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Energy analysis of active photovoltaic cooling system using water flow

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ABSTRACT

An active water-cooling system is one of several technologies that has been proven to be able to reduce heat losses and increase electrical energy in photovoltaic (PV) module. This research discusses a comparative experimental study of three pump activation controls in cooling of PV module with the aim of evaluating specifically the PV output power, net energy gain, water flow rate, and module temperature reduction. The three pump activation controls being compared are continuously active during the test, active based on setpoint temperature, and active by controlling the pump voltage using pulse width modulation (PWM) control in adjusting water flow rate smoothly. The results show that controlling the pump voltage using PWM in the PV cooling process produces energy of 437.95 Wh, slightly lower than the others and the average module cooling temperature is 35.24 °C, higher of 1-3 °C than the others. Nevertheless, PWM control of cooling pump has resulted the percentage of net energy gain of 9.94%, greater than other controls, and with an average flow rate of 2.17 L/min, more efficient than the others. Thus, this control is quite effective as it can produce higher net PV energy yield and lower water consumption.

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1. INTRODUCTION

The temperature of photovoltaic (PV) modules can generally increase drastically, influenced by high ambient temperature due to solar radiation, environmental conditions and geographical location [1], [2]. The high temperature can affect the characteristics of the PV module which illustrated in the form of a current/power-voltage (I/P-V) curves [3], [4]. Under constant solar irradiance, the output voltage decreases with the increasing trend of the module temperature, while the output current tends to be constant. The studies have reported that typically for every 1 °C increasing temperature of PV cell above 25 °C, voltage decreases around 2.2 mV/°C [5], the output current of the PV panel slightly increases [6], [7] even tent to be constant [8] and power decreases around 0.4% to 0.5% for crystalline silicon cell and 0.35% to 0.38% for amorphous cells [9]–[13].

Several methods have been carried out to improve PV module efficiency due to thermal effects by utilization of various cooling techniques in PV water-based cooling system. The methods developed from simple to complex techniques including passive, active, and hybrid cooling with different fluid materials. Passive cooling is a cooling technique that does not require power consumption to operate the system. This technique usually uses additional components to control natural convection cooling such as air ventilation [14], liquid immersion and floating [15], [16], heat pipe [17], heat sinks and phase change material (PCM) panel [18]. Meanwhile active cooling requires external power to move a coolant such as air [19] or water [20]. Although requiring external power, the active cooling still is feasible, effective, and suitable for integration with photovoltaic power plants, both small and large scale. Several authors have stated that water-based cooling technologies are quite mature, and the best solution by providing uniform cooling temperature and maintaining surface cleanliness. Other studies reported that 9% of the net gain in electrical yield achieved by this method [21] and the cooling process consumes less than 10% of the maximum PV power performance [22]. The rate of cooling is also determined by the water flow rate influenced by setpoint temperature [23], [24], setting the duration of time (on/off) in cooling process activation [25]. Water cooling systems on PV module can offer more economical solution with system optimization and intelligent process control. The advantages of cooling PV modules using a water-based photovoltaic system due to the cooling process is faster, improves efficiency, cleans dirt, extends lifetime, and the remaining heat obtained can be used for household or commercial purposes [12]. Increasing photovoltaic power output through active cooling that far exceeds cooling system power consumption is an essential factor that must be considered in resulting greater net energy gain. In addition, water availability and its sources are also the challenges for the active water-cooling method [26], except for floating photovoltaic where unlimited amount of water is available underneath.

This paper presents a comparison of experimental results from three water pump activation settings in the module cooling process of the PV cooling system. The three controls of pump activation include active continuously, active based on setpoint of desire temperature, and active by pulse width modulation (PWM) control in adjusting water flow. The purpose of the experiment is to determine which control system is more effective in reducing module temperature by minimizing the pump energy consumption and minimizing amount of water. Therefore, the key to this experiment is that increasing the PV output power is balanced with obtaining optimal net energy gain and saving amount of water. This paper is organized into several sections, where in the next section, namely section 2, discusses the materials and methods used for the experimental investigation. Section 3 presents the experimental results and analytical discussion regarding the comparative use of each pump control related to module temperature, increased efficiency, clean energy gain, and water flow rate, and concluding remarks are discussed in section 4.

2. MATERIALS AND METHOD

2.1. Overview of experiment setup

The schematic diagram of active water cooling of PV system in single module specifically is given in Figure 1. The 100 Wp of polycrystalline PV module with effectively 0.72 m^2 of surface area. The module was installed with the tilt angle of 15° to the horizontal and facing north with an azimuth angle of 5°. A 12 V DC centrifugal pump was used to circulate water by closed loop from the tank through 3/4-inch PVC pipe line through the water flow sensor (FS300A) then to the inlet channel installed at the top of the module. A 3/4-inch PVC pipe as inlet channel which has 60 holes with a diameter of 3 mm to drain cold water evenly from the top to the bottom of the front side the module surface. Warm water from the remaining cooling was collected in the outlet channel, then it cooled again by a heat exchanger and stored in the tank as well. The water circulation works continuously as long as the pump is active.

For measurement and analysis, the PV water-based cooling system was equipped with some measuring instruments. The three temperature sensors (DS18B20) were used to measure module temperature. It is attached on three points of the back side with a proportional distance that can represent the entire surface of the module. Other DS18B20 also installed in the water tank to measure the temperature of the cooling water. A 3 Ohm resistor as a load was connected to the positive and negative PV output terminals, then the voltage and current of PV output including pump power were measured by sensors integrated in PZEM-017 as energy meter. A pyranometer (SEM228) was used to measure solar irradiation during the experiments. The system also completed by DTT22 that used to read ambient temperature and humidity. Finally, a data logger was used to record and store measurements for various conditions at specific intervals. Details of component specifications and measuring instruments including measurement errors (%) of the PV cooling experiments are given in Table 1.

