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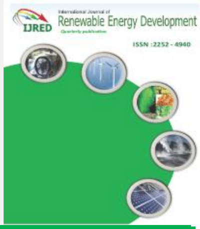

Research Article

Modeling and Experimental Studies on Water Spray Cooler for Commercial Photovoltaic Modules

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Abstract. This paper presents modeling and experimental studies on water spray coolers for commercial photovoltaic modules. This paper has compared the energy yield of four photovoltaic commercial modules that were installed with a fixed tilt angle being equal to the local latitude in central Vietnam, including one photovoltaic module using a water spray cooler and three photovoltaic modules without cooling. Experimental results on sunny days have been shown that the energy yield difference between four PV modules under the same working condition is lower than 1%. In addition, on sunny days when the set working temperature of the water spray cooler is 45 °C, the average improvement efficiency of a photovoltaic module using a water spray cooler compared to three reference photovoltaic modules is 2.64%, 3.83%, and 6.18%, for an average of 4.22%. A simple thermal–electrical model of a photovoltaic module with a water spray cooler has been developed and tested. The normalized root mean square error between simulated and measured results of photovoltaic module power output on a sunny day without cooling and with water spray cooler reached 6.5% and 8.5%, respectively. The obtained results are also demonstrated that the reasonableness of the simple thermal–electrical model of the photovoltaic module with water spray cooler and the feasibility of a cooling system is improved to increase the efficiency of the photovoltaic module. In addition, they can be considered as a basis for new experimental models in the future.

Keywords: Thermal–electrical model, photovoltaic, water spray cooler, efficiency.

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1. Introduction

As compared to other solar technologies, the electricity generated by a solar photovoltaic (PV) system not only does not cause the environmental pollution during operation, but it also reduces global warming problems and operating and maintenance costs (Phap and Nga 2020, Al-Shahri *et al.* 2021). However, PV technology in general, and grid-tied solar power in particular, has some general issues that must be addressed, such as low efficiency and being negatively affected by hail, dust, and surface temperatures (Santhakumari and Sagar 2019, Ngo *et al.* 2022). The temperature and direction of solar radiation relating to the work surface have the greatest influence on the performance of PV modules. As a result, a research model is developed to improve the efficiency of the PV system is critical. Furthermore, increasing PV system efficiency contributes to increasing grid-connected electricity output, reducing the investment payback period of solar power projects, saving system installation space, and using energy economically and efficiently (Bhandari *et al.* 2015, Ngo and Do 2022).

The efficiency of the module can be ranged from 5% to 24% (Aste *et al.* 2017, da Silva *et al.* 2021) depending on the type of PV cell technology used. However, the exposure to solar radiation in conjunction with high ambient temperatures causes a significant increase in the operating temperature of the PV module. The temperature profile of the PV modules is shown to range from 27 °C to 70 °C (Jones and Underwood 2001, da Silva *et al.* 2021). It is well known that the electrical efficiency of systems can be improved by the reduction of module temperature (Meral and Dincer 2011). This issue has been thoroughly researched in recent years through the development of various cooling techniques. For the currently available PV technologies on the market, electrical efficiency degradation is caused by a rise in module temperature, which is ranged from 0.25 %/°C to 0.5 %/°C (depending on the specific PV technology used) (Nižetić *et al.* 2016, Benato and Stoppato 2019). Therefore, the possible electrical efficiency improvement can be obtained with a proper cooling technique, keeping in mind that each cooling technique should have proven feasibility.

In an open-type PV module cooling system, where the liquid is directed into the PV module, it flows through an area of the PV module surface not limited by pipes, ducts and chambers. The liquid injection is mainly accomplished by spraying (Nižetić *et al.* 2016, Benato and Stoppato 2019)

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or dripping onto the upper surface of the PV module (Dorobanțu and Popescu 2013, Mohanraj *et al.* 2019, da Silva *et al.* 2021). The surface of the PV module is cleaned by the cooling water system.

An experimental study is conducted to test the PV module cooling system based on the sprayed water (Benato and Stoppato 2019). The experiments with the monocrystalline PV module of 230 W have been recently conducted in the Laboratory of Fluid Machines and Energy Systems in the Department of Industrial Engineering at the University of Padova. The obtained results have been shown that a cooling system is equipped with three characteristic nozzles with 90° injection angle, operating with an inlet pressure of 1.5 bar, and still operating for 30 s and off for 120 s. The module temperature is also reduced to 28 °C and the module performance is improved by around 14% (Benato and Stoppato 2019).

Research on active water spray cooling for the front, back, and both surfaces of photovoltaic modules has been conducted for a photovoltaic module of 50 W with an inclination angle of 17° in a Mediterranean climate (the city of Split is located on the Croatian coast) (Nižetić *et al.* 2016). The obtained results have been shown that the electrical efficiency will be linearly increased when increasing the flow of water sprayed on the surface of the photovoltaic module. The average temperature of photovoltaic modules will be decreased from 52 °C to 24 °C, and the lowest temperature of PV modules is limited by the water temperature in the pipeline, which remains constant at 17°C. The improved efficiency of PV modules using front surface spray, back surface spray, and both surface sprays is 14.6%, 14.0%, and 16.3%, respectively, compared with PV modules without the spray.

Under UAE weather conditions, Ahmed and his colleagues investigated various cooling techniques on a 20 W polycrystalline photovoltaic module (Hachicha *et al.* 2015). The cooling system consists of a direct spraying system on the PV module's backside and a spraying system on the front surface. In the case of equivalent solar radiation, cooling the back module can reduce the temperature of the photovoltaic module by 1.7% while increasing power output by 2.3%. The temperature was reduced by 11.3% when the front surface was cooled, and the power output of the photovoltaic modules increased by 3.6%. The temperature decreased by 18.3% in the case of combined front and back cooling, while the photovoltaic module power output increased by 5.5% (Hachicha *et al.* 2015). The results indicate that both front and side cooling are more efficient than back side cooling. This can be explained by the fact that the PV temperature is more sensitive to the front surface and the thermal diffusion of the glass.

