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An Assessment of Photovoltaic Array Cooling by Water Spray in Smart Standalone Multifunction Hybrid Energy System

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ABSTRACT

Only a part of solar radiation can be directly converted to electricity in Photovoltaic technology. The major portion of solar radiation is converted to heat, causing a rise in the temperature and decreasing the PV module's performance. Therefore, this paper presents the evaluation of the photovoltaic array performance with and without active water spray cooling in a hybrid standalone solar system. The experimental prototype of the system was developed for power generation, PV cooling, electrical power storage, and smart irrigation. A smart PV cooling system was designed and developed using 60 water sprayers to shower mist on each PV panel in the PV array. A solenoid valve was used to charge the PV cooling water when the PV temperature increased to NOCT or more. The measurements showed that the average PV temperature without cooling was around 69 °C at 995 W/m^2 solar irradiance. Results showed that the highest decrease in PV temperature with water spray cooling is 11.8% at solar irradiance of 754 W/m^2. A one-degree temperature rise of the PV module without cooling has decreased the electric efficiency by about 0.0463%. PV performance enhancement with water spray cooling is a maximum of 3.72% higher than PV without cooling at the highest solar irradiance.

1. INTRODUCTION

Solar energy stands as the primary renewable energy. Earth receives abundant solar energy in the form of light, which can be converted directly to electricity using photovoltaic (PV) technology. The commercially available PV cell today was invented in Bell Labs in 1954 and continues to develop. PV physics and energy conversion are discussed by Smets et al. [1], and the technology and applications are discussed by Polus and Abdullah [2]. Numerous developments have taken place to improve the PV panel performance due to its vast applications from home and industrial electricity demand, to running space programs [3]. The familiarized PV technology commercially preferred is polycrystalline and monocrystalline, which have the best efficiency of 15% and 24%, respectively. However, the second is expensive compared to the first [1, 4].

A downside to current solar PV technologies is that only a small part of solar radiation can be converted to electricity, but a major portion of solar radiation is unused and converted to heat. PV temperature increases with an increase in the heat. Further, the increase in PV temperature causes a decrease in PV efficiency and is referred to as thermal degradation. In crystalline-silicon PV, efficiency decreases by about 0.5% with an increase of every degree of temperature. The best solar PV efficiency is achieved at the Standard Test Conditions (STC), such as the PV operating temperature of 25 °C, irradiance of 1000 W/m^2, and air mass spectrum of 1.5 [5, 6]. Thermal degradation of PV performance is one of the key challenges under environmental losses. The performance of PV could critically drop around noon as the PV temperature can go up to 65 °C or more [7]. Operating PVs at temperatures higher than STC not only affects the PV performance but also affects the lifespan of the PV. According to a survey study presented by Dhimish and Badran [8] for 3.3 million PV modules to identify thermal defects, it was found that 36.5% of all PV modules have thermal defects.

Cooling PV panels is needed to operate them to their rated capacity and as per their estimated life span. Various active, passive, or combined cooling methods can be used to lower the PV temperature, such as air cooling [9], water cooling by spray [10], water cooling by dripping [11], water cooling by film [12], nanofluid cooling [13], phase change material (PCM) [14], heat sinks [15], and ground embedded heat exchangers [16, 17]. However, the state of the art on PV cooling is radiative cooling [18].

Elavarasan et al. [19] conducted an experimental analysis of PV cooling with the aid of PCM, fins, and water for the study location Thiagarajar College of Engineering, Madurai, Tamil Nadu, India. The authors found that PV temperature without cooling can go as high as about 73 °C. PV temperature with the cooling technique reduced to a maximum of 16.7 °C, and that led to an enhancement in PV electric efficiency by about 20.13%. In the study of Ibrahim et al. [20], the authors presented four PV cooling techniques consisting of PCM, fins, and free and forced convection for the location of Lebanon's Bekaa Valley. They found that integrating internal and external fins with PCM and applying forced convection is a better technique to minimize PV thermal degradation. Their best-suggested technique dissipated excess heat by 63.6% and increased efficiency by 20.36%. Hasan et al. [21] developed a micro-jet PV cooling system for the experimental analysis in the city of Bangi, Selangor, Malaysia. PV without cooling had an increase in temperature from 32.5 °C to 66.5 °C between 10 am and 1 pm. The increase in PV temperature reduced the PV efficiency from 14.5% at 32.5 °C to 12.25% at 66.5 °C. Meanwhile, the performance drop was found to be from 96% at 32.5 to 93% at 66.5 °C.

