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# Performance Improvement Optimisation of a Photovoltaic System located at the Tropical Climate using Water-Film Cooling Method

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**Abstract.** The temperature rise of solar panels can cause significant reduction in the energy generation especially for the countries located in tropical climate region. It is more effective to use water-film for cooling the front surface of solar panels, but the energy consumption of the water-cooled photovoltaic system (WCPV) needs to be reduced to obtain a higher net energy gain. In this study, a discrete water-supply water-cooling system (D-WCPV) has been proposed to reduce the energy consumption of the water pump and to improve the performance of a retrofit or building integrated photovoltaic system through reduction of the panel temperature. The discrete mechanism utilises a relay to switch on the power supply of the water pump whenever the temperature of the solar panel has reached the threshold of 45 °C. It is found that minimum flow rate for the D-WCPV is 8 L/min to form a full coverage of water on the surface of the solar panel for providing an uniform cooling effect and hence providing a better performance improvement. A comparison has also been made for the continuous water-supply water-cooling system (C-WCPV) and D-WCPV. D-WCPV has two advantages over C-WCPV as follows: 1) the energy consumption of the water pump operating at flow rate of 8 L/min has been reduced by 86.7% from 0.057 kWh/h to 0.0076 kWh/h and (2) the net energy gain (NEG) of the system at solar irradiation ranging from 806 Wh/m<sup>2</sup> to 950 Wh/m<sup>2</sup> has been increased by 80.2% from 5.5% to 10.0%.

## 1. Introduction

The main reason of deterioration in the output performance of a solar photovoltaic (PV) system for the sites located in the tropical region is the temperature rise of the PV panels during the operation. There are two manners to reduce the temperature of a PV system: (1) a passive cooling method that utilises fluids or phase change material (PCM) [1, 2]; (2) an active cooling method that improves the heat dissipation by adding an active mechanism which requires required an external input power [3]. Practically, an active water-cooled PV system (WCPV) has a few advantages over the other methods [1–5]. 1) The system design is simple, and it can be retrofitted to the existing PV system; 2) the size or space needed to implement the active water-cooling system is considerable miniature; 3) the capital investment costs required is less than that of other methods and 4) the method provides a cleaning effect



to the front surface of solar panels to reduce the optical loss. In spite of that, the previous studies were carried out either without considering net energy gain, without finding out the optimal flow rate of the cooling water, or without knowing the water consumption. The optimisation of a WCPV has not yet been thoroughly performed to achieve a higher net energy gain (NEG), which is the crucial indicator for the feasibility of implementing this approach. NEG is defined as the net energy gain between the energy generated and the energy consumed by additional active components such as a water pump.

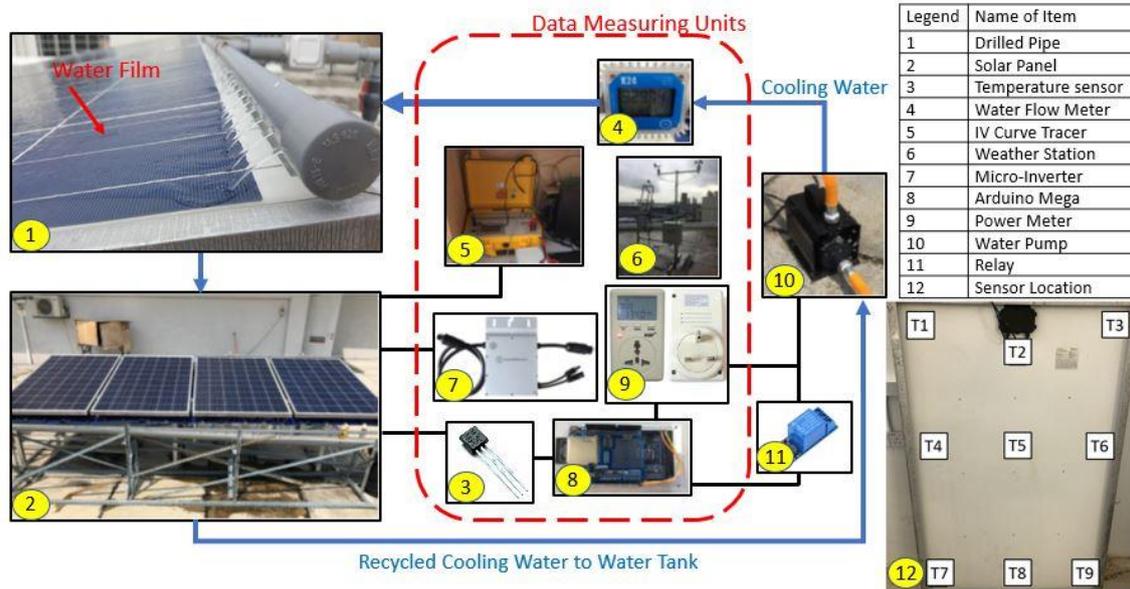
The key considerations for optimising a WCPV include the energy consumption and water consumption of the system. The energy consumption of the system directly reduces the NEG and hence affects the return on investment (ROI). It is possible to reduce the energy consumption of the system via appropriate pump selection, pipe sizing and most importantly, reducing the operating time of the water pump. Furthermore, the water consumption of the system contributes to the daily operation costs, which also affect the ROI. A feedback system equipped with rainwater collection function can reduce the water consumption of the system. The previous study on the optimisation of the performance improvement were carried out to find out the optimal flow rate and to harness the abundant rainwater for a system operating in the tropical region [6]. Nevertheless, a continuous supply of cooling water does not provide a promising NEG. In this paper, it is aimed to improve the NEG of a front-surface water-film WCPV system with the use of discrete control of water supply for the WCPV, abbreviated as D-WCPV. This method can significantly reduce energy consumption as compared to a continuous water supply water-cooled PV system (C-WCPV) and thus can improve the overall NEG.