A cooling system that sprays water onto the reverse of an 85 Wp PV module was tested in Taiwan (Yang *et al.* 2019). This cooling system has two nozzles and was turned on when the panel temperature reached 45 °C, ran for 240 s, then shut down until the temperature reached 45 °C again. The experimental results show that the PV panel temperature can reach 65 °C, and the proposed system can increase efficiency by 14.3%, with the equipment costs being recovered in 8.7 years (Yang *et al.* 2019).

In addition, the experimental evaluation and mathematical models of the water-film cooling system for commercial photovoltaic modules was conducted at the Polytechnic School, University of São Paulo, São Paulo, Brazil (da Silva *et al.* 2021). The obtained results have been also shown that the temperature of cooling system is reduced by an average of 15–19% and a maximum of 35%. Power output increases from 5% to 9% on average, and up to 12%. The total yield is increased by a maximum of 12% and an average of 2.3–6% (da Silva *et al.* 2021).

An experimental study into the effect of cooling a module with air and water was carried out in Coimbatore, India (Mohanraj *et al.* 2019). According to experimental results, the temperature of PV modules are ranges from 31°C to 62°C in the absence of cooling, from 30°C to 43°C in the presence of air cooling, and from 30.6°C to 37.8°C in the presence of water cooling. The power output during the study day of PV modules without cooling, with air cooling for the upper surface, with air cooling for the bottom surface, with water cooling for the upper surface, and with water cooling for the bottom surface reaches 3.1 kWh, 3.4 kWh, 3.6 kWh, 3.9 kWh, and 4.2 kWh, respectively (Mohanraj *et al.* 2019).

Kordzadeh and colleagues investigated the impact of PV module nominal power on the operation of a photovoltaic water pump with a water film covering the module surface (Kordzadeh 2010). For nominal arrays of 90 W and 135 W, the average efficiency improvement is approximately 3.66% and 0.69%, respectively.

According to research on the water-cooler model to improve PV module efficiency, the proposed working modes improve energy efficiency by 2.06% to 5.97% (Schiro *et al.* 2017). According to the numerical model outputs, the pay-back time is 7 years and 10 months, and with the hypothesis of water derived from a river and no cost for water rights, the pay-back time is 3 years and 9 months (Schiro *et al.* 2017).

A study on the effect of water cooling on single and polycrystalline PV modules was conducted on August 6, 2020, in Tehran (Shahverdian *et al.* 2021). The PV modules are installed at a south angle and an angle of inclination equal to the latitude of the study site. The cooling water flow is allowed to flow directly onto the surface of the PV modules to form a water film. By using the mathematical modelling and experimentation on a hot summer day, it has been shown that the optimum water flow rate is around 0.01 kg/s and the improvement of power and efficiency for cooled poly and monocrystalline PV modules is 3.84% and 4.20%, respectively, compared with uncooled PV modules. The obtained results also have indicated that the effect of wind speed on PV module output power is present, but its increase rate is much smaller than that of water cooling.

An experimental study was conducted with a 75 W mono-crystalline PV module which is cooled by a continuous film of water that pours on the working surface of the PV module (Dorobanțu and Popescu 2013). The achieved results have shown that the temperature of the cooled PV modules is reduced by 10 °C with the water temperature of 24 °C and the air temperature of 31 °C. In addition, the energy yield can be increased up to 9.5% (Dorobanțu and Popescu 2013).

As the above analysis, it has been shown that the efficiency of PV modules is improved by the use of water coolers. Although, many studies have investigated the efficiency of cooled PV technology energy solutions, relatively a few of are based on simulation and experimental studies of water spay coolers.

The novel contribution of this paper is dealed with two issues: Firstly, simple models for the PV modules with water spray cooled on the top surface are presented.

Secondly, a detailed experimental analysis based on outdoor collected data, designed and built to study the performance of uncooled and cooled PV modules is also proposed to be verified results obtained from the simulated method.

2. Research method and system description

2.1 Research method

As presented in Section I, in this part, the methods are presented to carry out for researching, that is:

- Modelling: Under certain assumptions, PV modules using the water spray cooler are described by simple thermal–electrical model;
- Experiment: Through measurement of parameters including total solar irradiance shining on the surface area of solar cells of PV module, air temperature, PV module temperature, water temperature, wind speed, and DC power output of uncooled and cooled PV modules;
- Data analysis: Selection of typical sunny days to analyze the efficiency of cooled versus uncooled PV modules. Verify the model and experiment through statistics.

2.2 System Description

A rooftop grid-connected photovoltaic (GCPV) system with 4 polycrystalline PV modules is used as an outdoor test system, where the PV modules are installed at an angle being equal to the latitude of the study area of 17°N (in Hue City, Vietnam) (Ngo *et al.* 2022). In which, one PV module is used with a water spray cooler and the remaining three PV modules are used for references. All four modules are connected to a grid-tied microinverter with four independent MPPT inputs. The parameters of PV modules are presented in Table 1.