2.2. Pump activation settings

In water-based PV cooling system, pump is the heart of the cooling system that increase the working pressure of the water coolant in the circulating system and prevent the operating temperature of PV module from overheating. Meanwhile, in modern cooling system, the pump control plays the most important role as well. It regulates the pump’s electric motor, which has a direct impact on operation performance and consumption. In this experiment, the three cooling controls were compared in water-base PV cooling system based on pump motor activation as given in Figure 2.

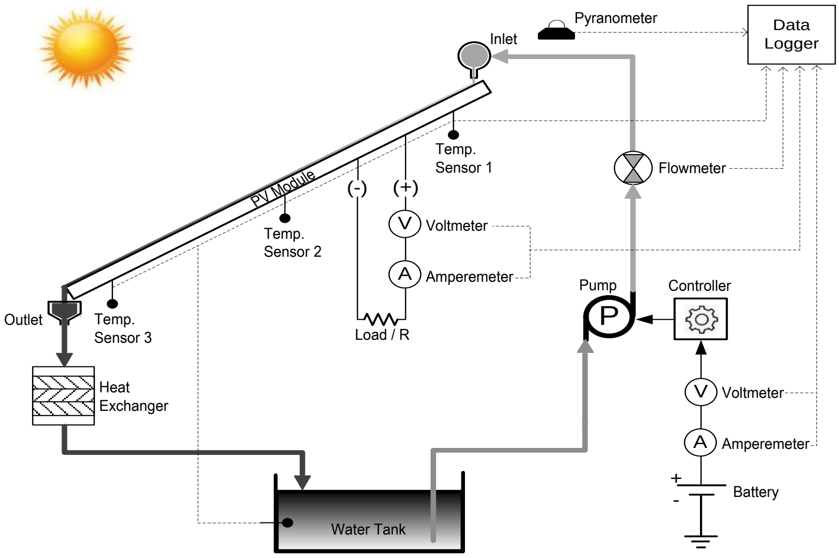

Figure 1. Schematic diagram of PV cooling experiment setup

Table 1. Specification of the experimental setup

Items	Description
PV module*:	
PV cell type	Polycrystalline
Module effective area	0.72 m^2
Number of cells per panel	36
Maximum power, P_{max}	100 W
Open circuit voltage, V_{oc}	21 V
Short circuit current, I_{sc}	6.4 A
Voltage at maximum power, V_{mp}	17.5 V
Current at maximum power, I_{mp}	5.71 A
NOCT	45±2 °C
PV angle (tilt; azimuth)	15°; 5° North
PV cooling system:	
Coolant	Water
Pipe	PVC, ¾ inch
Inlet	PVC, ¾ inch
Outlet	PVC gutter, 1 inch
Water tank	900×600×600 mm
Centrifugal pump	Brushless DC motor, 12 V, 18 W, 13.3 L/min
Measuring instruments:	
Water flow meter	FS300A, 1-45 L/min, (ε: 2-5%)
Temperature Sensor	PV and water: DS18B20, (ε: ±0.5°C) Air: DHT22, (ε: ±5%)
Sensor module	PZEM-017
Volt meter	V: 0.05–300 V, (ε: ±1%)
Ampere meter	A: 0.02–10 A, (ε: ±1%)
Power meter	P: 0.1–3 kW, (ε: ±1%)
Energy meter	E: 0–9999 kWh, (ε: ±1%)
Pyranometer	SEM228, 0-1800 W/m^2, (ε: ±3%)

*Refers to manufacturing datasheet, standard test conditions (STC): 1000 W/m^2; 25 °C; AM 1.5

First arrangement was cooling based on pump that continuously active during the test with a constant nominal power providing full speed as given in Figure 2(a). Thus, the PV module was supplied by water coolant at fixed flow rate continuously with full capacity. However, this control is only to determine the effect of continuously of constant flow rate on the maximum decrease in module temperature achieved until steady state conditions, then the pump energy consumption was evaluated. Second arrangement was pump activation that limited based on the temperature setpoint as given in Figure 2(b). In this control, the upper limit temperature setpoint of 35 °C was chosen to activate the pump (turn-on), and 30 °C of the lower limit was chosen to deactivate the pump (turn-off). The principle is that when the pump is active (on), it consumes full power for circulating water through PV module at full water flow rate. Contrary, when pump is not active (off), there is no pump power and no water circulation. Thus, this control only has two speeds in cooling the module, namely full flow rate and no flow rate at all. This control causes the water flow rate to be intermittent with the aim of considering energy saving and minimize the amount of water to make cooling more efficient. In fact, pump control by the on/off cycle has been widely applied in engineering fields that require temperature regulation. The last arrangement was pump that continuously active during the test, but with pump voltage regulation by using PWM controller as given in Figure 2(c). It was done to reduce the pump power smoothly which has the effect of decreasing speed and manage water flow rate as well. This control has various speeds with very subtle changes. The percentage of duty cycle (*D*) in the high frequency PWM signal is proportional to regulated the average pump voltage. It obtained based on the feedback signal from the module temperature reading as the input reference of controller. The decrease in pump voltage by controller was carried out by continuously reducing duty cycle (*D*) from 100% at maximum module temperature to a certain percentage where the decrease in module temperature reaches steady state. The purpose of this setting is to determine the effect of reducing the water flow rate smoothly on reducing the module temperature by minimizing gradually the pump's energy consumption. The optimal point of net energy gain is obtained by balancing pump energy, water flow rate and PV module temperature.