Alharbi et al. [22] coupled the PV panel with an evaporative cooling system for Saudi Arabia. They found that cooling of PV has reduced PV temperature from 62.3 to 40 °C at a water flow rate of 0.3 Liter/hour. PV cooling has led to an improvement in PV efficiency by about 12.7%. In the study of Atia et al. [23], they used 24 monocrystalline PVs at Egypt's electronics research institute to determine the effect of environmental parameters, such as temperature, on the PV performance. They reported that PV energy output degrades with temperature. The performance ratio obtained was 85.9% for their case study location. In the numerical study of Khelifa et al. [24], they provided an optimal solution for air cooling of PV using a single slot at the bottom side of PV. With an optimized design, the improvement of thermal efficiency was reported by about 15.68%. Santiko Wibowo et al. [25] investigated various types and diameters of nozzles for optimum PV spray cooling. Their experimental results show that a cone nozzle with a 2 mm outlet diameter could reduce the PV surface temperature from 61.96 to 36.51 °C and increase efficiency from 11.0% to about 14.45%.

More recently, Polus and Abdullah [2] performed an experimental investigation on PV cooling by water spray. They show that the three-sided installations of the spray nozzles are superior to the one-sided arrangement. A three-sided water spray with a 5 l/min flow rate has increased the power production of the PV module by 20.3%.

Literature shows that the previous studies of PV cooling have been mostly performed on PV modules. According to the best knowledge of the authors, PV cooling performance assessment within an integrated PV in a hybrid standalone energy system is not reported in the literature. This study evaluates and presents an experimental assessment of a 2.5 kW PV array within a hybrid solar-rain energy system. The array consists of 10 PV modules. The paper presents an analysis of variables affected due to an increase in the PV cell temperature. Active water spray cooling has been carried out on a smart PV cooling system that does not require human intervention. PV module temperature, power output, electric efficiency, and performance ratio are compared for the PV with cooling and without cooling.

2. RESEARCH METHODOLOGY

The effect of PV water cooling was assessed as part of a solar-integrated standalone system for power generation. A smart PV cooling system was designed and developed to operate without human intervention. This section also provides a detailed procedure for weather data and PV cooling data acquisition and analysis.

2.1 Case study location

Performance analysis of an array of PVs with active water spray cooling was carried out at the Solar Research Site in Universiti Teknologi PETRONAS, located at Bandar Seri-Iskandar, around 28 km from Ipoh City, as pointed in the map of Malaysia shown in Figure 1. Malaysia receives abundant amounts of solar radiation throughout the year. The average solar irradiation in Malaysia ranges from 4.7 to 6.5 kWh/m^2 [26]. The average number of hours is around 4.2 to 5.2 for the PV power yield at different locations in Malaysia. For the city of Ipoh in Malaysia, the average PV power yield is around 5.0 kWh [27].

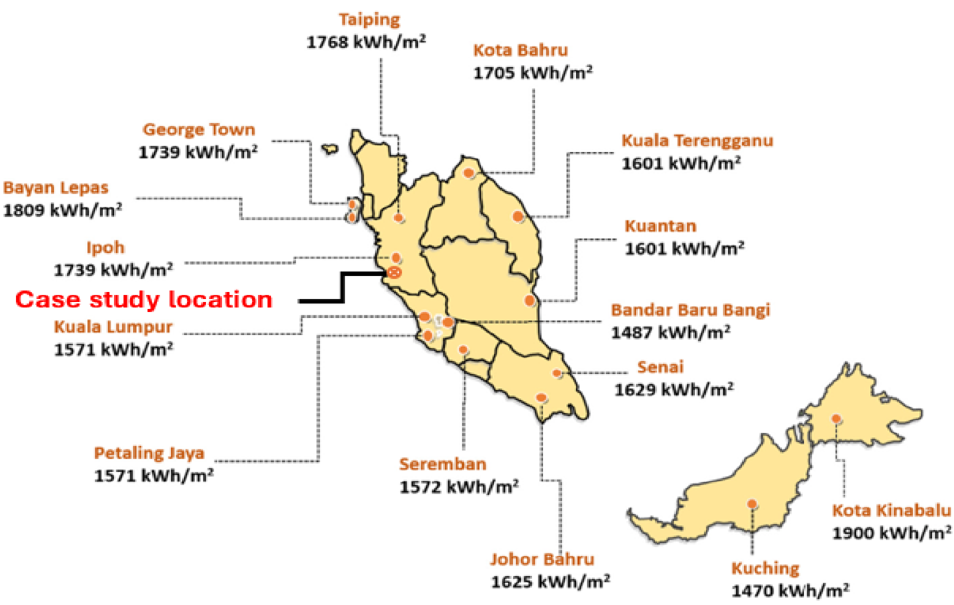

Figure 1. Yearly global solar irradiation at different locations of Malaysia [26]