In this context, the cooler in this study is designed with 6 nozzles placed at the high part of the PV module width so that they do not cast shadows all the time. As pointed out in Figure 1, each nozzle is spaced 16 cm apart. The actual image of PV modules using a water spray cooler is shown in Figure 2. Cooling water is stored in a 100 - liter tank, and is supplied by a 12 V pump motor with a maximum water flow of 3.5 l/min, a pressure of 0.48 bar, and the cooling effect of the spray stream directly over the entire area of the PV modules. The pump motor of the cooler is controlled by the L298n driver with a voltage of 3.3 V through the NodeMCU ESP32S board. The water spray cooler is operated in on/off mode with a preset temperature.

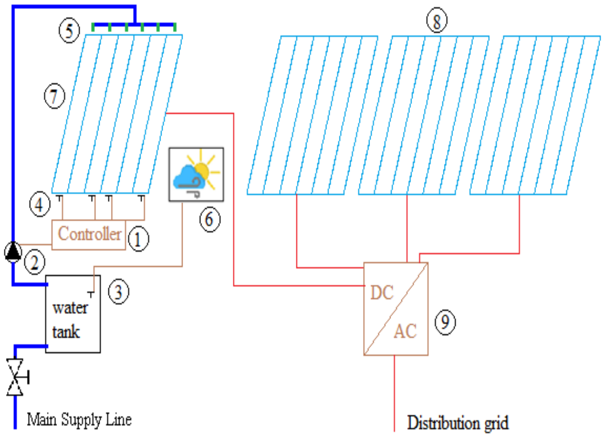

Fig. 1. Water spray cooler and measurement system (1. Cooler controller; 2. Water pump; 3. Water temperature sensor; 4. Four temperature sensors PV module; 5. Six water spray nozzles; 6. Weather monitoring system; 7. PV module with cooler; 8. Three PV module without cooler. 9. Microinverter).

Fig. 2. A prototype of the water spray cooler for PV module.

Table 1
Characteristics of PV module at STC.

PV module	Specifications
Type	SUN330-72P
Type of cells	Polycrystalline
Power rating	330 Wp
Module Efficiency	17.09%
Number of cells	72
Voltage at maximum power	37.8 V
Current at maximum power	8.73 A
Short circuit current	9.22 A
Open circuit voltage	45.5 V
Temperature coefficient of P_{max}	−0.41 %/°C
Temperature coefficient of I_{sc}	0.06 %°C
Temperature coefficient of V_{oc}	-0.33 %°C
Module dimension	1950x990x40 mm
Weights	23 kg

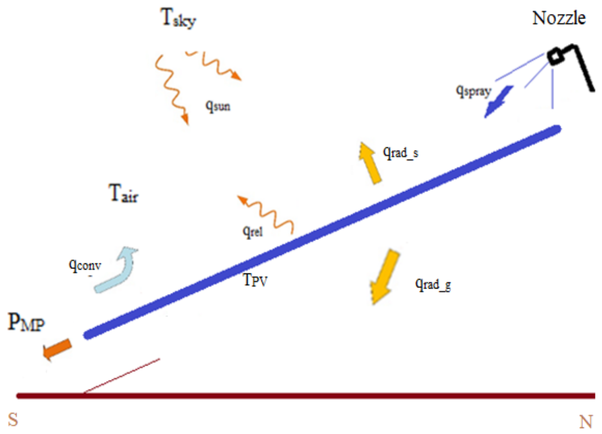

Fig. 3. Thermal–electrical model of PV modules with water spray cooler.

2.3. Photovoltaic modules measurement and weather monitoring system

The Cooler controller uses 4 DS18B20 temperature sensors placed on the back surface of the PV module to measure the average temperature of the PV module and control the water pump (Huang *et al.* 2012). The DC power of each PV module is collected from the solar data logger built into the grid-tied microinverter with a sampling interval of 5 min.

Weather monitoring system with sampling time of 20s including sensors:

i. 01 digital temperature sensor DS18B20 type used to measure the temperature of water in the tank (Huang *et al.* 2012).
ii. 01 pyranometer based on MAX44009 light sensor installed on the tilted surface of the PV module (Karabulut *et al.* 2020).
iii. 01 wind three-cup tower crane anemometer (Yang *et al.* 2019).
iv. 01 air temperature humidity sensor DHT22 (Koestoer *et al.* 2019).

2.4. Model Validation

The model estimates and the measured data were compared using the normalized root mean square error (NRMSE). The value of NRMSE is always positive and the smaller the better. NRMSE value is calculated according to the calculation formula (Marion 2008, Abe *et al.* 2020).

$$NRMSE = 100 * \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{1/2} / \bar{x} \qquad (1)$$

where y_i is the i^{th} simulated value, x_i is the i^{th} measured value, n is the number of measured or simulated values and $\bar{x}$ is average measured value.

3. Thermal–electrical model of PV modules

3.1. Assumption

The parameter inputs of the model consist of the solar irradiance on PV module surface, air temperature, wind speed, cooling water temperature, and pump motor speed. The output of the model is the PV module temperature, power output of PV module.

In this research, a thermal–electrical model of PV modules with and without water spray cooler is constructed. For the PV modules without a water spray cooler, the heat exchanger component by water spray cooler is omitted. The heat exchanger components of the PV modules are presented in Figure 3. Initial assumptions include:

(1) The PV modules can be modelled as a single solid mass at a uniform temperature (T_{PV}).
(2) The temperature of the ground where the installation is located being equal to the air temperature.
(3) PV modules receive heat as insulation and lose heat to the surrounding environment via convection, radiate to the ground, radiate to the sky with sky temperature (T_{sky}), and generate electrical power (P_{MP}). Furthermore, heat transfer between the mist stream and the cooling water temperature (T_w) and evaporation during the cooling misting process will cause the PV modules to lose heat.