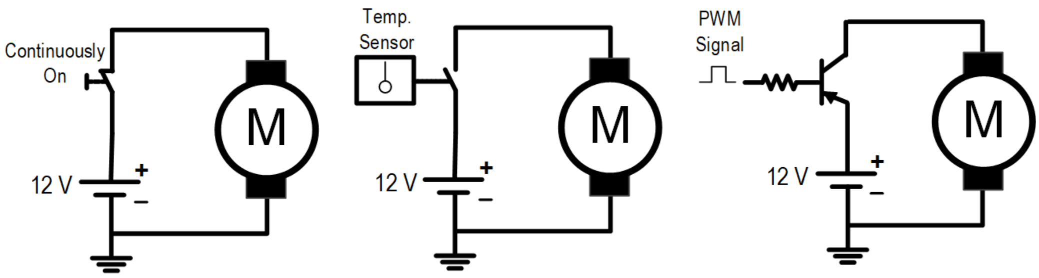

Figure 2. Comparison of three pump motor activation settings (a) full speed, (b) limited based on the temperature setpoint, and (c) using PWM controller

2.3. PV cells parameters and temperature effect analysis

In PV module technology, there are several parameters that need to be known before applying it in real conditions include: maximum power (P_{max}), voltage at maximum power (V_{mp}), current at maximum power (I_{mp}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (*FF*), module efficiency (η), and nominal operating cell temperature (*NOCT*). The maximum power (P_{max}) generated is the maximum voltage (V_{mp}) multiplied by the maximum current (I_{mp}) of the PV module under load conditions. The fill factor (*FF*) is a measure of the quality of a PV module obtained by comparing the theoretical maximum power and output power at open circuit and short circuit conditions. It can be determined based by (1) [27].

$$FF = \frac{P_m}{V_{oc} \cdot I_{sc}} = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}} \tag{1}$$

The greater of fill factor (*FF*) value indicates higher energy conversion efficiency and better PV cell performance. PV cell efficiency (η_{pv}) is related to the maximum output power (P_m) and solar radiation (G) in W/m^2 over the PV cell area (A_c) in m^2. PV cell efficiency can be calculated with (2).

$$\eta_{pv} = \frac{P_m}{G \cdot A_c} = \frac{I_m \cdot V_m}{P_i} = \frac{I_{sc} \cdot V_{oc} \cdot FF}{P_i} \tag{2}$$

The temperature of cells and modules increases at higher ambient temperatures which is influenced by the intensity of solar radiation. As a result, the cell temperature and the rear-surface module temperature can be very different. If the cell temperature is difficult or cannot be measured directly, then the rear-surface module temperature can be measured first. Then the relationship between cell temperature and the rear-surface module temperature can be written using (3) [27].

$$T_c = T_m + \frac{G}{G_0} \cdot \Delta T \quad (3)$$

where T_c is the cell temperature inside module, T_m is rear-surface module temperature, G is solar irradiance on the module, G_0 is the reference solar irradiance at 1000 W/m^2, and ΔT is temperature difference between the cell inside and the rear-surface of the module which ranges from 2 °C to 3 °C for plate modules (glass/cell/polymer) in open rack mounts [28]. However, if the rear-surface module temperature is unknown, then the cell temperature can be determined by (4).

$$T_c = T_a + \left(\frac{T_{NOCT} - 20}{800}\right) \cdot G \quad (4)$$

The increasing temperature means that electrons are more easily excited, causing a lower open circuit voltage (V_{oc}). The decrease in V_{oc} cannot be compensated by the short circuit current (I_{sc}) which slightly increases due to the increase in carrier concentration. The effect leads to (5) [29]:

$$\eta_{pv} = \eta_{stc}[1 - \beta(T_c - T_{STC})] \quad (5)$$

where η_{pv} is the module's efficiency at the reference temperature, η_{pv} is the module's efficiency at temperature of STC standard (25 °C, 1000 W/m^2), β is the temperature coefficient of maximum power, P_m (%/°C) referring to the manufacturer's datasheet [23], [30], [31]. Therefore, the relationship between output power of PV module and temperature can be determined using (6) [29]:

$$P = G\eta_{stc}A[1 - \beta(T_c - T_{STC})] \quad (6)$$

where G is solar irradiance and A is the surface area of the module.

2.4. Raw and net gain

The raw gain of a PV cooling system (ΔE_{Raw}) is the extra energy produced by the PV module due to the use of the cooling system (ΣE_{cooled}) in watt hour (Wh). This can be calculated simply with (7) and (8):

$$\Delta E_{Raw} = \Sigma E_{cooled} - \Sigma E_{uncooled} \quad (7)$$

$$Raw\ Gain\ (\%) = \left(\frac{E_{cooled} - E_{uncooled}}{E_{uncooled}}\right) \times 100\% \quad (8)$$

Meanwhile, the net gain from the PV cooling system (ΔE_{Net}) is the extra energy produced by the PV module considering energy of cooling system, then compared with the energy produced by the module without cooling ($\Sigma E_{uncooled}$). In other words, the net gain takes into account the total energy consumed by the circulating pump (E_{CP}) to circulate water coolant through the module surface at a certain flow rate during the active cooling process. For a given period of time, the net gain can be calculated as expressed in (9) to (10).

