature of the PV module increases due to exposure to sunlight, heat generation commences in the process. When this heat reaches a point where the output of the PV module drops, overheating becomes evident. This overheating is one of the major challenges, which confronts Photovoltaic module's smooth operation and it is because of exposure to more than required solar radiation and high-level ambient temperatures. The overheating decreases the efficiency as well as the power output of the module. The efficiency, as well as the output power, reduces substantially as temperature rises, the extent of the reduction is a function of the material used to fabricate the solar cell (Grubišić-Čabo et al., 2016)

In order to find a solution to this challenge of overheating and loss of valuable energy as heat, cooling of PV modules is required.

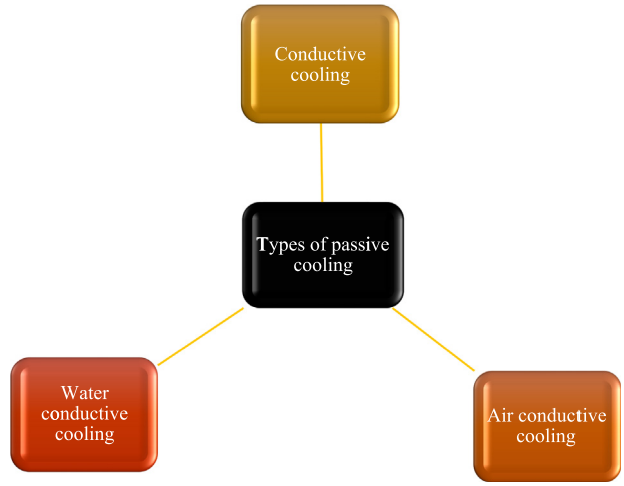


Fig. 2. Types of passive cooling.

1.5. Cooling of Photovoltaic module

A lot of research took place in the past and several others are ongoing on ways to tackle this challenge of overheating. Heat energy can be lost from a Photovoltaic module through conduction, radiation and convection, two major cooling techniques can be identified, namely Passive cooling, which requires natural means for heat removal without energy consumption and active cooling where energy consumption is needed for heat removal (Grubišić-Čabo et al., 2016). For the purpose of energy conservation, this research work embraces the concept of passive cooling. Passive cooling grouped into three major types is as shown in Fig. 2.

The process of cooling involves spraying the surface of the PV module with water while an Aluminium heat sink made of aluminium sheet with fins, is attached to the rear of the module; the PV module is also mounted at a height of 137 cm above ground level to create room for air-cooling.

2. Materials and methods

All necessary precautions observed during the conduct of this experiment, the method adopted and the materials used in the process are as shown below.

2.1. Materials

The materials used in this experiment consist of the following:

i. Two Suntech 250 watts solar PV module with the specifications shown in Table 1.

ii. The Aluminium heat sink used in this work is made of Aluminium sheet, which serves as the base of the heat sink attached with 56 Aluminium sheets as fins. Aluminium material became the choice for this design because it has lightweight and high thermal conductivity. I applied thermal grease to the base of the aluminium heat sink to help eliminate air gaps and improve thermal conductivity. The fins have openings to aid the passage of pipes for future heat extraction from the rear of the module and for generation of hot water. Furthermore, the module mounted at a height of 137 cm keeps the heat sink at a considerable height for proper air-cooling. The dimension of the heat sink is as shown in Table 2.

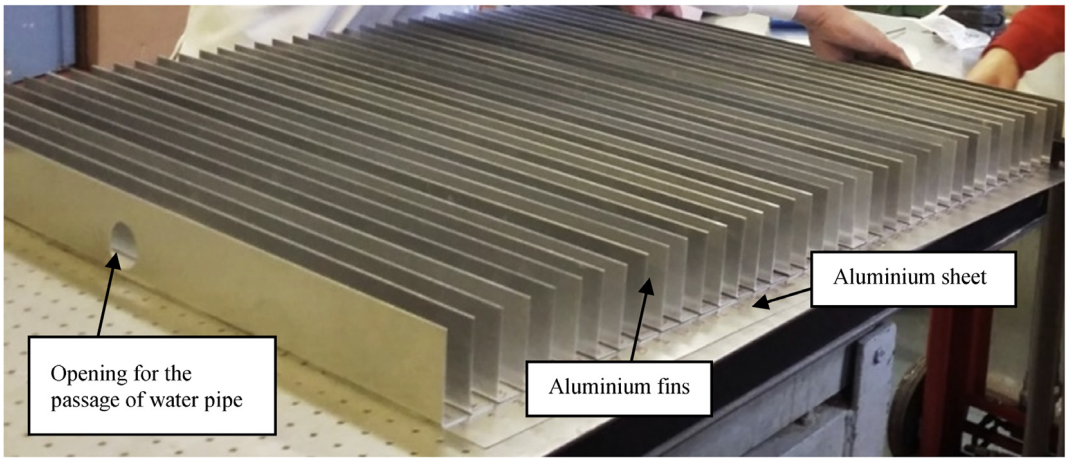


Fig. 3. Aluminium heat sink fabrication at the mechanical workshop University of Strathclyde Glasgow UK.