The energy balance equation is given as:

$$C_{PV}\frac{dT_{PV}}{dt} = G_t.A_{PV} - q_{rel} - P_{MP} - q_{rad_s} - q_{rad\_g} - q_{conv} - q_{sp} \qquad (2)$$

where C_{pv} is the equivalent thermal capacitance of PV module (J/K), T_{PV} is the PV module temperature (°C), G_t is the solar irradiance on PV module surface (W/m²), q_{ref} is the reflected solar irradiance (W), P_{MP} is electric power output of PV module (W), q_{conv} is the convective heat transfer between the PV module surface and the air (W), q_{rad_s} is the radiation heat transfer between the PV module and the sky (W), q_{rad_g} is the radiation heat transfer between the PV module and the ground (W) and q_{sp} is convective heat transfer between the PV module and water spray (W).

3.2. Reflected solar irradiance

Solar irradiance strikes the surface of the PV modules, where it is partially transmitted through the protective glass and partially reflected back into space. The component reflected back to the sky is calculated using the formula:

$$q_{rel} = (1 - \tau_g).A_{PV}G_t \qquad (3)$$

where τ_g is Transmissivity of PV module protection glass and A_{PV} is surface area of PV modules (m²).

The transmissivity of PV module protection glass varies with the angle of incidence of solar irradiance on the PV module. For the sake of model simplification, an annual mean is assumed for this parameter with no loss of precision and it is set to 0.96 (da Silva *et al.* 2021).

3.3. Thermal capacitance of PV module

PV modules are considered as a single block of solid material at a uniform temperature with thermal capacitance calculated as follows:

$$C_{PV} = A_{PV}\sum_i \rho_i.x_i C_{p\_i} \qquad (4)$$

where ρ_i is density of the i^{th} layer of material (kg/m³), x_i *is* the thickness of the i^{th} layer in mm, C_{p_i} is the specific heat capacity (kJ/kg.K) and A_{PV} is surface area of PV modules (m²).

Table 2
Thermal parameters of PV module layers.

	Glass	Cell	Tedlar	EVA
Thickness, mm	4	0.5	1	0.5
Specific heat capacity, kJ/kg.K	0.8	0.7	1.01	3.135
Density, kg/m^3	2482	2328	1720	1720

Conventional PV modules have four layers with thermal parameters given in Table 2 (Mohanraj *et al.* 2019). Thermal capacitance of PV modules is calculated to be equal to 25464 J/K. This data is also close to 22800 J/K in the study (Perovic *et al.* 2019), it should be also noted that the exact value of C_{PV} is not required, because a 50% change in the value of C_{PV} will not significantly change the results of the model.

3.4. Radiation heat

The radiant heat loss component can be calculated by taking the emissivity and temperature of the emitter and receiver surfaces into account. For simple modeling purposes, the sky is considered to be a black body with temperature T_{sky}, and the ground where the PV modules are installed to have a temperature equal to the plate temperature of the air. As a result, two components with the following expressions can be used to estimate radiation heat transfer (Mohanraj *et al.* 2019):

$$q_{rad\_s} = A_{PV}.\sigma.\varepsilon_{rad}.\left[(T_{PV}+273)^4-\left(T_{sky}+273)^4\right)\right]$$
$$q_{rad\_g} = A_{PV}.\sigma.\varepsilon_{rad}.[(T_{PV}+273)^4-(T_{air}+273)^4)] \quad (5)$$

where, q_{rad_s} is radiation heat transfer between the PV module and the sky, W; q_{rad_g} is radiation heat transfer between the PV module and the ground, W; ε_{rad} is the thermal emissivity of the PV module (about 0.98), σ is the Stephan-Boltzmann constant 5.68x10^{-8} W/m^2.K^4; T_{PV} is the PV module temperature, ^{o}C; T_{sky} is the sky temperature in ^{o}C and is estimated according to Eq. (6) (Mohanraj *et al.* 2019):

$$T_{sky} = 0.0552.{T_{air}}^{1.5} \quad (6)$$

3.5. Convective heat transfer between the PV module surface and the air

The convection heat exchanger component is concerned with heat transfer between the PV module and the environment, which occurs primarily as a result of forced convection caused by wind speed. This study takes into account a linear model between wind speed and convective heat transfer coefficient, modeling convective heat exchange between PV modules and air using the following formula (Shahverdian *et al.* 2021, Sohani *et al.* 2021):

$$q_{conv} = A_{PV}.h_{conv}(T_{PV}-T_{air})$$
$$h_{conv} = 3.v_{wind}+2.8 \quad (7)$$

where v_{wind} is the wind speed (m/s); h_{conv} is the convection heat transfer coefficient (W/m^2.K), T_{air} is the temperature of the air around the PV module (^{o}C).

3.6. PV module electrical model

Common commercial PV modules will be supplied with specifications which include maximum power (P_{MP_STC}) at standard test conditions, thermal coefficients of power. The maximum power of PV modules generated under the influence of solar irradiance is calculated in Eq. (8) (Marion 2008):

$$P_{MP}(G,T_C) = P_{MP\_STC}\frac{G}{G_{STC}}[1+\alpha_P.(T_{PV}-T_{STC})] \quad (8)$$

where G_{STC} is solar irradiance at standard test conditions (1000W/m^2); T_{STC} is temperature at standard test conditions (25 ^{o}C), P_{MP_STC} is maximum power at standard test conditions (W), α_P *is* thermal coefficient of power, %(^{o}C^{-1}), and G *is* the total solar irradiance shining on the surface area of solar cells of PV modules, (W/m^2) and is calculated by:

$$G = G_t.\tau_g \quad (9)$$

where, τ_g is the transmissivity of PV module protection glass.