$$\Delta E_{Net} = \Delta E_{Raw} - E_{CP} \quad (9)$$

$$\Delta E_{Net} = (\Sigma E_{cooled} - \Sigma E_{uncooled}) - \Sigma E_{cp} \quad (10)$$

$$Net\ Gain\ (\%) = \left(\frac{\Delta E_{Raw} - E_{CP}}{E_{uncooled}}\right) \times 100\% \quad (11)$$

Optimal net gain is the key to the technical feasibility of a PV cooling system. It also highlights the actual energy gain in this study. Therefore, in controlling an active cooling system, it is necessary to identify the points where the gain is optimal in terms of the water flow rate and the effective energy of the circulation pump (E_{CP}).

3. RESULTS AND DISCUSSION

One of the objectives of this study was to evaluate the cooling process of PV cooling system based on the temperature reduction achieved, the increased PV output power, net energy gain and water flow rate. The complete scheme of the experimental setup can be seen as shown in Figure 3. In this study, a comparison of the cooling process performed based on three pump system activations, namely the first was active continuously, the second was active based on setpoint temperature, and the last was active based on the pump PWM control.

The experiment also involved an uncooled PV module as a comparison. In the process all the parameters needed for analysis are measured in real time for every 1-minute interval of data collection throughout the day. The initial of the process of cooling or activating the pump was when the module temperature has reached 50 °C or more.

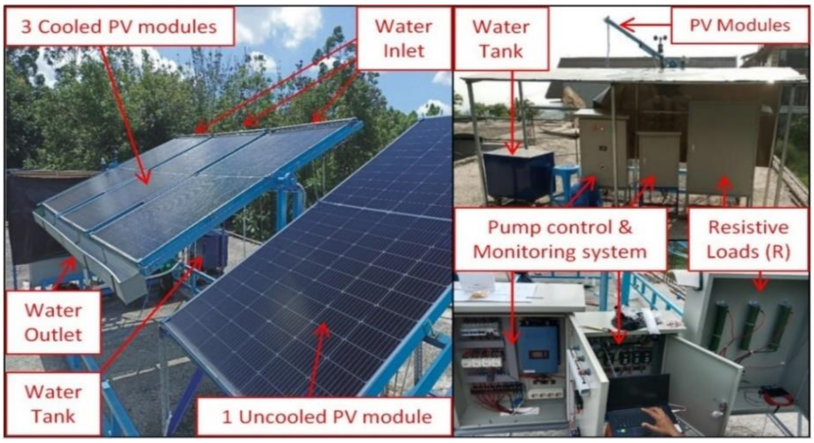

Figure 3. Experimental setup of PV modules cooling

3.1. General circumstances

The module was tested in a geographic location with a tropical climate (Bandung City, Indonesia) on a clear summer day and there were only thin clouds at certain times. Figure 4 shows the intensity of solar irradiance (*G*) in W/m2 measured using irradiance meter during one of the experimental days in August, air temperature (T_A) in degrees Celsius measured using DHT22 sensor, and water coolant temperature (T_W) in degrees Celsius measured using DS18B20 sensor. Meanwhile the air velocity was neglected because it is less than 1 m/s.

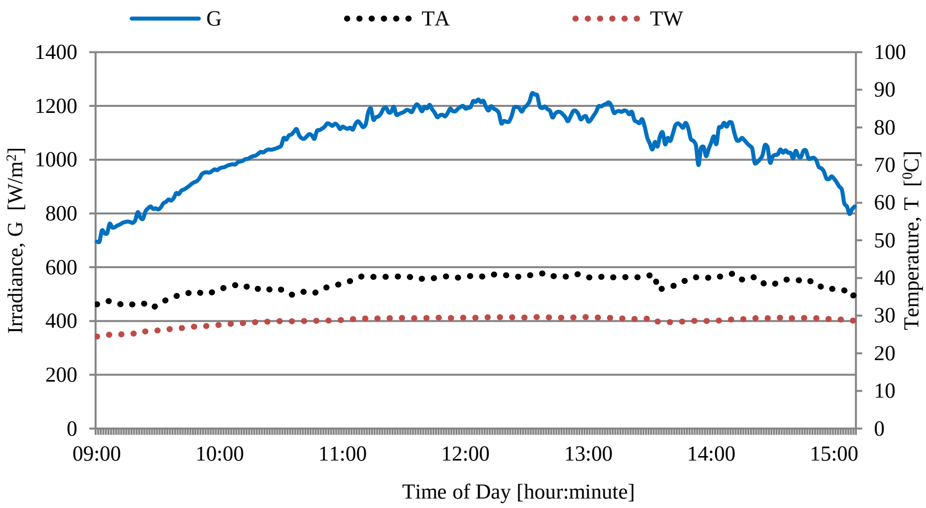

Figure 4. Solar irradiation intensity (POA), temperature of air and water, in different hours

Series of measurements was carried out from 09.00 a.m. to 15.00 p.m. within 1-minute intervals of time. The solar irradiance ranged from 695 to 1247 W/m^2 occurs at 09.00 a.m. and 12.32 p.m., respectively. According to Indonesian Solar Atlas, 4.71 to 5.25 kWh/m^2 are the daily average irradiation during a day in

August in Bandung city. The minimum of air temperature (T_A) is equal to 32.2 ºC, and the maximum is equal to 41.3 ºC with average of 38.43 ºC, also with average water coolant temperature (T_W) of 28.56 ºC.