Table 1
Suntech 250 watts PV module (Anon, 2017b).

250 Watts Suntech PV module	
Maximum Power at STC Pmax	250 W
Optimum operating voltage (Vmp)	30.7 V
Optimum operating current (Imp)	8.15 A
Operating circuit voltage (Voc)	37.4
Short circuit current (Isc)	8.63 A
Operating module temperature	−40 °C to +85 °C
Temperature coefficient of Pmax	−0.44%/°C
Temperature coefficient of Voc	−0.34%/°C
Temperature coefficient of Isc	−0.060%/°C
Solar cell	Monocrystalline silicon 156 × 156 mm (6 inches)
No of cells	60 (6 × 10)
Dimensions	1640 × 992 × 35 mm (64.6 × 39.1 × 1.4 inches)

Table 2
Aluminium, AL heat sink dimensions.

Parameter	Value
Length of Aluminium sheet	154 cm
Length/height of Aluminium Fin	84 cm
The depth of Aluminium Fin	10 cm
The thickness of Aluminium Fin	1 mm
The width of the Fin base	2.4 cm
Spacing between fins	3.12 cm

The fabrication of the aluminium heat sink took place in the mechanical workshop of the University of Strathclyde, Glasgow. A snapshot of the fabrication process is as shown in Fig. 3.

iii. Other equipment used include:

Watering can, Infrared thermometer, Al 300 data logger (6 channels), a set of Spanners, measuring tape, combination plier, long nose plier, four multimeters, two for each of the PV modules, Meteon Irradiance meter with Pyranometer, PV module stand, flexible cable, ice blocks and 2 variable resistors, one for each module.

2.2. Experimental setup

Mounting of both 250 w, PV modules carried out as shown in Fig. 4 with one module mounted without any form of cooling, referred to as the reference PV module while the other with an attached aluminium heat sink served as the efficiency test PV module.

With the Pyranometer properly mounted, and the Al 300 six-channel data logger connected to the PV module, channels, four, five and six temperature probes were connected and fastened to the rear of the PV module without Al heat sink with the help of a tape. Conversely, with channels, one, two and three temperature probes connected to the rear of the PV module with aluminium heat sink; completes the first stage of the setup. With the modules, data logger and Pyranometer in place, two out of the four multimeters and a rheostat connected to the PV module without Al heat sink while the remaining two multimeters and the second rheostat connected to the PV module with attached Al heat sink makes up the second stage as shown in Fig. 5.

2.3. Site selection

This experiment took place in Sokoto State, Nigeria located within Latitude 13.1274 and longitude 5.2046 with the PV module tilted properly to ensure maximum reception of radiation from the sun. The PV modules and Pyranometer did not experience any form of shading each day from the rising of the sun to the setting of the sun.

2.4. PV module orientation and tilting

The PV modules were initially mounted without Aluminium heat sink attached to any at two different tilt angles, one module was tilted at an angle of 13° facing due south while the other was tilted at an angle of 15° facing due south so as to determine the best tilt angle for the PV module at the research location. After comparison, the result of the module tilted at an angle of 15° was better, which is the recommended tilt angle for a fixed system in site latitude between 0° and 15°.

Mounting of the PV module with attached Aluminium heat sink and that without Aluminium heat sink carried out facing due south and tilted at an angle of 15°. With the help of the Pyranometer, recording of the solar irradiance data in W/m^2 took place successfully and all the readings taken at an interval of 15 min.

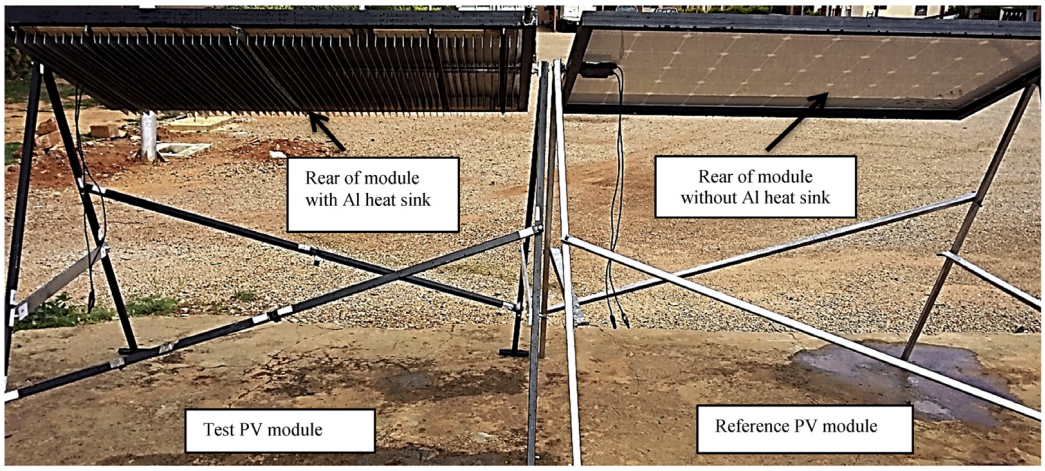


Fig. 4. Test PV module and Reference PV module.