The manufacturer's maximum power at standard test conditions typically degrades over time with an annual degradation constant of 0.6% (Branker *et al.* 2011). Therefore, maximum power at standard test conditions at the time of study can be calculated by the following formula:

$$P_{MP\_STC\_i} = P_{MP_{STC_i}}.(1-D)^i \quad (10)$$

where i is the usage time (year), D is the annual degradation factor (%). At the time of experiment, the research PV modules were used for 1 year.

3.7. Model of water spray cooler

The spray cooling procedure is as follows: Water is pumped into the air through small holes, causing a dispersion of water droplets to impact the surface of the PV modules. Water droplets spread on the surface and evaporate or form a thin liquid layer, removing a significant amount of energy from the latent evaporator and convection effects. Some of the heat is also exchanged with the surrounding air, complicating the physical process. Despite the fact that research in this area is very active, the mechanisms of heat transfer are still unknown. Because this study is only concerned with very low heat flow and temperature, the heat loss due to spray generated between the water spray and the PV module surface is calculated using the formula (Wang *et al.* 2010):

$$
\begin{aligned}
q_{sp} &= A_{PV} h_w (T_{PV} - T_w) \\
h_w &= Nu_{sp} \frac{k_w}{L_{PV}} \\
\xi &= \frac{T_{PV}}{T_{boiling} - T_{air}} \\
Nu_{sp} &= 7.144 Re_{sp}{}^{0.438} \xi^{0.9016} \\
Re_{sp} &= \frac{MF.L_{PV}}{\mu_w} = \frac{MF_w.\rho_w}{A_{pv}} \frac{L_{PV}}{\mu_w}
\end{aligned} \tag{11}
$$

where h_w is the average heat transfer coefficient between water spray and PV module surface (W/m^2.K), Nu_{sp} is the Spray Nusselt number, k_w is the water thermal conductivity (W/m.K), L_{PV} is the characteristic length of PV module (L_{PV} =*Area/Perimeter*) (m), T_{PV} is the temperature of PV module (^{o}C); T_w is the water spray temperature (^{o}C), A_{PV} is the surface area of PV modules (m^2), ζ is the non-dimensional temperature, T_{air} is the air temperature (^{o}C), $T_{boiling}$ is the evaporating temperature of water (^{o}C); Re_{sp} is the Spray Reynolds number, MF is the mass flux of water based on the unit area of the target PV module surface (kg/m^{2}s), μ_w is the water dynamic viscosity (Pa.s) and MF_w is the mass flow rate (m^3/s), ρ_w is water density (kg/m^3).

In this study, a pump motor with a maximum flow of 3.5 liters per min (equivalent to 5.83x10^{-6} m^3/s) is chosen. The cooling water is supplied from a large tank, so the temperature fluctuates less, so the parameters of the selected cooling water are constants: water density of 997.1 (kg/m^3), water dynamic viscosity of 0.0008905 (Pa.s), and water thermal conductivity of 0.5948 W/m.K are calculated (Dinçer and Zamfirescu 2016).

4. Results and discussion

4.1. Energy yield of PV modules on typical sunny days

The study selects 10 typical sunny days in April 2022 to compare the similarity of PV modules, compare the average yield deviation of fist PV module (PV1) compared with three reference photovoltaic modules (PV2, PV3, and PV4).

The energy yield of PV modules on typical sunny days in April 2022 is shown in Table 3. It is clear that, on sunny days, the average yield deviation of the modules is less than 1%. The total yield of PV3 module is the largest, followed by PV1, PV2, and PV4 modules. Study on choosing a typical sunny day (April 24, 2022) is considered as a case for detailed analysis of PV modules without cooling. The solar irradiance, wind speed, air temperature and cooling water temperature on April 24, 2022 is pointed out in Figure 4. Solar irradiance peaks at 955 W/m^2 at 12 PM, the temperature of the air fluctuates from 25 ^{o}C to 38 ^{o}C, peaks with 38.46 ^{o}C at 10 PM. The power output of PV modules and the average temperature of PV1 module, with the maximum temperature reaching 56.7 ^{o}C at 10 PM is shown in Figure 5. The output of PV module power is peaked at 256 W at 12 PM.

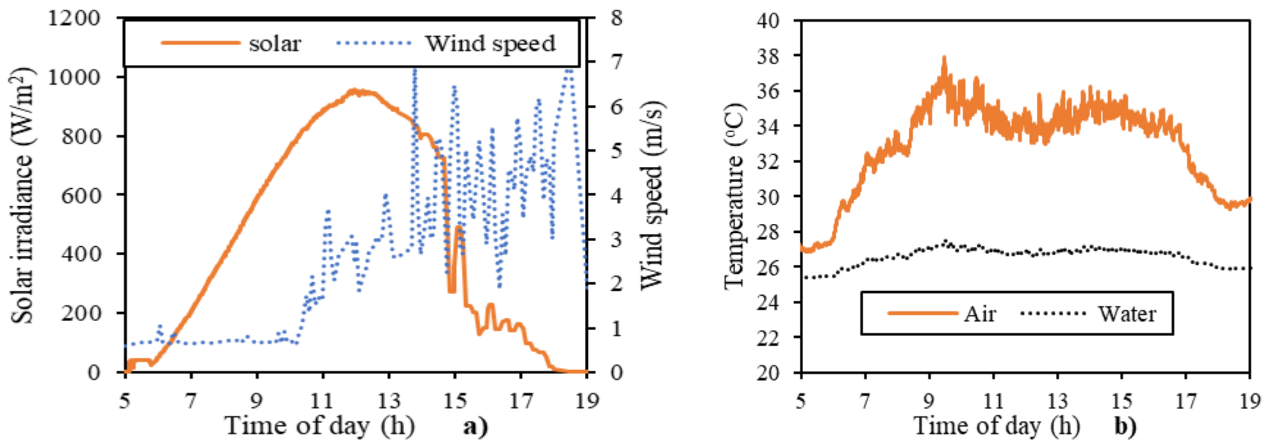

Fig. 4. Weather data April 24, 2022. a) Solar irradiance and wind speed; b) Temperature of air and water.