3.2. Effect of water cooling on temperature of PV module

Simultaneous measurement results with the reading parameters are displayed completely in Figure 5. It shows the flow rate effect of cooling water mass (m_w) on the temperature (T_m) of the cooled PV modules of PV cooling and its comparison to the uncooled PV module. In naming curves, uncooled PV module is denoted by M_{uc}, cooled PV module by using pump activation 1 (constant flow rate), pump activation 2 (intermittent flow rate), and pump activation 3 (smooth decrease in flow rate) are denoted by M_{c1}, M_{c2}, and M_{c3}, respectively.

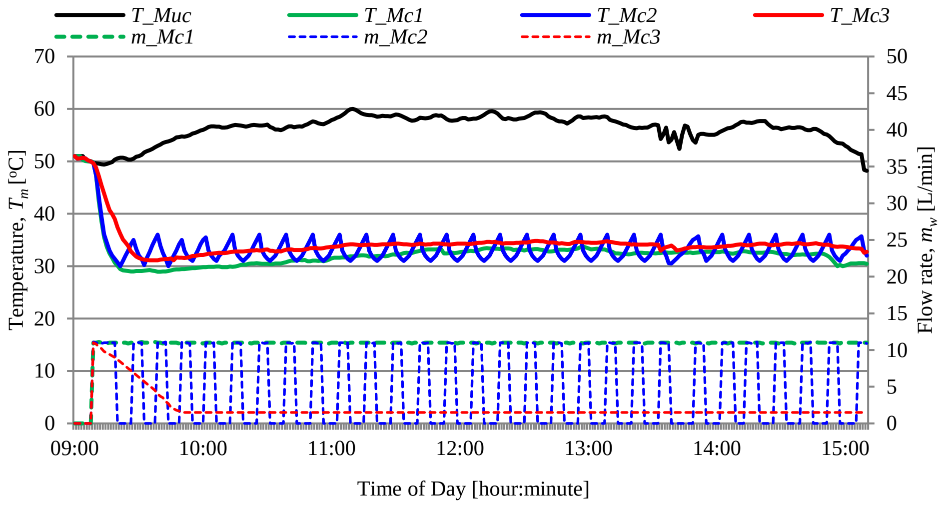

Figure 5. Comparison of the effects of various water flow rate on module temperature

The temperature readings of modules start to be recorded at 09.00 a.m., when the sunlight began to rise and the temperature of modules increased exceed normal conditions (*NOCT*). At this point the temperature of all modules tested exceeds 45 ºC. During the test, the average temperature of uncooled module (T_M_{uc}) reached 56.21 ºC with a min. of 48 ºC and a max. of 59 ºC as shown by black line curve. While at 9.08 a.m., all cooled modules of PV cooling systems (M_{c1}, M_{c2}, and M_{c3}) started to activate the cooling process. Furthermore, from the three cooling activation controls can be explained as follows:

- Continuous pump activation results constant water flow rate of cooled module (m_M_{c1}) around 11 L/min as shown by green dotted line as shown in Figure 6. During the test, the average temperature of cooled module 1 (T_M_{c1}) is around 32.42 ºC with the average of flow rate of 10.73 L/min according to green line curve. A sharp reducing in temperature of the cooled module 1 (T_M_{c1}) occurs from 49.82 ºC to 29.43 ºC at 09:08 to 09:19 a.m. This cooling process results in a maximum decrease in module temperature ($\Delta T\_\ M_{c1}$) around 20.39 ºC for 13 minutes with water flow rate of 11 L/min. Hence, the declaim rate of module temperature is 1.57 ºC/min. After reaching a minimum temperature (29 ºC), there is no further decrease in module temperature, even it tends to steady and only rises back towards 33 ºC due to the increase in air temperature and solar irradiance.
- Activation of the pump based on the setpoint temperature reading by sensor results in the cooling module water flow (m_M_{c2}) being intermittent between 11 L/min and 0 L/min as shown by blue dotted line in Figure 6. According to blue line curve, reducing the temperature of the cooled module 2 (T_M_{c2}) relatively same as the temperature of the cooled module 1 (T_M_{c1}). It occurs at the beginning of the cooling process until the lower limit setpoint of 31 ºC reached, and then the process stops. Next, a new cooling cycle will begin to start after the temperature of the module 2 (T_M_{c2}) exceeds 35 ºC. During this cooling, the temperature of the cooled module 2 (T_M_{c2}) is maintained in the range of 30 ºC to 35 ºC. The aim of this cooling process is to minimize pump energy and the amount of water consumption. In Figure 6, the blue line curve shows the average increase rate in module temperature above 30 ºC is 1 ºC/min when cooling is not active. While when it is active, the average of decline rate in module temperature is 1.67 ºC/min, depending on air temperature and solar irradiance.

– Activation of the pump based on a decrease in the pump PWM voltage results the cooling module water flow (m_M_{c3}) decreasing from 11 L/min to 1.5 L/min during the test. Here, as long as the module temperature decreases, the controller will automatically reduce the PWM voltage. According to red line curve, reducing the temperature of the cooled module 3 (T_M_{c3}) from 49.64 ºC to 31.12 ºC, occurs at 09:08 to 09:27 a.m. This cooling process results in a decrease in module temperature ($\Delta T\_ M_{c3}$) around 18.52 ºC for 22 minutes as shown in Figure 6. Hence, the declaim rate of module temperature is 0.84 ºC/min. Because the module temperature of 31.12 ºC cannot be reduced any further (steady state) at a flow rate of 1.5 L/min, then based on the temperature sensor reading, the controller automatically cannot reduce the pump PWM voltage any lower. In this condition the PWM value was maintained until the end of the test. Under conditions of constant water flow rate at 1.5 L/min, the temperature of the cooled module 3 (T_M_{c3}) ranges between 31 ºC to 35 ºC depending on the air temperature and solar irradiance.