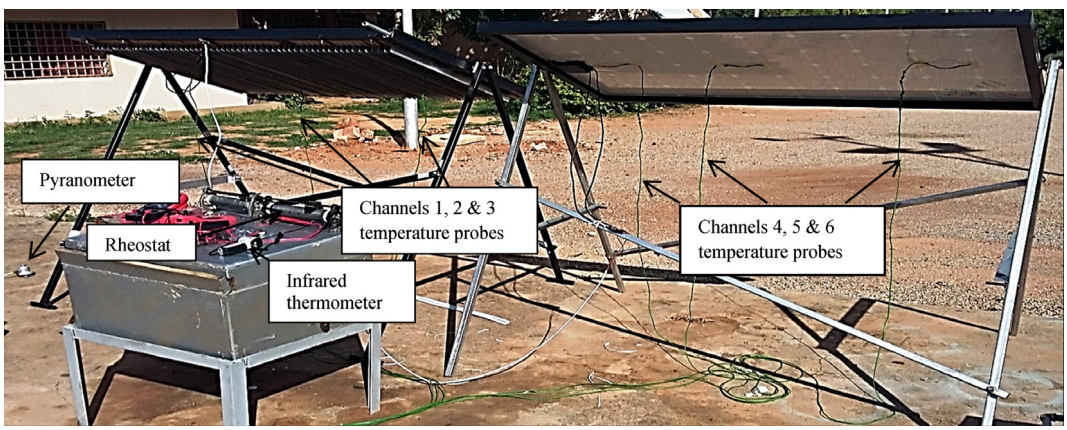


Fig. 5. Experimental setup.

2.5. PV module temperature

In this experiment, several temperature readings were taken, the temperatures in the rear of both PV modules were taken with the help of Al 300 six channels data logger while the temperatures at the surface of both PV modules were taken with the help of an infrared thermometer. I had the temperature probes of the data logger attached to the rear of the panel with the help of a tape, to aid accurate determination of the rear temperature of the PV module.

On the other hand, I used an Infrared thermometer to take the surface temperature of the PV module. This is because, attaching a data logger temperature probe at points on the surface of the PV modules, like I did with the rear of the module, will cast a shade on some part of the module surface and in the process, lead to energy loss due to shading. Another step taken was the spraying of water on the PV module surface carried out at intervals, to help reduce the temperature of the panel to enhance its energy conversion efficiency as shown in Fig. 6.

Temperature readings during the experiment were taken at intervals of 15 min, it was observed after spraying the module with water, because of the high ambient temperature in the location, the surface temperature of the module rises almost immediately. Ice blocks became useful in this work when added to the cooling water as it helps to reduce the temperature of the cooling water and the quantity of water used for cooling. Ice blocks are cheap and affordable in this community, and as such, a number of blocks of ice added to the cooling water helped to reduce the temperature as using cold water-cooling would go a long way to enhance the energy conversion efficiency of the PV module. Samples of Ice blocks and ice blocks in the watering can are as shown in Fig. 7(a) and (b) respectively.

2.6. Output current and voltage

The voltage and current of each of the modules were obtained with the help of the multimeters, which were used as voltmeters and ammeters respectively, two variable resistors of 10 Ω each was used in this experiment. With the output terminal of each of the PV modules short-circuited with a wire, the short circuit voltage and the module output voltage measured with ease. Conversely, I had a variable resistor of 10 Ω connected to each of the modules, and readings for the current and voltage were taken starting from the lowest resistance to the highest. Other readings taken include current and voltage when the module is in open circuit, voltage and current for the following values of resistance, 1.43 Ω, 2.86 Ω, 4.29 Ω, 5.27 Ω, 7.15 Ω, 8.58 Ω and 10.0 Ω.

2.7. PV module power output

The setup achieved electricity production via the ability of the PV modules to generate current through the 10.0 Ω variable resistor and voltage across the same variable resistor simultaneously at constant Irradiance. The expression for the module output power is as given in Eq. (1).

Fig. 6. Manual water spraying of the module.

(a) (b)

Fig. 7. (a) Ice blocks and watering can. (b) Ice blocks in a watering can.

3. Results and discussion

3.1. Solar radiation

Recording of the Pyranometer readings took place between 9: am and 4: pm on a daily basis at an interval of 15 min as shown in Fig. 8.

During the rising of the sun in the morning, the radiation from the sun is low and it increases as the intensity of the sunlight increases, but with little drops until 13.00 pm when the solar radiation reaches its peak, after which there are some fluctuations in the radiation, but as the setting of the sun approaches, the radiation reduces progressively.

3.2. Temperature readings

The temperature readings such as ambient temperature, the temperature at different sections of the two modules alongside the solar radiation taken at intervals of 15 min are as shown in Figs. 9–12.