2.2 Photovoltaic and smart Photovoltaic cooling system

The study location had an installed PV capacity of 10 kW for powering the site. However, for the performance analysis of PVs with cooling, an array of PVs was formed by connecting two strings in parallel. A string was formed by connecting 5 PV modules in series for the increased voltages to five times and the same current output. The PV modules were from CanadianSolar with model number CS6P-250P, and their technical parameters are shown in Table 1. The nominal power output of a PV panel is 250 watts under STC. The PV panel's open-circuit voltages and short-circuit current are 37.2 V and 8.87 A, respectively.

Table 1. Technical specifications of the photovoltaic (PV) panels at Standard Test Conditions (STC) (AM1.5, 25 ℃, 1000 W/m^2)

Parameter	Data
Manufacturer	CandianSolar
Photovoltaic Model	CS6P-250P
Type/Number of Cell	Poly/60
Power at STC, P_{mp}	250 W
Optimum operating Voltage at STC, V_{mp}	30.1 V
Optimum operating Current at STC, I_{mp}	8.30 A
Module Efficiency	15.54%
Temperature Coefficient (α)	-0.43% per ℃
Nominal Module Operating Temperature (NOCT)	45 ± 2 ℃
Area of a Photovoltaic panel	1.61 m^2
Photovoltaic life span	25 Years

Note: Standard Test Conditions=STC.

As shown in Figure 2, water sprayers, or known water nozzles, were connected at the top side and top edge of the PV module. The water sprayer inlet was 4 mm. A string of PV modules was provided with around 30 water sprayers to let the water flow on each column of the solar cells in the string of 5 PV modules. Each water sprayer was adjusted to cover the misting area by 6 cm. An adjusted water sprayer measured the maximum water flow to around 6 liters/hour. Water tanks with a combined water capacity of 4.1 m^3 were used to supply water for the PV cooling, with a net water pressure head at the inlet of the sprayer of 2 m and 0.6 m as the maximum and minimum, respectively, corresponding to the water level in the tanks.

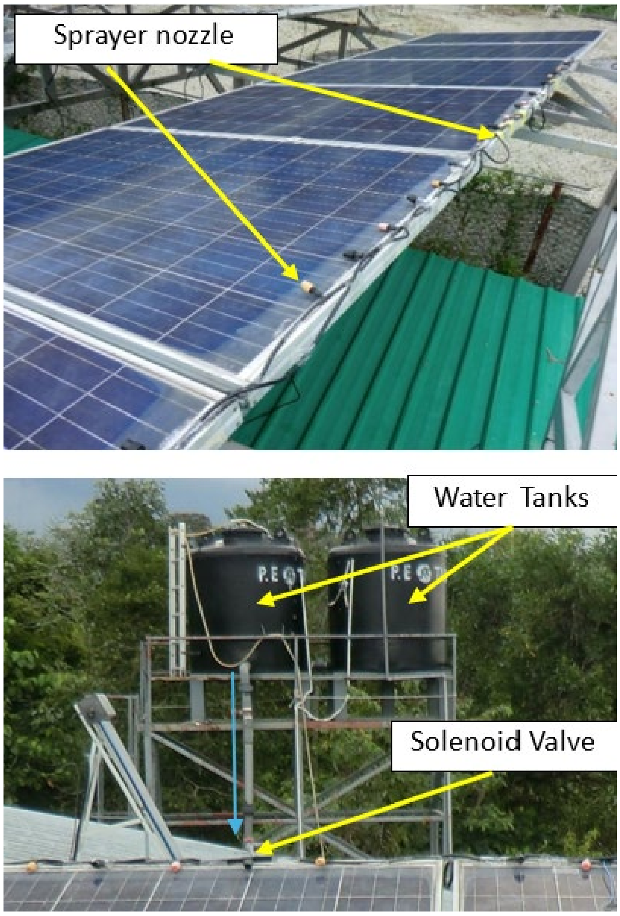

Figure 2. Arrangement of water sprayers used for the photovoltaic (PV) cooling

A smart PV cooling system was designed, as shown in Figure 3. The smart PV cooling system consists of a Controller, a Relay, a solenoid valve, and thermocouples. PV cooling was conditioned on the average PV cell temperature to be equal to or more than the nominal operating cell temperature (NOCT), i.e., 45 ℃ for PV. The PV cooling continued until the PV cell temperature decreased by 10 ℃ from NOCT. The set condition for the PV cooling to enhance the performance on a hot day is the same as that adopted by Moharram et al. [28].