## 2. Methodology

The experimental setup of the D-WCPV system is shown in Figure 1. Metal decks were installed onto a commercial aluminium mounting structure to imitate the common building roofs in Malaysia. Four units of 260 W crystalline silicon solar panels (model MYS 60 CF-260) were installed side-by-side to form a commercial retrofitted PV system setup. The solar panels were fixed on the mounting rack with a 10 cm gap from the metal decks with  $10^\circ$  tilted angle and facing south. The initial power output of the solar panels was measured by an I-V curve tracer (PVPM1040X) during stable solar irradiance of about  $770 \text{ W/m}^2$ . The calculated normalised outputs of the solar panels under standard test conditions (STC) were less than 1%. PVC pipes drilled with 3 mm diameter holes and with a spacing of 2 cm between holes were fixed on the top of the solar panels without creating any shadow to the solar cells. Cooling water was supplied to the solar panels through the drilled pipes from a 100-gallon water tank using a water pump. A PVC pipe was installed at the downside and slightly bottom of the metal decks. The purpose of PVC pipe is to collect and to reuse the cooling water after it have absorbed the heat from the solar panels as well as to collect the rainwater.

During experiments, the measurements taken include the temperature of the solar panels, flow rate of the cooling water, power and energy generation of the solar panels, energy consumption of the D-WCPV (water pump and electronic circuit) and solar irradiance. DS18B20 temperature sensors were used to measure the temperature of the solar panels. Temperature sensors were calibrated, and the error is within 5%. Nine temperature sensors were attached to the back surface of each solar panel in a  $3 \times 3$  matrix position as shown in Figure 1. A FLIR i5 thermography camera was used to capture the images of the temperature distribution profile of the solar panels, and the images were compared with the data collected from the temperature sensors. An Arduino Mega 2560 board and a data logger shield were used to collect and to record the temperature data of the solar panels at the interval of 15 seconds. A relay is used to control the switching of water pump based on a pre-set temperature threshold. During the experiment, the temperature threshold is set to  $45^\circ \text{C}$ , which means that the water pump will be switched on when any temperature sensor has achieved  $45^\circ \text{C}$  or higher otherwise it will be switched off. The flow rate of cooling water for each solar panel was controlled using a ball valve, and it was measured using a digital water flow meter. The power output from the solar panels and the energy produced were measured using two micro-inverters (Hoymiles MI-500) at an interval of 5 minute. The energy consumptions of the water pump and the Arduino board were measured using a power meter.

Solar irradiance data was collected using a Pyranometer (TBQ-2) of a weather station at an interval of 1 minute.



**Figure 1.** The experimental setup of a discrete water-cooling photovoltaic system (D-WCPV). ①the water-film flows from the holes of the PVC pipe. ②the four panels installed in a side-by-side configuration and one solar panel acted as the reference panel. ③to ⑪ are the components for the system. ⑫the positions of the nine temperature sensors attached to each panel.