The ambient temperature increases with an increase in the intensity of the sun and as a result, there is an increase in both the surface and rear temperature of the PV. The surface of the PV module experiences the effect of sun intensity mainly; as a result, the temperature on the module surface is higher. Heat usually flows from the hotter object or surface to the cooler object or surface, there was heat transfer from the module surface to the rear of the module attached with Aluminium heat sink, this makes the temperature of the rear of the PV module, higher than the ambient temperature. At the start of the experiment, the module surface temperature was 40.3°C, after which, it rises with few fluctuations. The module surface temperature remains higher than that of the rear and the ambient temperature, but at 12:45 pm, 13:45 pm, 14:45 pm and 15:45 pm, the module surface temperature was lower than the ambient temperature and its rear temperature, and this is because the module surface was sprayed with water during those periods. The module surface reached a peak temperature of 57.2°C at 12:15 pm as shown in Fig. 9.

Unlike Fig. 9, the peak temperature of the module surface was 66 °C while the peak temperature of the rear of the module was 60 °C, and this module is not fitted with aluminium heat sink, and not sprayed with water. The graph shows that the module surface temperature is highest, followed by the module rear temperature, the rear temperature is higher than the ambient temperature because of the heat transfer from the module surface to the rear.

The temperature of both modules was the same at the start of the experiment, but as time progresses, there was a progressive difference in temperature between the two modules. The temperature reading obtained from the module without attaching aluminium heat sink, at each interval appears higher than the values obtained from the module attached with the heat sink. The difference in temperature progresses gradually, the difference becomes more at 12:45 pm, 13:45 pm, 14:45 pm and 15:45 pm after spraying the module with water to reduce the module temperature.

Temperature readings from the module without attaching aluminium heat sink, appear higher than the readings obtained from the module with attached aluminium heat sink & water cooling, this is because heat energy is extracted from the rear of the module with the help of the attached aluminium heat sink.

3.3. Maximum voltage, maximum current and maximum power output

Cooling of the PV module with well water at a temperature of 35°C and cooling of the PV module surface temperature to 20 °C by introducing blocks of ice into the cooling water performed with

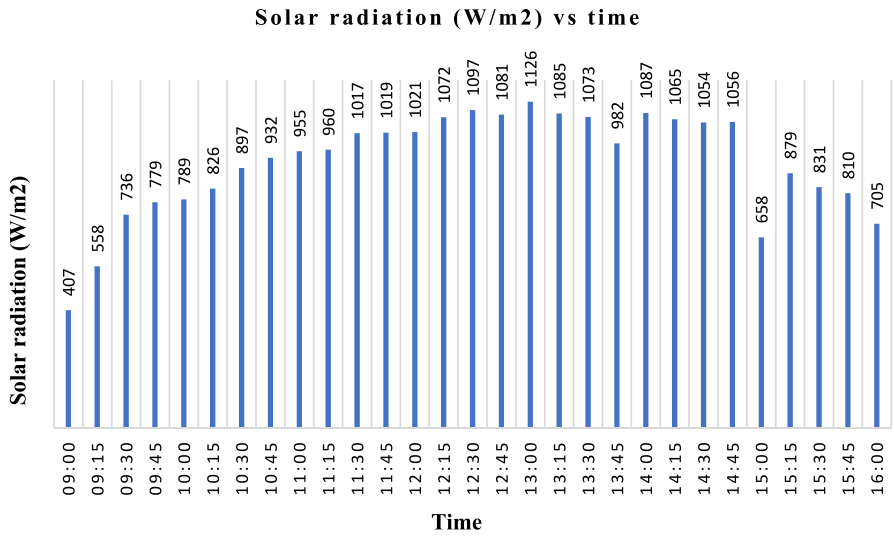


Fig. 8. A graph of solar radiation Vs time.

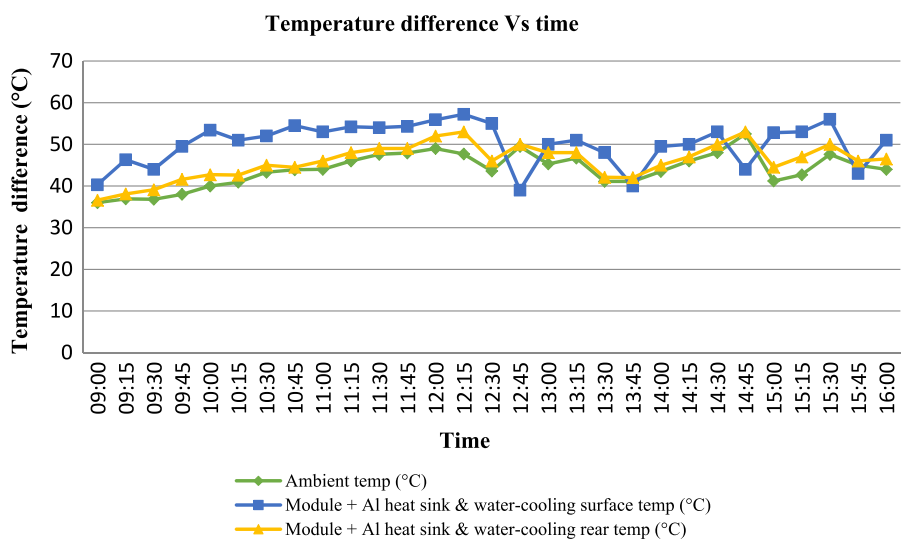


Fig. 9. A plot of ambient temperature, module + Al heat sink & water cooling surface and rear temperature (°C) Vs time.