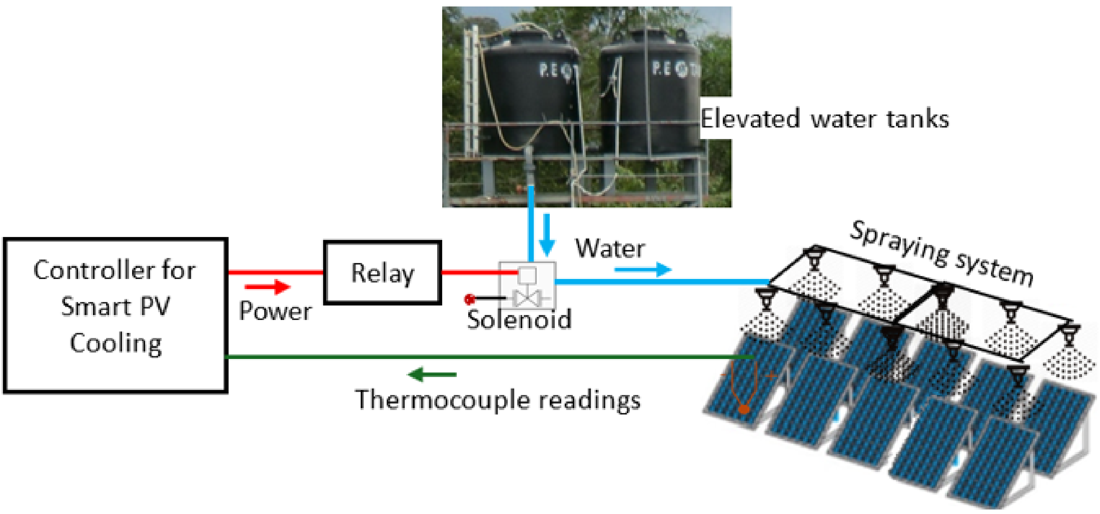

Figure 3. Layout of the smart hybrid standalone energy system, including the photovoltaic (PV) cooling and setup

The smart PV cooling system was developed using three K-type thermocouples, a GP 2 advanced datalogger and controller from Delta-T, and a solenoid valve, as shown in Figure 4. PV surface temperature was recorded with three thermocouples, and those were placed to touch the top surface of a PV panel to record the temperature reading at the position 100 mm below the top edge towards the left side, the center position, and the position 10 cm above the bottom edge towards the right side. The GP2 advanced datalogger and controller were accessed through DeltaLINK software, and conditions for the relay operation were defined to supply power for operating the solenoid valve. An average PV cell temperature was calculated based on predefined user instructions. When the average PV cell temperature was more than or equal to the NOCT of PV, the relay contact was closed to open the solenoid valve for commencing the PV water cooling. PV water cooling continued until the average PV cell temperature decreased by 10 °C from NOCT.

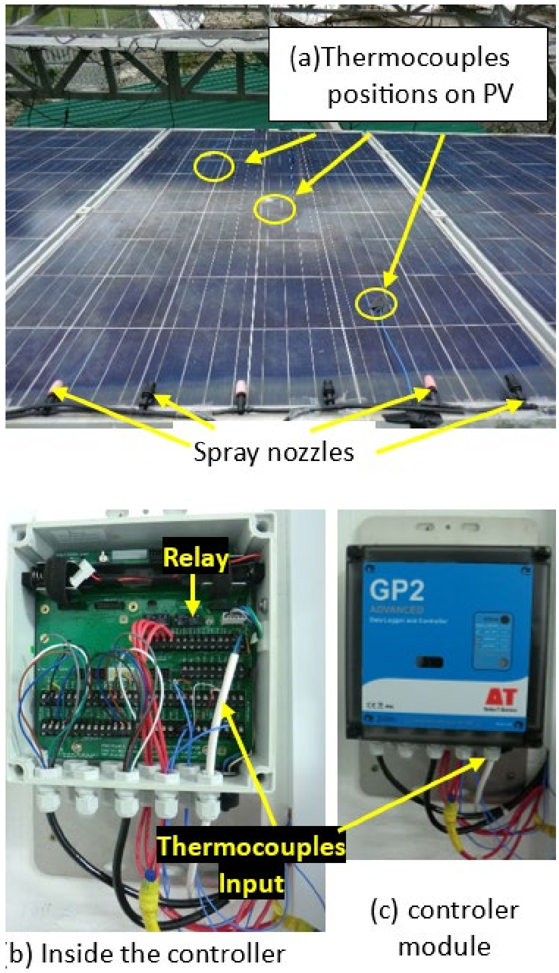

Figure 4. Photovoltaic (PV) cooling system (a) thermocouple positions, (b) inside controller, and (c) controller module