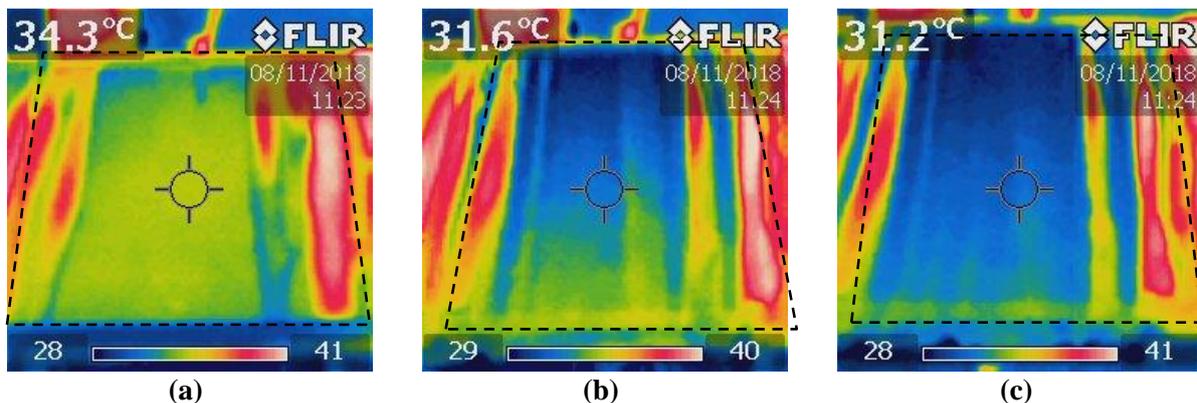
Throughout all the experiments, one solar panel was used as a reference panel without being water-cooled, whilst the other solar panels were water-cooled at different water flow rates. This method is adopted to avoid the inconsistency of measurement due to the passing clouds occurring in the tropics (intermittent condition) if the measurements are carried out in a sequential manner. All data were taken from August to November 2018 in Bandar Sungai Long, Malaysia. Some data were omitted for the case of the high-frequency cloud passing by because the accuracy of the data is affected by these events.

### 3. Results and Discussion

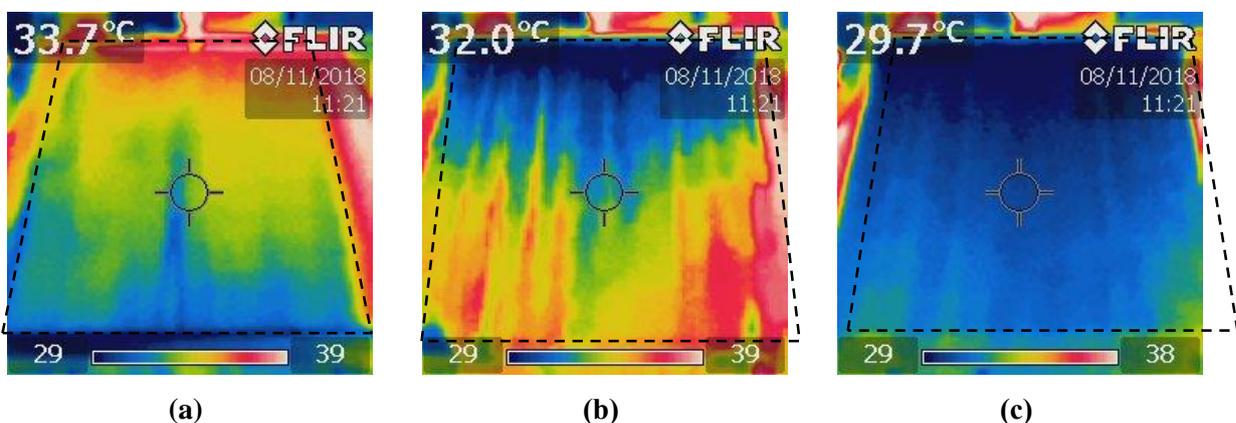
The thermography images of the solar panels for before, during and after the solar panel were water-cooled at a flow rate of 6 L/min and 8 L/min are shown in Figure 2 and Figure 3, respectively. During a sunny day with the solar irradiance ranging from 600 to 900 W/m<sup>2</sup>, thermography images were taken during the period which the average solar irradiance was 806 W/m<sup>2</sup>. The flow rate of 6 L/min was used because it is the optimal flow rate for the best performance improvement of C-WCPV [6]. However, for D-WCPV case, the solar panels were not cooled uniformly at this flow rate. Instead, the cooling water tends to converge towards the middle part of the surface of the solar panel during the initial stage of the cooling period. The water-film will only be gradually distributed to the whole surface of the solar panel if it is given sufficient time. Sometimes before the panel surface was fully covered by water-film, the water pump had to be stopped as the panel temperature had gone below 45 °C. The unevenness cooling is also observed from the temperature readings where T7 has been identified as the sensor that always trigger the water pump to operate during the experiment. The location of sensor T7 was the least-cooled area on the surface of the solar panel. The minimum flow rate to have a uniform cooling is 8 L/min. Therefore, this flow rate was chosen for the comparison study. Most of the time, the pump was triggered by temperature sensor T1 and it happened simply because the temperature of a solar panel is higher at the upper part of the solar panel.