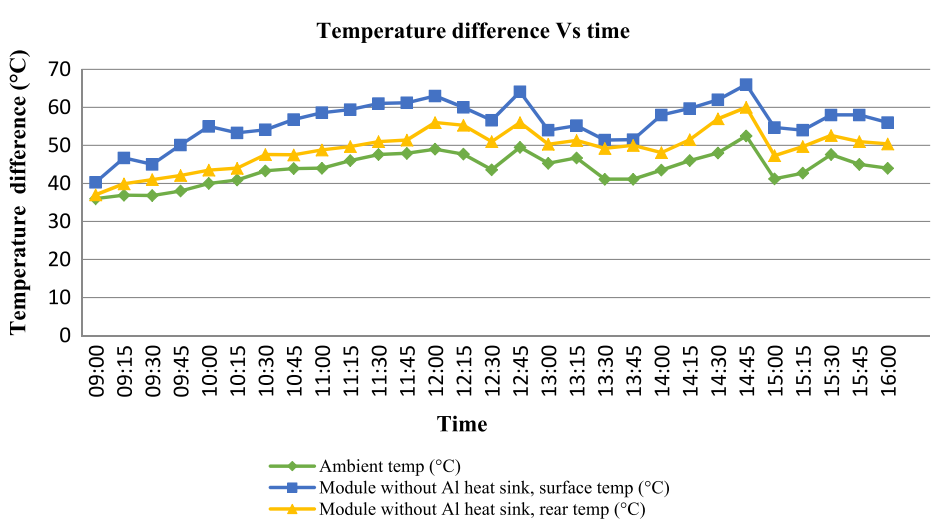


Fig. 10. A plot of ambient temperature, module without Al heat sink's surface and rear temperature (°C) Vs time.

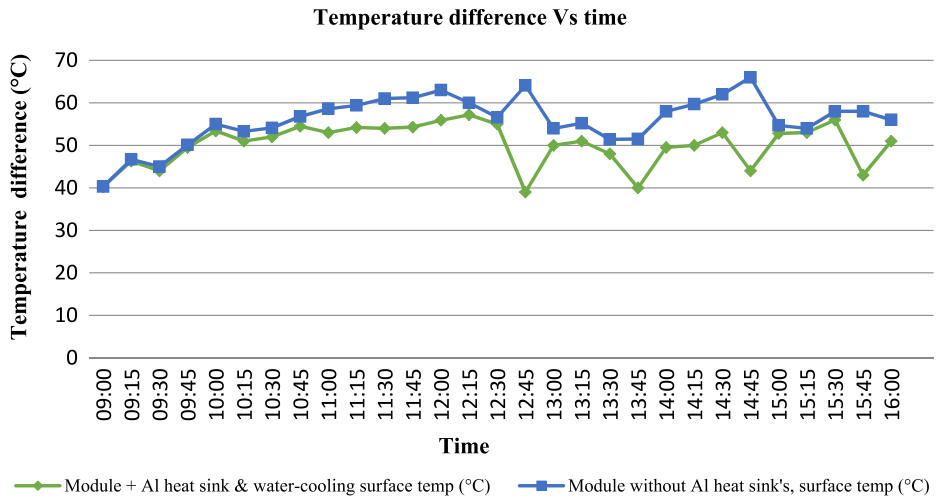


Fig. 11. A plot of module + Al heat sink & water-cooling and the module without Al heat sink's surface temperatures (°C) Vs time.