2.3 Data acquisition procedure

Data for the smart PV cooling, such as the PV surface temperature and water flow rate required to cool the PV, are recorded using the thermocouple type-K and an area-reducing flow meter, respectively. The reading for the average PV surface temperature was recorded for every one-minute interval. An area-reducing flowmeter was used to record the maximum and minimum flow passing through the pipe based on the minimum and maximum water levels in the water tanks. Data for the PV power output was recorded through an IoT using the Victron Cloud. An MPPT used for the PV power output was from Victron Energy, and it recorded the current and voltage output of PV at every 5-minute interval.

Weather data for the input solar irradiance, ambient temperature, and rainfall for one-minute intervals were recorded using the weather station available at the case study location. The weather station consisted of a pyranometer, rain gauge, humidity sensor, and temperature sensor, as shown in Figure 5. Data for the weather was recorded in the datalogger, namely DataTaker.

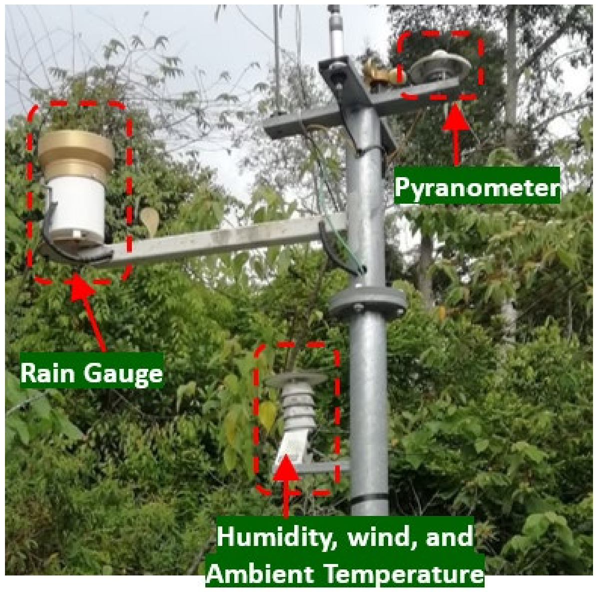

Figure 5. Weather station at solar site, Universiti Teknologi PETRONAS, Malaysia

2.4 Mathematical representations

PV module temperature in local weather conditions can be determined by referring to the IEC International Standards for NOCT of PV. NOCT is used to determine the PV thermal characteristics in hot weather environments where the standard test conditions (STC) are impossible to achieve in ambient conditions. PV manufacturers provide a NOCT value for the more realistic environment referred to as the standard environment at which the solar irradiance, G of 800 W/m^2, ambient temperature, T_{amb} of 20 °C, and wind speed of 1.0 m/s [29]. The equivalent PV module temperature, T_c can be determined by Eq. (1).

$$T_C = T_{amb} + \left(\left(\frac{NOCT - 20}{800} \right) . G \right) \quad (1)$$

The power output of a PV panel mainly depends on solar irradiance and solar cell temperature. Eq. (3) was used to determine the PV power output. The variations in solar irradiance, G, cause variations in the current output of PVs. However, the increase in PV cell temperature due to an increase in ambient temperature affects the output voltages negatively [30].

$$I_{PV} = n_{pv} . I_{PV,r} . \left(\frac{G}{G_{STC}} \right) \times \left(1 + \alpha . (T_C - T_{C,STC}) \right) \quad (2)$$

$$P_{PV}(t) = I_{PV} \times Volt_r \qquad (3)$$

where, $P_{PV}(t)$ is the power output of an array of PV at time hour, *npv* is the number of PVs or PV strings in parallel for constant voltage output, $I_{pv,r}$ is the rated current output of a PV panel, $Volt_r$ is the output of the rated voltage of the PV panel, G is the incident global solar irradiance (W/m^2), GSTC is the solar irradiance under STC, α is the temperature coefficient of PV from supplier specifications. $T_{C,\ STC}$ is the cell temperature under STC, T_C is the cell temperature.