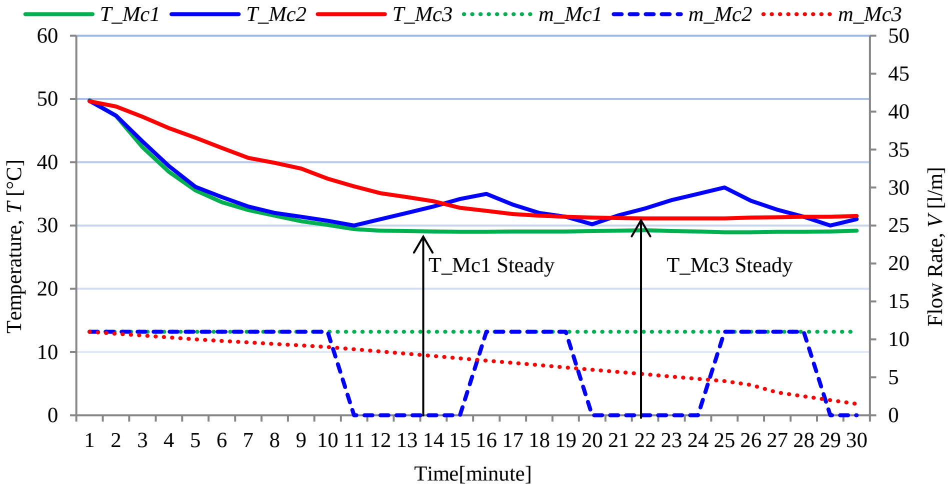

Figure 6. Comparison of the effects of various water flow rate on minimum steady state module temperature

According to Figure 6, it is further observed that there is a non-linear relationship between the temperature of the cooled module and the water flow rate at a specific solar irradiance. By constant flow rate (m_M_{c1}), the temperature of the cooled module 1 (T_M_{c1}) decreases non-linearly such that at a certain point a further constant flow rate does not result in significant decrease in the module temperature 1 (T_M_{c1}). Another observation was also on the cooled module 3 (M_{c3}) where at a certain point, the decreasing PWM or water flow rate (% / m_M_{c3}) does not result in significant increase in the temperature of the cooled module 3 (T_M_{c3}). This observation is in accordance with what has been reported by previous studies [23], [30]–[33]. However, the results of the non-linear equations cannot be generalized, depend on the thermal design of the PV cooling system and require further investigation.

3.3. Electrical energy and efficiency analysis of PV module due to cooling process

In this section the effect of the cooling technique of PV cooling system on the output energy and electrical efficiency of the PV module was investigated. Figure 7 shows comparative profile of electrical power generated by uncooled PV module compared to cooled PV modules, as well as the electrical power consumed by the pump during the cooling process. In fact, all cooled PV modules produce greater electrical energy output than uncooled module at all time during the test. The lower the module temperature lead to the greater electrical energy generated, as the consequence was greater the electrical energy and amount of water in an active cooling system. The maximum power output of all PV modules tested occurred at 12:33 p.m., with maximum solar irradiance of 1247 W/m^2. This correlation was in accordance with (2). At that point, the output power of the uncooled module (P_M_{uc}) is 79.96 W. Meanwhile, the output power of the cooled modules by constant flow rate (P_M_{c1}), by intermittent flow rate (P_M_{c2}), and by decreasing flow rate (P_M_{c3}) are 97.47, 97.50, and 96.41 W, respectively. The minimum power output of all PV modules tested occurred at 09:00 a.m., with solar irradiance of 749 W/m^2. It's resulted the output power of the uncooled module (P_M_{uc}) equal to the output power of all cooled module ($P\_Mc_{1,2,3}$) around 63 W where the instantaneous cooling process has just begun. Thus, for 6 hours of the test, the total energy produced by the module without cooling (E_M_{uc}) is 370.54 Wh, while the output power of the cooled modules by constant flow rate (E_M_{c1}), by intermittent flow rate (E_M_{c2}), and by decreasing flow rate (E_M_{c3}) are 444.65 Wh, 439.19 Wh, and 437.95 Wh, respectively.