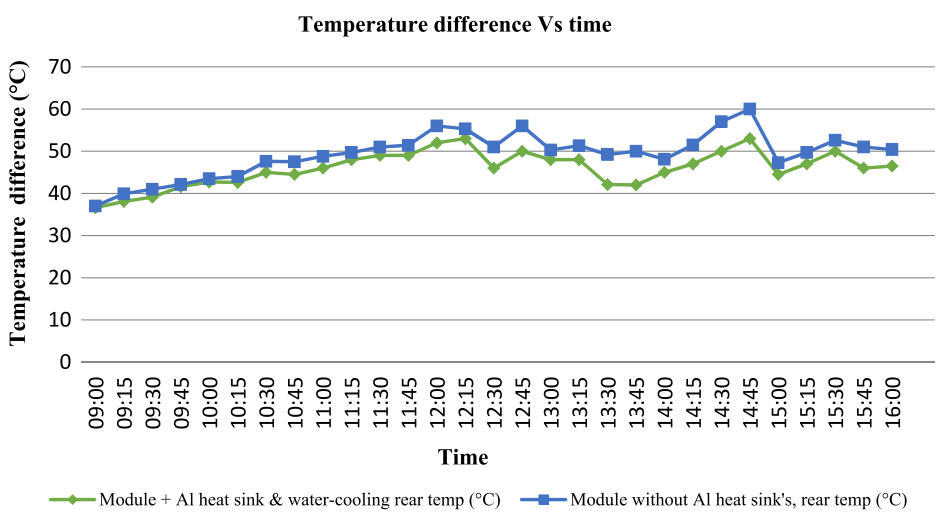


Fig. 12. A plot of module + Al heat sink & water-cooling and the module without Al heat sink's rear temperatures (°C).

readings taken. A plot of resistance against maximum Voltage, maximum current and maximum power is as shown in Fig. 13(a), (b) and (c) respectively.

From Fig. 13, in (a) the maximum voltage increases progressively as the load increases, in any of the three cases, it can be seen that the maximum voltage obtained increases with an increase in the load. Conversely, the maximum voltage obtained cooling the module with water to a temperature of 20°C is more, and that obtained from the module + heat sink & water-cooling is more than that obtained from the module without a heat sink & water-cooling.

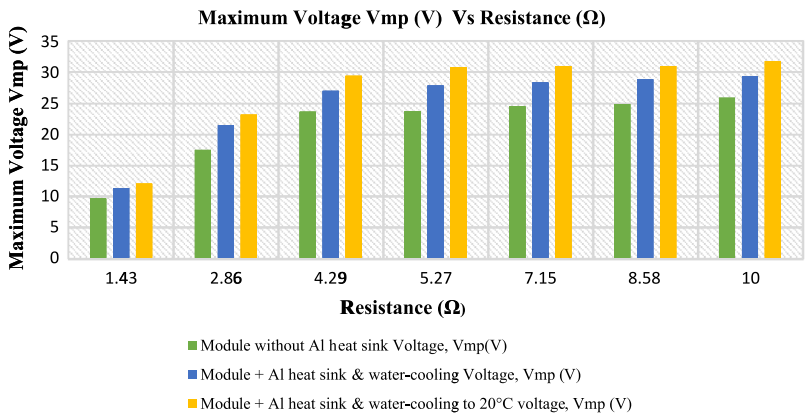
In (b) the value of the current obtained in each case, reduces as the load increases, but with the highest values for current obtained with water cooling of the module to a temperature of 20 °C, this is followed by the values of the current obtained from module + Al heat sink & water cooling.

Conversely, the maximum power measured as shown in (c), increases with the peak power obtained at a load of 4.29 Ω, the power shows that the power output obtained with the module + Al heat sink & water-cooling is more than the power output achieved with module without Al heat sink and also. The highest power output was achieved with module + Al heat sink & water-cooling of module surface to a temperature of 20 °C.

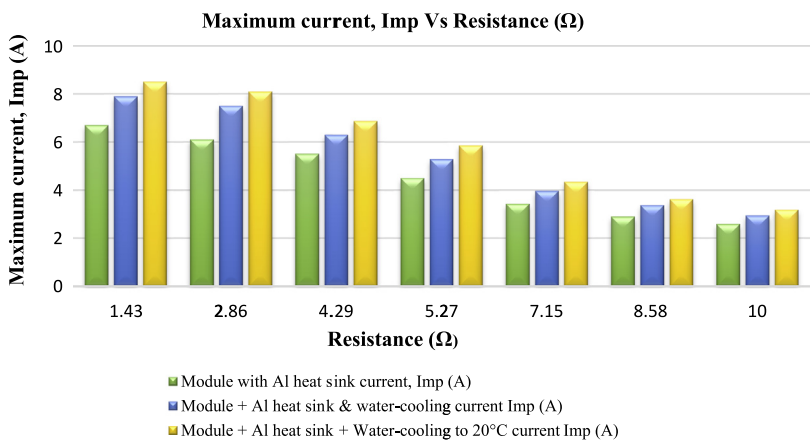
In order to consider the temperature coefficient of power, the calculation of the power output considered a derating factor of 0.8 and 1 using Eq. (5), the results are as shown in Figs. 14 and 15.

In Fig. 14, the temperature of the module increases as the intensity of the sun increases, but with a reduction at 12:45 pm, 13:45 pm, 14:45 pm and 15:45 pm during which cooling of the module with water took place. The experiment recorded an increase in power output at each stage of cooling except at 13:45pm where it recorded a decrease in the power output even with water-cooling and this was because of a reduction in solar radiation experienced at that time. The reduction in solar radiation experienced at 13:45 pm is as shown in Fig. 15.