PV electric efficiency, $\eta_{PV,}$ is obtained by dividing the output electric power by the incident solar irradiance, *G,* over the PV area, $A_{PV,}$ as shown in Eq. (4).

$$\eta_{PV} = \frac{P_{PV}}{G \times A_{PV}} \times 100 \qquad (4)$$

The performance ratio is a ratio of the PV power output in situ conditions to the PV power output under STC. It is determined by dividing the ratio of actual PV power output to the installed capacity by the ratio of incident solar irradiance to the radiance at STC. The performance ratio is a technical parameter that provides knowledge of the feasibility of installed PVs at a case study location. Performance ratio, or PR, can be determined as

$$\text{PR} = \frac{Actual\ Power\ Output / Installed\ Capacity}{Incident\ Solar\ Irrdiance / G_{STC}} \qquad (5)$$

3. RESULTS AND DISCUSSIONS

Performance analysis of PV with cooling has been carried out and compared to PV without cooling. Analysis was carried out for 6 days at the case study location. Four days are without PV cooling, and two days are with PV cooling. A smart PV cooling system was designed and developed to reduce the PV array temperature and increase the PV performance without any human intervention. Analysis has been presented for the solar irradiance, ambient temperature, and PV module temperature. A comparison of PV without cooling to PV with cooling was carried out irrespective of time but at almost similar weather conditions, i.e., solar irradiance and ambient temperature.

Figure 6 shows the hourly average PV temperature, ambient temperature, and solar irradiance for 144 hours starting from 1:00 pm on 7th April and continuing recording till 12th April. The days from 7th April to 10th April are without PV cooling, and the days 11th and 12th April 2021 are with PV cooling. High solar irradiance has led to high PV cell temperature. The highest PV temperature of about 65 °C is observed at noon on 9th April. On all operational days without cooling, PV temperature increased to more than 50 °C at 11:00 am and 2:00 pm. It is noticed that once the solar is blocked by temporarily passing clouds, the PV temperature is reduced considerably. For instance, looking for the data trend on day 9, clouds passed at around 1:00 pm, causing the solar irradiance to reduce from 880 to 480 W/m^2. Consequently, the PV temperature is reduced from 65 to 47 °C. For the PV cooling to initialize the solenoid valve, the set condition is that the PV temperature should be equal to or greater than 45 °C. The water spray on the PV surface reached a maximum of 56.5 °C.

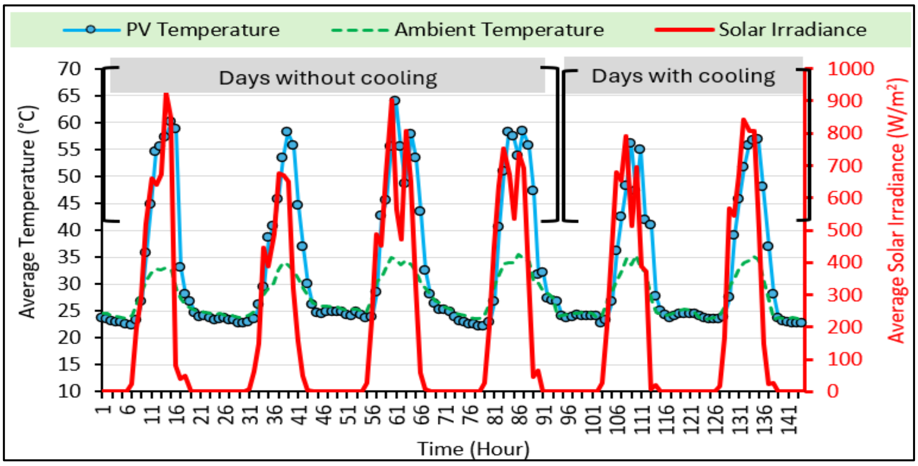

Figure 6. Hourly average photovoltaic (PV) array temperature, ambient temperature, and solar irradiance

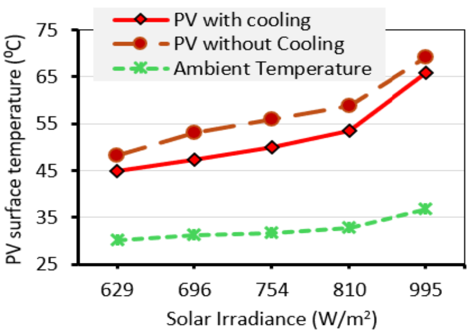

Figure 7. Photovoltaic (PV) array temperature with and without cooling at a specific solar irradiance