Table 3
Energy yield of PV modules on typical sunny days in April 2022.

Date	PV1	PV2	PV3	PV4
7/4/2022	1692.9	1686.9	1710.3	1681.9
8/4/2022	1822.9	1807.4	1841.1	1808.6
9/4/2022	1951.4	1936.1	1958.3	1933.5
10/4/2022	1624.0	1616.3	1633.9	1612.1
11/4/2022	1548.5	1539.0	1558.5	1534.5
15/4/2022	1604.7	1594.4	1618.8	1592.4
16/4/2022	1627.3	1619.4	1633.0	1614.3
17/4/2022	1705.2	1691.5	1715.0	1697.1
22/4/2022	1496.9	1492.1	1504.5	1486.7
24/4/2022	1763.8	1752.5	1759.7	1751.7
Total yield, Wh	16837.7	16735.6	16933.0	16712.7
Average yield deviation, %	0	0.61	-0.56	0.75

Table 4
Energy yield and efficiency improvement of PV1 module compared with reference modules.

	Energy yield, Wh				Efficiency improvement of PV1 module compared with, %		
Date	**PV1**	**PV2**	**PV3**	**PV4**	**PV2**	**PV3**	**PV4**
25/4/2022	1715.7	1653.0	1670.8	1618.3	3.79	2.69	6.02
26/4/2022	1833.3	1758.2	1772.1	1714.9	4.27	3.45	6.90
27/4/2022	1724.6	1664.9	1693.2	1634.2	3.58	1.85	5.53
28/4/2022	1889.2	1800.4	1827.0	1761.8	4.94	3.41	7.23
29/4/2022	1880.1	1832.4	1847.3	1787.7	2.60	1.78	5.17
Total	9042.9	8708.9	8810.4	8516.9	3.83	2.64	6.18

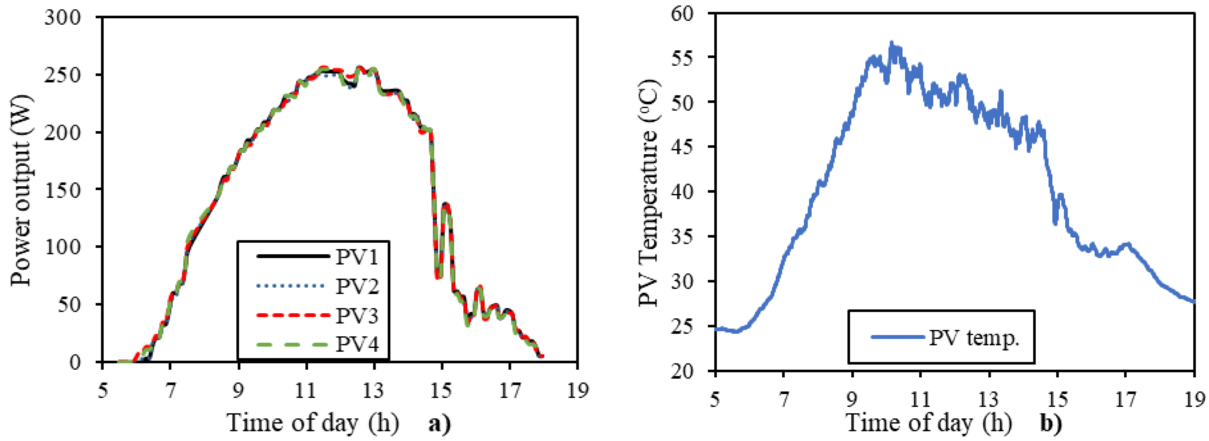

Fig. 5. Power output of PV modules (a) and PV1 module average temperature (b).

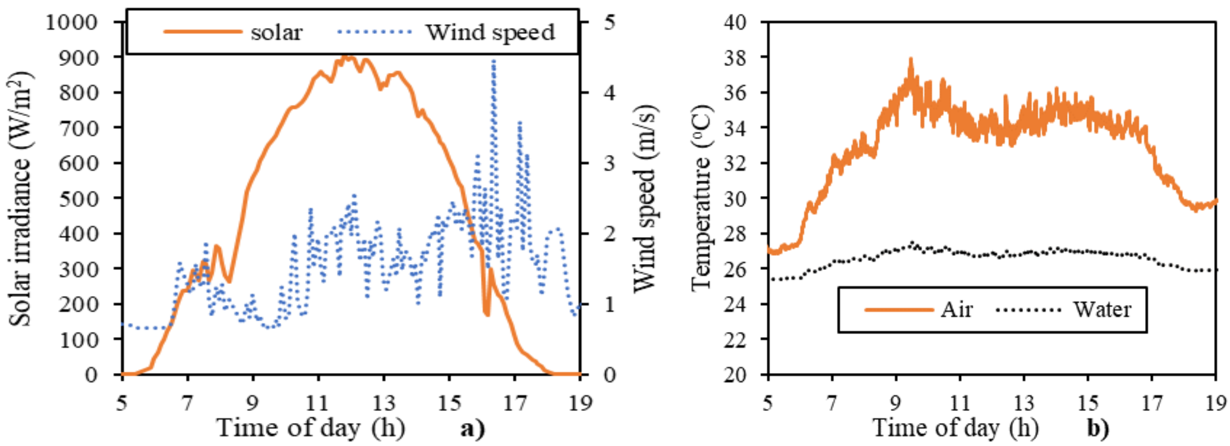

Fig. 6. Weather data on April 26, 2022. a) Solar irradiance and wind speed; b) Temperature of air and water.