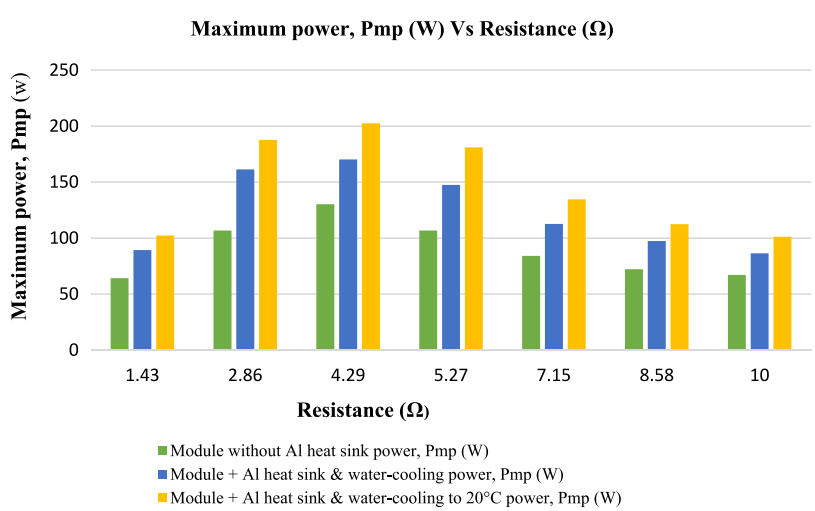
The power output at a derating factor of 0.8 and 1 as shown in Figs. 14 and 15 indicate that the experiment considers losses for the setup at a derating factor of 0.8 and no losses at a derating factor of 1. The graphs show that power output increases with time, but with fluctuations due to changes in the intensity of the sun or ambient temperature. The setup achieved peak power both at a derating factor of 0.8 and 1 at 12:45 noon, this is because the solar irradiation was high at the time and the temperature of the module was 39°C. This experiment considers the values of power output obtained with a derating factor of 0.8 to account for losses.



(a) Maximum voltage measured.



(b) Maximum current measured.



(c) Maximum power measured.

Fig. 13. (a) maximum voltage Vs load (b) maximum current Vs load (c) maximum power Vs load.

Fig. 16 shows the effect of using the Aluminium heat sink at the rear of the module. The first attempt to cool the module using water took place at exactly 12:45 pm; before this time, the power output obtained from the module + Al heat sink & water-cooling gradually increases above that of the module without a heat sink and water-cooling. This implies there is a slight improvement in the module efficiency.

Water flow on the module surface may act as a reflecting mirror and reflect the solar radiation away from the module during water spraying on the surface of the module, in order to minimize this, spraying of water on the module surface was not done continuously, instead, it was done intermittently. Furthermore, in order to improve the efficiency of the PV module during water flow on the module surface, I used a semi-transparent PV module for the

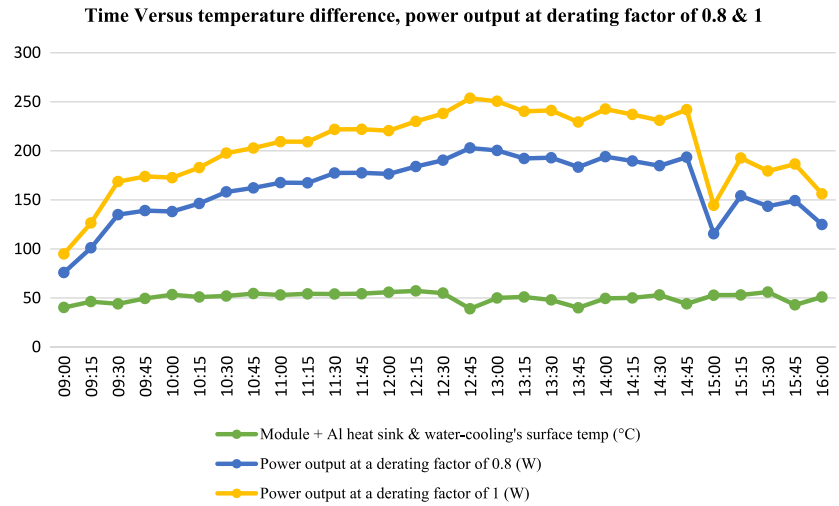


Fig. 14. A plot of time against temperature difference and power output at a derating factor of 0.8 & 1.