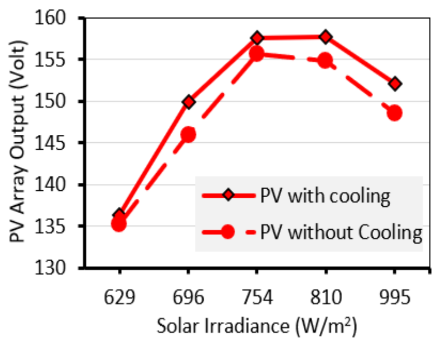

Figure 8. Photovoltaic (PV) array output voltages with and without cooling

Figure 7 shows the PV array temperature with and without PV cooling and ambient temperature at their corresponding solar irradiance. Ambient temperature is primarily caused by solar irradiance. An increase in solar irradiance increases the ambient temperature. As presented in Eq. (1), solar irradiance directly affects the PV temperature with or without cooling. PV array temperature without cooling has increased by 8.5 ℃ and 10.5 ℃ with an increase of solar irradiance from 629 W/m^2 to 810 W/m^2 and 810 W/m^2 to 995 W/m^2, respectively. In contrast, the PV array with cooling has a temperature rise of 8.5 ℃ and 12.5 ℃ with an increase in solar irradiance from 629 W/m^2 to 810 W/m^2 and 810 W/m^2 to 995 W/m^2, respectively.

The peak PV temperature without cooling is 65.9 ℃ at 995 W/m^2. The peak PV temperature with cooling has decreased by 5.16% compared to the PV without cooling. At the same time, the highest decrease in PV temperature with cooling is 11.8% at solar irradiance of 754 W/m^2. The highest decrease in PV temperature without cooling at lower solar irradiance and vice versa can be due to a lower solar irradiance. The cooling water has a lower inlet temperature and a higher tendency to absorb the heat of PVs.

Figure 8 shows the PV array output voltages with an increase in solar irradiance. PV with cooling has a maximum voltage of 157.8 V at 810 W/m^2, and PV without cooling has a maximum voltage of 155.7 V at 754 W/m^2. Initially, with an increase in solar irradiance, the voltages of PV increase. However, the increase in solar irradiance for the PV with and without cooling from 810 W/m^2 and 754 W/m^2, respectively, has decreased the voltages. The decrease in voltages is due to the increase in PV temperature. An increase in PV temperature with and without cooling of 12.5 and 10.5 ℃ has decreased the PV voltages by 5.7 and 6.21, respectively.

Figure 9 shows the PV power output with and without water cooling at their corresponding solar irradiance. PV power output without cooling at the lowest solar irradiance is about 1190 W, and at maximum solar irradiance, the PV power output is 2068 W. With water cooling, the PV power output has increased to a minimum of 2.93% and a maximum of 4.47% compared to the PV without cooling. The rise in PV power output with a rise in unit solar irradiance is about 2.4 W for PV without cooling and about 2.56 W for PV with cooling.

Figure 10 shows the PV electric efficiency with and without water cooling. PV electric efficiency for the PV array without cooling has a minimum of 11.75% and a maximum of 13.53%. PV with cooling has increased electric efficiency by about 2.9% at 629 W/m^2 to 4.49% at 995 W/m^2. However, the peak PV electric efficiency with or without cooling is at a solar irradiance of 754 W/m^2. The peak power output by PV has also increased with cooling than without cooling by about 3.25% at a solar irradiance of 754 W/m^2. As noted earlier, the peak PV power output is at maximum solar irradiance. However, the increase in PV cell temperature when the solar irradiance increases from 754 W/m^2 to 995 W/m^2 has decreased the electric efficiency. For PV without cooling, PV temperature increased by 13.4 ℃ with an increase in solar irradiance from 754 to 995 W/m^2. A one-degree temperature rise in PV without cooling has decreased the electric efficiency by about 0.0463%. For PV with cooling, PV temperature increased by 15.9 ℃ with an increase in solar irradiance from 754 W/m^2 to 995 W/m^2. The rise in PV temperature, even with cooling, is due to a constant water flow rate over the PV panel. With an increase in PV temperature due to increased leftover solar irradiance, the water flow rate needed to be increased to dissipate heat from the PV panel and maintain it at a constant lower operating temperature. Nevertheless, in our study, no water flow rate variation system with an increase or decrease in solar irradiation was embedded. However, PV with water cooling has reduced electric efficiency degradation with a rise in PV temperature by about 3.5%, contrary to PV without cooling.

Figure 11 shows the PV performance ratio for the study location. PV performance ratio has increased for the PV with cooling than for the PV without cooling. PVs are designed to harness solar irradiance to useful electric power at STC conditions. However, PV performance varies due to the varying potential of solar irradiance and thermal degradation. The peak PV performance without cooling is about 87.12% at 754 W/m^2, and the peak PV performance with cooling is about 90.12% at 810 W/m^2.