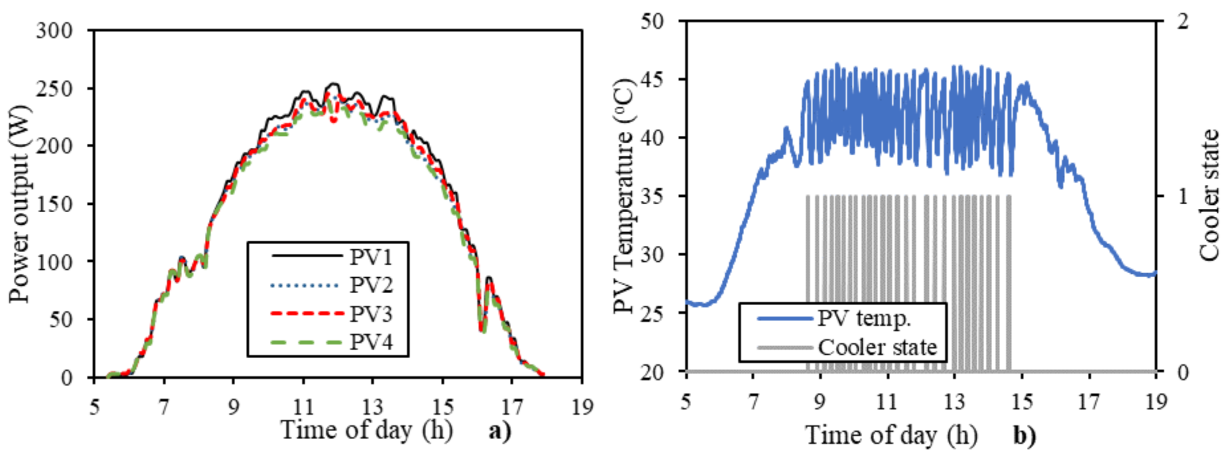

Fig. 7. Power output of PV modules (a); PV1 module average temperature and cooler state (b).

4.2. Efficiency improvement

Experimentally conduct research on coolers in actual operating conditions with the controller is installed to work when the average PV modules temperature reaches 45 ^{o}C, and stops when the PV module temperature reaches 44 ^{o}C. The obtained results are summarized in Table 4. In which, a PV1 module is used by the water spray cooler, the remaining modules (PV2, PV3, PV4) are not used. The obtained results have been shown that the average improvement efficiency of a PV module using a water spray cooler (PV1) compared to three reference photovoltaic modules (PV2, PV3, PV4) is 3.83%, 2.64%, and 6.18%, for an average of 4.22%. The difference in the above results can be explained by the difference in the initial efficiency of PV modules, as shown in the previous section. These results are equivalent to those obtained at (da Silva *et al.* 2021), however it is still lower than that of both surface cooling experiments (Nižetić *et al.* 2016) or keep lower PV module temperature (Mohanraj *et al.* 2019).

For a more detailed analysis of the efficiency of the water spray cooler, a typical day is selected for analysis. The weather data on April 26, 2022 is presented in Figure 6. The solar irradiance is evenly distributed throughout the day, with some clouds throughout the day. The wind speed is stronger after noon, which makes the air temperature decrease after noon compared to morning. The cooling water temperature is kept quite stable at 26-27 ^{o}C at the time of working.

The power output of PV modules, it is clear that the PV1 module is cooled for higher power output than the three reference PV modules at the time the cooler operates is shown in Figure 7. The average temperature of the PV1 module is kept at 45 ^{o}C, after the cooling period, the temperature of PV modules tends to drop below 40 ^{o}C, starting cooler time from 8am to about 3 PM daily.

4.3. Model verification with experiment

The thermal electrical model of PV modules is built on Matlab-simulink software with the inputs measured data including solar irradiance, air temperature, and wind speed. The simulation of PV modules is conducted to verify simulation and experimental results. The measured and simulated results of the PV modules power output during the day without coolers (April 24, 2022) and day with coolers (April 26, 2022) shown in Figure 8. In general, the model is following the experiment with reasonable accuracy, the power output varies throughout the day with overlapping peak values. The NRMSE between simulated and measured results of PV module power output on a sunny day without cooling and with water spray cooler reaches 8.5% and 6.5%, respectively.

The results of measurement and simulation of the PV1 module temperature during the day without cooler and with cooler is shown in Figure 9. The NRMSE reaches 6.5% and 7.5% respectively. Obviously, the PV module temperature of the simulated method is checked to be close the measurement.

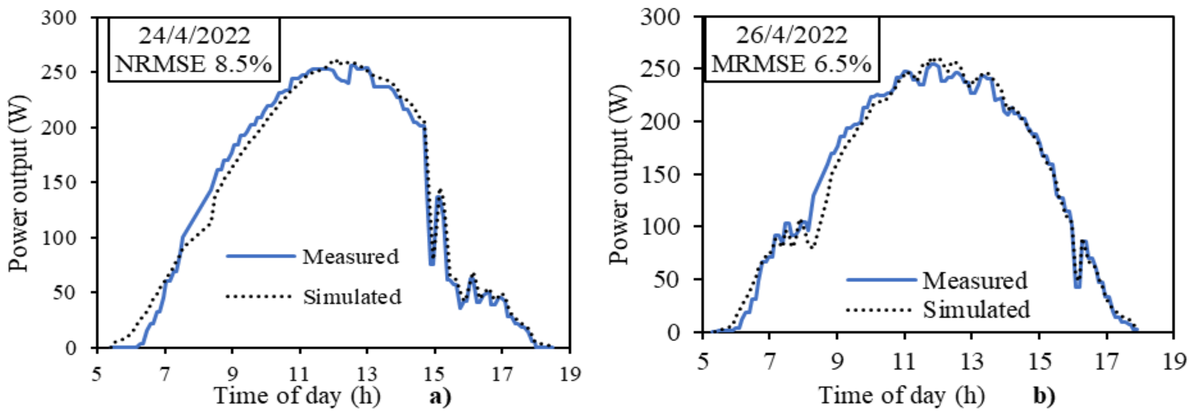

Fig. 8. Results of measurement and simulation of power output during the day without cooler (a) and with cooler (b).