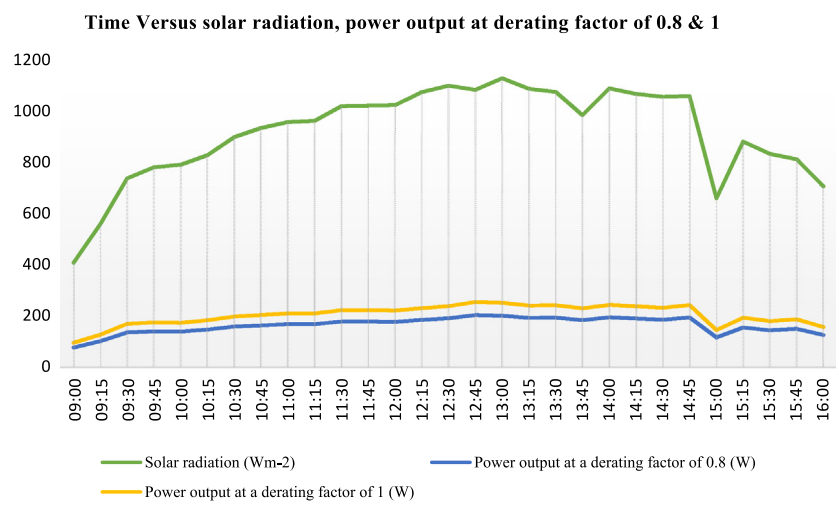


Fig. 15. A plot of time against solar radiation and power output at a derating factor of 0.8 & 1.

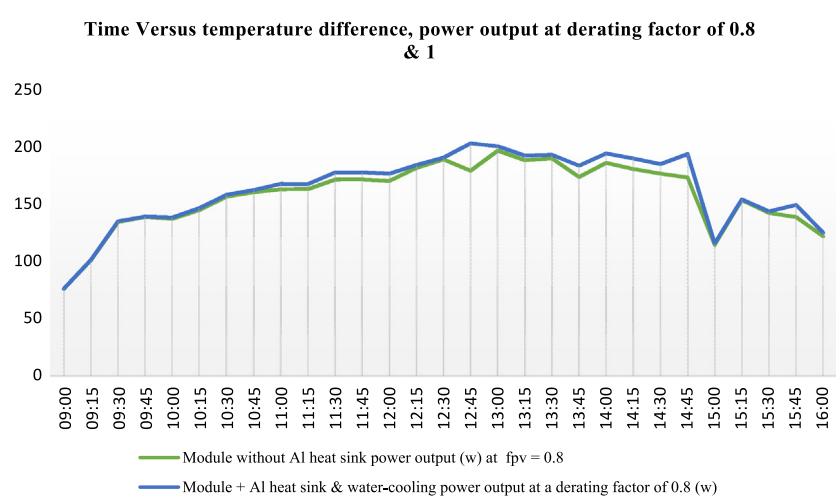


Fig. 16. A plot of time against power output at a derating factor of 0.8 for module with cooling and module without cooling.

Table 3
Module power output at a derating factor, f_{pv} = 80%.

Time	Module without Al heat sink power output (w) @ a f_{pv} = 80%	Module + Al heat sink & water-cooling, power output (w) @ a f_{pv} = 80%	Module + Al heat sink & water-cooling of module surface to 20 °C, power output (w) @ a f_{pv} = 80%
12:45	179	202.9	220.96
13:45	173.5	183.4	200.72
14:45	173.1	193.5	215.85
15:45	138.48	149	165.56

experiment (Tiwari et al., 2015). The PV modules stand the risk of experiencing increased leakage current, which will result in potential induced degradation of the PV modules as Luo et al. (2017). The measures to help minimize potential induced degradation of the PV modules include:

- The use of certified PID resistant PV modules
- The use of strings with negative terminal grounded
- The use of isolation transformers between the strings and inverters
- Early installation of anti-PID equipment.
- Ensuring reduced accumulation of water on the module to avoid leakage of charges

Water-cooling of the PV module and the cooling of the PV module surface to 20 °C performed at 12:45 pm, 13:45 pm, 14:45 pm and 15:45 pm generated the result shown in Table 3.

A 250 W PV module considered with a derating factor of 80% implies that the power output expected from the module in an ideal situation is 200 W. Since the maximum power expected from the PV module is 200 W, power output in excess of 200 W is an addition. In Table 3, module + Al heat sink & water-cooling generated more power than the module without Al heat sink and the higher power output generated by the PV module was achieved with module + Al heat sink & water-cooling of module surface to 20°C. At 12:45 pm, 13:45 pm and 14:45 pm, power output exceeded 200 W by 20.96 W, 0.72 W and 15.85 W respectively.

Eq. (7) for PV module efficiency was used with the following values $Ppv = 250$ watt, $fpv = 1$, $T_C = 25$ °C and $T_{C,STC} = 25$ °C and an efficiency of 15.4% was achieved. This 15.4% is the value of the SUNTECH 250 watt module efficiency as stated in the manufacturer's specification sheet. Using a module surface temperature, $T_C = 20$ °C, with an irradiation of 1081 at a derating factor of 0.8 yields an efficiency of 18.8%. Conversely, by using Eq. (4) at a temperature of 20°C gives an efficiency of 18.48%.

4. Conclusion

This experiment achieved the following results:

- An appreciable increase in the module output power with module + Al hint sink & water-cooling of the module surface temperature to 20°C.
- An output power increase of 20.96 W at 12:45 pm at 80% derating factor used in order to account for losses. This increase in output exceeds 250 Watts with 0% losses.
- An increase in efficiency above 3%, hence the PV module and the power output were enhanced using the multi-concept cooling technique.

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