Uniform cooling is very important for a WCPV system because the energy gain will be affected. In the first experiment, the operational duration of cooling water was set to be the same for both flow rates.

The energy gain of WCPV over non-WCPV for the two flow rates for five days are plotted as illustrated in Figure 4. It depicts that when the cooling water is supplied at a flow rate of 6 L/min, the energy gain of a solar panel is less than that of 8 L/min. The 5-day energy gain at flow rate 6 L/min was 95.4 Wh whereas it was 171 Wh at a flow rate of 8 L/min. The difference is 75.6 Wh, representing an improvement of 79.2%. The improvement indicates that when the switching function is incorporated, the optimal flow rate is no longer at 6 L/min, as it was obtained in C-WCPV.



**Figure 2.** The thermography images of before (a), during (b) and after (c) the solar panel was water-cooled at a flow rate of 6 L/min. (a) The temperature distribution of the solar panel was not even. Cooling water was supplied to the solar panel due to the temperature rise at the T7 position. (b) The cooling water supplied to the solar panel was not able to cover the whole front surface. (c) The supply of cooling water stopped after 45 seconds. The cycle repeats and the thermography image as shown in (a) was observed again.



**Figure 3.** The thermography images of before (a), during (b) and after (c) the solar panel (rectangular dash-line) was water-cooled at a flow rate of 8 L/min. (a) The solar panel had a higher temperature at the upper part. The water pump is triggered by the T1 sensor. (b) The cooling water had full coverage on the surface of the solar panel. (c) The solar panel was water-cooled uniformly at this flow rate. The cycle repeats and the thermography image as shown in (a) was observed again.

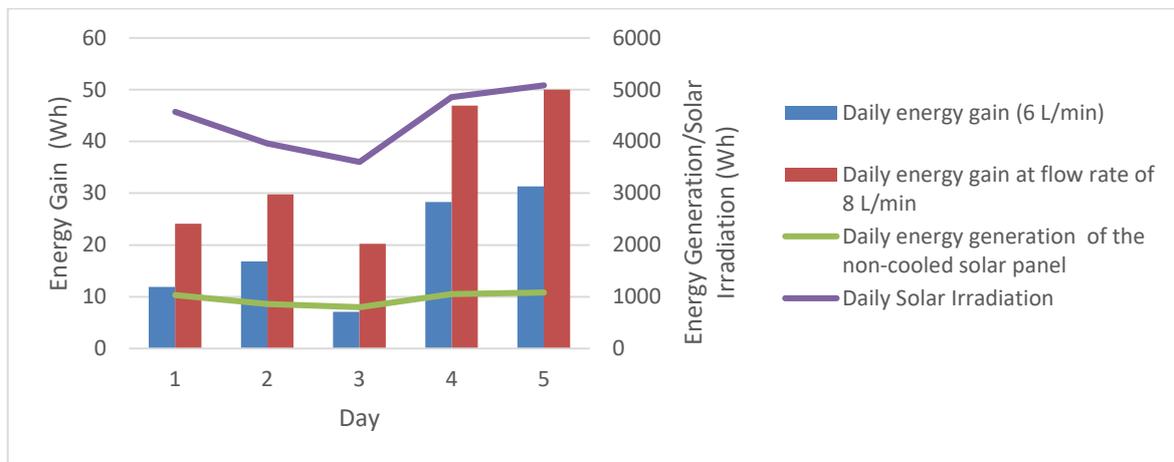
As the operating time of the water pump affects the energy consumption of the system linearly, a further experiment was conducted where one water pump was used for each solar panel, and the temperature thresholds were both set at 45 °C. The water pumps were turned on for 11 times and 8 times for the flow rate of 6 L/min and 8 L/min respectively. The number switchings were corresponding to the operating time of 17.8 minutes per hour and 6.9 minutes per hour for 6 L/min and 8 L/min respectively. During the period of the experiment, the solar irradiance ranged from 600 W/m<sup>2</sup> to 900

W/m<sup>2</sup>. The operating period for each time the water pump was turned on, and the cycle of the supply of cooling water was different for each flow rate. At a flow rate of 6 L/min, the average time for each cycle was 5.5 minutes whereas it was 7.5 minutes for 8 L/min.