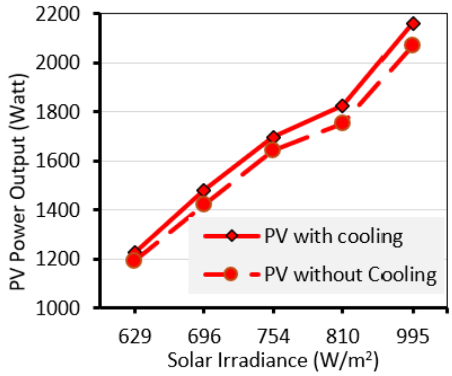

Figure 9. Photovoltaic (PV) array power output with and without cooling at a specific solar irradiance

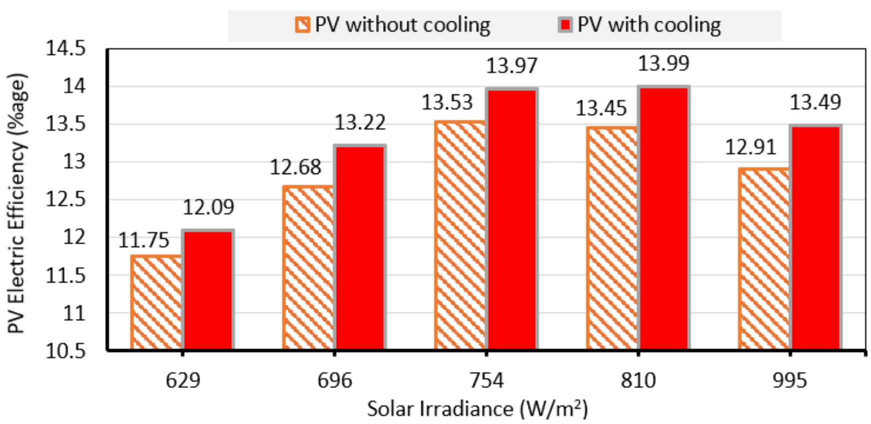

Figure 10. Photovoltaic (PV) array electric efficiency with and without photovoltaic (PV) cooling

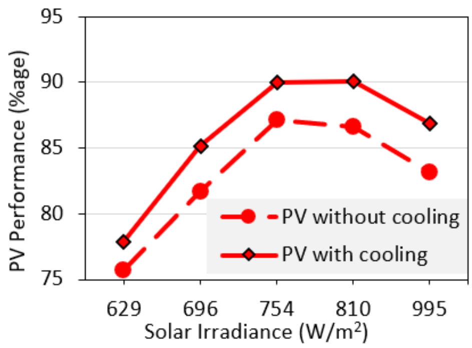

Figure 11. Photovoltaic (PV) array performance ratio at a specific solar irradiance for the study location

A notable increase in PV performance with and without cooling occurs when the solar irradiance has increased from 629 W/m^2 to 754 W/m^2. PV performance increased about 12.09% and 11.45% for the PV with and without cooling when the solar irradiance increased by about 19.87%. PV performance enhancement with cooling is a maximum of 3.72% than PV without cooling at the highest solar irradiance. This is also noticed by Hariyanto et al. [31] in their experimental investigation of the solar irradiation impact on the performance of a 50 W PV panel.

4. CONCLUSIONS

An experimental assessment of 10 PV arrays with and without cooling by water spray has been performed. Water sprayers were used to provide water misting on the top surface of PVs. A smart PV cooling, as part of a smart hybrid energy system, was designed and developed to commence the water cooling based on the average reading of three K-type thermocouples and operate a solenoid valve. The peak PV temperature without cooling is 65.9 ℃ at 995 W/m^2. A decrease of 5.16% in peak PV temperature has been observed with cooling. A one-degree temperature rise in PV without cooling has decreased the electric efficiency by about 0.0463%. A degree temperature rise in PV with cooling has minimized the decrease in electric efficiency to about 0.0302%. PV performance increased by about 12.1% and 11.45% for the PV with and without cooling when the solar irradiance increased by about 19.87%. PV performance enhancement with cooling is a maximum of 3.72% than PV without cooling at the highest solar irradiance.

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NOMENCLATURE

G	solar irradiance, W/m^2
I	current, A
$I_{pv,r}$	rated current output of a PV array
n_{pv}	number of PVs
T_{amb}	ambient temperature, K, °C
T_c	PV cell equivalent temperature K, °C
P_{PV}(t)	PV array power output, W
V	voltage, V

Greek symbols

α	PV temperature coefficient
η_{PV}	PV electric efficiency

Abbreviations

MPPT	maximum power point tracker
NOCT	nominal operating cell temperature
PCM	phase change material
PR	performance ratio
PV	photovoltaic
STC	standard test conditions