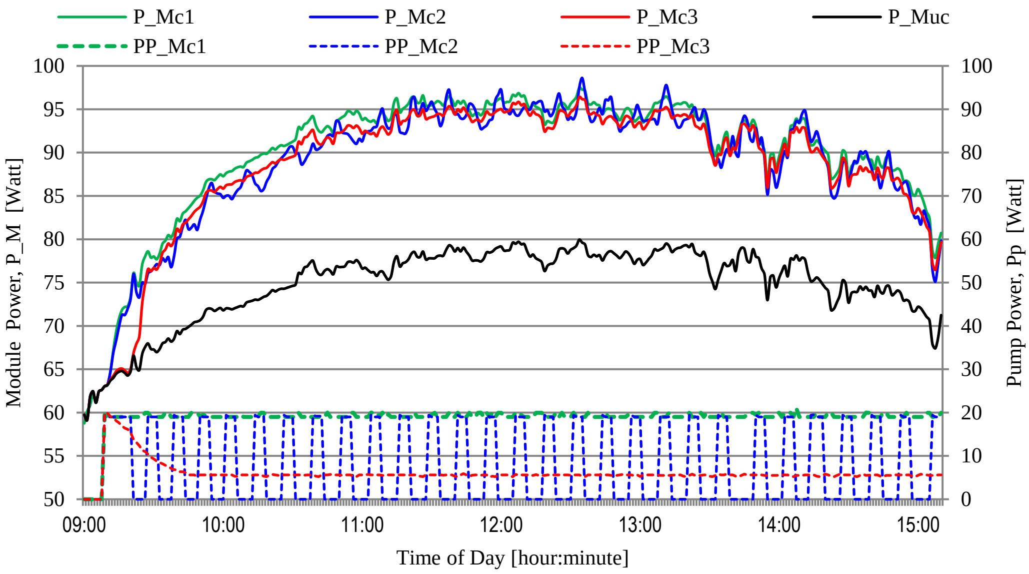

Figure 7. Electrical power profiles of cooled/uncooled modules and cooling process requirement

The electrical power consumed by the pump in the process of cooling the PV modules are shown by the dotted line curves. The pattern of pump power curves always equal to the flow rate ones, as shown in Figure 5). Refers to pump name plate, the nominal voltage, power, and flow rate are 12 V DC, 19 W, and 11 L/min, respectively. The total energy consumed of cooling pump ($\sum E_{cp}$) for 6 hours of the test on cooled modules by constant flow rate (PP_M_{c1}), by intermittent flow rate (PP_M_{c2}), and by decreasing flow rate (PP_M_{c3}) are 97.16, 46.38, and 30.66 Wh, respectively. Figure 8 shows the profiles of electrical efficiency of cooled PV modules ($\eta\_M_{c1,2,3}$) including uncooled PV module (η_M_{uc}) as a comparison. After that, the electrical efficiency of all cooled PV modules was always higher than that of uncooled modules until the end of the test.

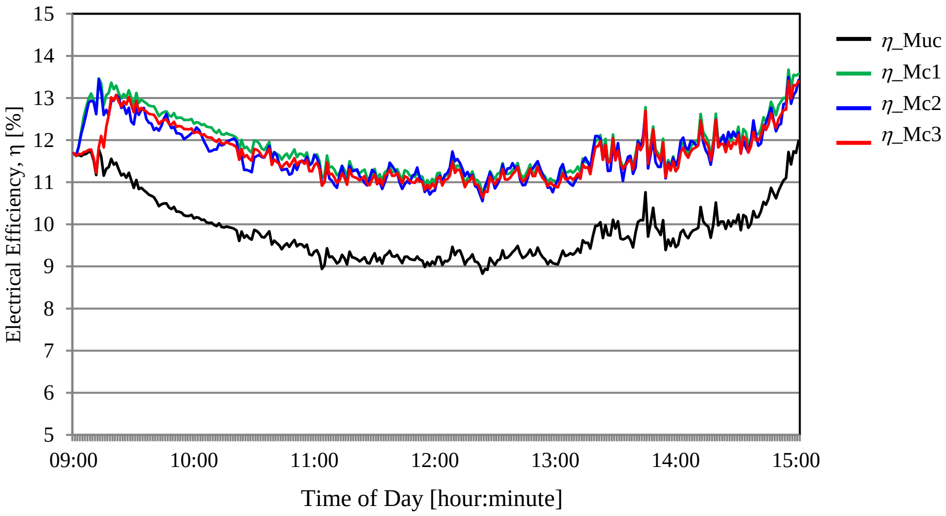

Figure 8. Electrical efficiency profiles of cooled/uncooled modules

Electrical efficiency of all PV modules experiences a downward trend from the beginning of the test until the middle of day (12:33 p.m.) due to the increasing temperature of the PV modules influenced by air temperature during that period. However, the trend reversed after 12:33 p.m. when both the air temperature and PV module's temperature began to decrease. It is clear that increasing the temperature of the module can reduce its electrical efficiency. The average electrical efficiency recorded during the test for the cooled modules by constant flow rate (η_M_{c1}), by intermittent flow rate (η_M_{c2}), and by decreasing flow rate (η_M_{c3}) are 11.84%, 11.69%, and 11.65%, respectively, with increase in efficiency are 20.10%, 18.53%, and 18,16% respectively against 9.86% for an uncooled module (η_M_{uc}). Thus, the higher the water flow rate lead to the higher the increase in module efficiency.

3.4. Analysis of raw and net energy gain

The profiles of the raw and the net energy gain of all cooled PV modules can be seen in Figure 9. As presented in (7), the raw energy gain (ΔE_{Raw}) was determined based on the difference in total energy produced between cooled PV modules ($\Delta E\_M_{c1,2,3}$) and uncooled PV module ($\sum E\_M_{uc}$). It highlights the potential extra energy due to cooling process in PV cooling system (in Wh/kWh). As presented in (9), the net energy gain is determined based on the difference between raw energy gain (ΔE_{Raw}) and the total energy consumed by the cooling pump ($\sum E_{cp}$) during the test.