Equation 1 illustrates the calculation of the NEG per panel per hour.

$$NEG/(panel.hour) = \frac{[EGPH \times N] - [t \times EC]}{N} \quad (1)$$

where  $N$  is the number of solar panels can be supplied by one water pump,  $EGPH$  is the energy gain per solar panel per hour,  $EC$  is the energy consumption per hour for a continuous supply of water and  $t$  is the operating time of the water pump with switching function within one hour.



**Figure 4.** The bar chart shows the performance improvement of the D-WCPV relatively to the non-cooled solar panel for the flow rates of 6 L/min and 8 L/min. The lines show the daily energy generation of the non-cooled solar panel and the daily solar irradiation for each day.

**Table 1.** Comparison between different types of cooling system and flow rates. The last column is the percent NEG per panel per hour over non-cooled solar panel

System	Flow Rate (L/min)	Solar Irradiation (Wh/m <sup>2</sup> )	Energy yield of the uncooled panel (kWh)	EGPH (kWh/h)	N	EC (kWh/h)	NEG per panel per hour kWh/(panel.h)	%
C-WCPV	6	950	0.1907	0.0248	4	0.0570	0.0106	5.5
D-WCPV	6	806	0.1766	0.0215	4	0.0195	0.0166	9.4
D-WCPV	8	806	0.1782	0.0203	3	0.0076	0.0178	10.0

The energy consumption of the water pump and Arduino board was measured to be 0.057 kWh per hour for C-WCPV [6]. The energy consumption of the D-WCPV can be prorated from this value by multiplying the operating time of the water pump. To calculate the NEG, there is a need to know the number of solar panels that can be cooled by using a water pump. A pipe test had been carried out to determine these numbers for a water pump operating at different flow rates. It was measured that the number of solar panels can be cooled for flow rates 6 L/min and 8 L/min are four and three units, respectively. As such, the energy consumptions and the NEG for the C-WCPV and the D-WCPV at the two different flow rates were calculated and compared, as listed in Table 1. Even at an unfavourable comparison condition of having lower solar irradiation during the period of data collection (950 Wh/m<sup>2</sup> for C-WCPV while it was only 806 Wh/m<sup>2</sup> for D-WCPV), the D-WCPV shows a higher NEG per solar panel per hour. The percentages of improvement in NEG per panel per hour of the D-WCPV to the C-

WCPV were 70.2% and 80.2% for the flow rate of 6 L/min and 8 L/min respectively. The improvement is a notable sign that shows the advantage of using D-WCPV over the C-WCPV. The increment of NEG is a result of reducing the energy consumption of the WCPV by implementing a relay to control the water pump according to the temperature of the solar panel. It was recorded that the energy consumption of the D-WCPV as compared to that of C-WCPV was reduced by 65.8% and 86.7% for 6 L/min and 8 L/min respectively, calculated from the consumption of C-WCPV system of 0.057 kWh per panel per hour to 0.0195 kWh per panel per hour and 0.0076 kWh per panel per hour for D-WCPV, respectively. Nevertheless, the NEG calculated here can only represent the improvement of the energy generation for a short period at a relatively high solar irradiance. A fair comparison should be conducted for a long-term operation, which includes a period with lower solar irradiance. In addition, the optimal flow rate has been changed for D-WCPV. Therefore, to obtain the new optimal flow rate with the D-WCPV, a further experiment is needed. With the improvement shown, water-cooled PV system can be applied to the PV industry with a promising improvement in the performance.

#### 4. Conclusion

A D-WCPV system was set up at the site with tropical climate. The performance loss due to the temperature was reduced by using a water-film cooling method on the front surface of the solar panel. Under the comparison between the D-WCPV and C-WCPV, it is shown that the energy consumption was reduced by 86.7% when the temperature threshold was set at 45 °C for a flow rate of 8 L/min. The NEG of the system under the same setting was 10.0% when compared with a reference solar panel without any cooling mechanism. This value is 80.2% higher than that of a C-WCPV, which the NEG was 5.5% when compared with the energy generated from an uncooled solar panel. Besides, the importance of having full coverage of water-film on the surface of a solar panel was observed through the non-uniform temperature distribution profile, and it causes a longer operation period of water pump. Uniform cooling has advantages over non-uniform cooling, which include better performance improvement and lower energy consumption. Uniform cooling of a solar panel surface for a D-WCPV can be achieved by adjusting the cooling water flow rate to 8 L/min and above. It was also found that the optimal flow rate was no longer 6 L/min as for the case of C-WCPV. In short, this paper has provided one option for optimising the energy consumption of a water-cooled PV system.

#### 5. Acknowledgement

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