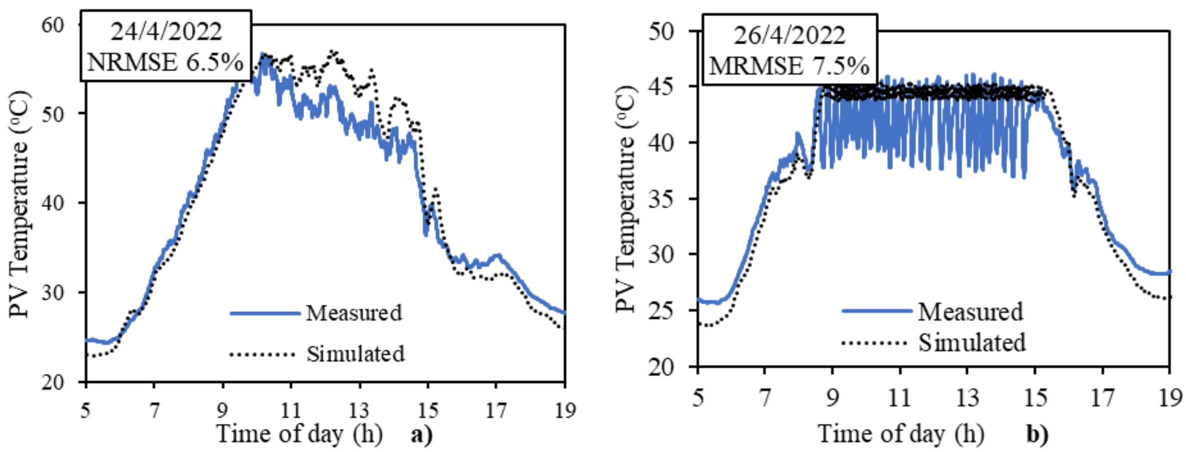

Fig. 9. Results of measurement and simulation of PV1 module temperature during the day without cooler (a) and with cooler (b).

5. Conclusion

In this paper, experiments have been successfully conducted to verify the efficiency of PV modules using the water spray cooler and constructed its simple thermal–electrical model. The study has used four PV modules with an average yield deviation being less than 1% under the conditions of sunny days, including one PV module with a water spray cooler and three reference PV modules. The obtained results have been shown that the average improvement efficiency of a PV module using a water spray cooler compared to three reference photovoltaic modules is 3.83%, 2.64%, and 6.18%, for an average of 4.22%.

The NRMSE between simulated and measured results of PV module power output on a sunny day without cooling and with water spray cooler has reached 8.5% and 6.5%, respectively. These results have demonstrated the reasonableness of the simple thermal–electrical model of the PV module with water spray cooler. These results have also provided important data for future experimental models. In addition, it is necessary to study real models with different cooling modes in many regions and other conditions to better understand the enhanced efficiency of PV modules using the proposed system.

Notations

A_{PV}	Surface area of PV modules, m^2
Cp	Specific heat, kJ/kg.K
C_{PV}	Equivalent thermal capacitance of PV module, J/K
G	Total solar irradiance shining on the surface area of solar cells of PV modules, W/m^2
G_t	Solar irradiance on PV module surface, W/m^2
h_{conv}	Convection heat transfer coefficient, W/m^2.K
h_w	Average heat transfer coefficient between water spray and PV module surface, W/m^2.K
k_w	Water thermal conductivity, W/m.K
L_{PV}	Characteristic length of PV module, m
MF	Mass flux of water based on the unit area of the target PV module surface, kg/m^2.s
MF_w	Mass flow rate, m^3/s;
Nu_{sp}	Spray Nusselt number
P_{MP}	Electric power output of PV module, W
P_{MP_STC}	Maximum power at standard test conditions, W.
q_{conv}	Convective heat transfer between the PV module surface and the air, W
q_{rad_s}	Radiation heat transfer between the PV module and the sky, W
q_{rad_g}	Radiation heat transfer between the PV module and the ground, W
q_{ref}	Reflected solar irradiance, W
q_{sp}	Convective heat transfer between the PV module and water spray, W
Re_{sp}	Spray Reynolds number
T_{air}	Air temperature, °C
$T_{boiling}$	Evaporating temperature of water, °C
T_{PV}	Temperature of PV module, °C
T_{sky}	Sky temperature, °C
T_w	Water spray temperature, °C
v_{wind}	Wind speed, m/s
x	Thickness, mm
α_P	Thermal coefficient of power, %.°C^{-1}
ε_{rad}	Thermal emissivity of the PV module
ζ	Non-dimensional temperature
μ_w	Water dynamic viscosity, Pa.s
ρ	Density of material, kg/m^3
ρ_w	Water density, kg/m^3
σ	Stephan-Boltzmann constant, W/m^2.K^4
τ_g	Transmissivity of PV module protection glass

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