Based on the total power of all cooled modules ($\sum P_{raw}\_M_{c1,2,3}$) calculation for 6 hours of the test, the raw energy of cooled modules by constant flow rate ($\sum E_{raw}\_M_{c1}$), by intermittent flow rate ($\sum E_{raw}\_M_{c2}$), and by decreasing flow rate smoothly ($\sum E_{raw}\_M_{c3}$) are 74.13, 68.63, and 67.49 Wh, respectively. Meanwhile, net energy gain of cooled modules by constant flow rate ($\sum E_{net}\_M_{c1}$), by intermittent flow rate ($\sum E_{net}\_M_{c2}$), and by decreasing flow rate smoothly ($\sum E_{net}\_M_{c3}$) are -23.03, 22.25, and 36.83 Wh, respectively, with a percentage increase are -6.21%, 6.01%, and 9.94%, respectively. Thus, the process of cooling the PV module with a smooth decrease in water flow rate by pump PWM voltage setting, resulting more superior net energy gain.

A negative net energy gain indicates that the energy required for the PV cooling process is unbalanced and not efficient. Even resulting a low positive energy gain, it requires the optimal control design and proper calculations related to technical and economical viable. As explained in the previous section that under certain conditions, there is non-linear relationship between cooling the module temperature and the constant water flow rate. For a long time, cooling process in this specific PV cooling system, large differences in flow rates do not have any significant on large differences in module temperature reduction as well, especially after each reaches a steady temperature. The several factors influence it such as the material heat property, air temperature, water temperature, irradiance, and other environmental factors that require further investigation.

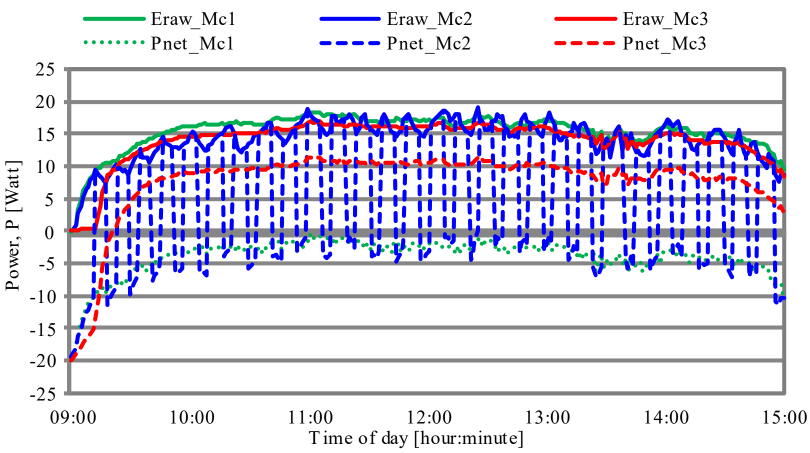

Figure 9. The raw and the net energy profiles of uncooled PV modules

3.5. Overall performance analysis

As the experimental objectives stated in the introduction, this section describes essential points of the cooling pump activation settings in cooling the PV modules in the PV cooling system. The pump activation settings with PWM controllers are more superior than other controls in cooling PV module due to greater net energy gain, and with minimal water flow rate, although it resulting higher final temperature of PV module cooling. However, the percentage of both net energy gain and the amount of water in this experimental result cannot be generalized, it depends on the cooling design of the PV cooling system. For example, in controlling cooling pump activation based on setpoint temperature, a lower temperature setpoint does not necessarily result in a higher net energy gain. Even though the output PV module produces more energy, it requires larger cooling process energy as well. Meanwhile, in the case of PV module cooling by maximum power of pump and constant flow rate, it is very effective in rapidly reducing the module temperature at the beginning. However, over time the cooling will experience certain conditions where after the module temperature reaches steady state, the constant flow rate is not significant in cooling the module. This is where pump energy being wasted. Selection of cooling pump control with a PWM controller in this experiment have been considered previously. The PWM controller has the ability and flexibility to control pump speed and torque over a wide range, so that the water flow rate can be managed precisely.

4. CONCLUSION

This paper deals with the comparison of cooling pump activation controls on the cooling performance of the PV cooling system through the net energy gain and water flow rate approach. Three cooling pump activation controls including continuously active with full power rate, active base setpoints temperature, and active by managing PWM pump voltage have resulted in varying values in each measured parameter. All controls applied in the PV cooling system experiment simultaneously under the same environmental conditions on clear sunny day where no extreme fluctuations both solar irradiance or air temperature.

The three controls have been successful in cooling the PV module with a temperature reduction varying between 37.31% to 42.32%, and an increase in module efficiency between 18.16% to 20.10%. So, it is proven that reducing the temperature of the PV module will increase its efficiency. However, as an active cooling, there are losses in the PV cooling system such as energy losses and water losses that must be considered to obtain more realistic and viable results. Therefore, the aim of this paper is not only limited to analyzing the effect of water-based cooling on temperature, efficiency, output energy (raw energy gain) in a PV module as a measurement object, but the performance of pump and water coolant is an essential factor to evaluate.

Pump activation control by managing the PWM pump voltage has the greatest effect on net energy gain of 9.94%, followed by pump activation control based on set point temperature of 6.01%, and pump continuously active of -6.21%. This is because managing the pump's PWM voltage is intended to consider the energy savings required during the cooling process, and the impact is that it led to the final temperature of the module cooling being relatively higher than other controls. However, by managing the pump's PWM voltage, water consumption is more efficient with average of flow rate of 2.17 L/min, followed by pump activation control based on set point temperature of 5.08%, and pump continuously active with constant flow rate of 10.74 L/min. The greater in water flow rate for a specific input of solar irradiance effectively decreases module temperature rapidly until such a value that any further increase will not result in any significant changes in module temperature. This condition lead to losses in the cooling process, both energy losses and flow rate losses.

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