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Increasing the Power Output of a PV Solar System by Using a Cooling-Reflector Assembly

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Abstract

There are various methods that can be employed to increase the lifespan and power output of photovoltaic (PV) systems. This study aims to increase the power output of a grid-connected PV system by using a water-cooling unit and solar reflectors. The PV modules of the current PV system are divided into two clusters. The first cluster, which is considered an improved cluster, has a solar reflector-cooling unit added to it, while the second cluster is used as a reference. The results show that the maximum efficiency and performance ratio values of the improved and reference PV modules at 10:30 AM are 14.7% & 13.7% and 97.5% & 91.2%, respectively. The maximum electrical power values of the improved and reference PV modules at 12:00 PM are 2.55 W and 1.69 W, respectively. The maximum gain value for electrical power is 43%.

Keywords: performance, efficiency, cooling, solar reflectors, grid-tied

1. Introduction

Renewable energy resources can aid in solving global energy insecurity [1]. Electrical energy requirements are gradually increasing, while fossil fuel resources used in traditional systems for electrical power generation are limited and are predicted to become less and more expensive in the future [2]. Traditional fuels harm the environment by causing acid rain, global warming, ozone layer depletion, air pollution, and ground and surface water pollutants. Global warming is a major issue that harms the environment and threatens mankind as a result of carbon dioxide emissions into the atmosphere. The global amount of CO_2 emissions in 2014 was about 32,381 million tons, whereas the use of solar PV systems decreases the amount of CO_2 emissions by more than 100 gigatons (International Energy Agency 2018) [3]. The concentrated solar photovoltaic (CSP) material decreases approximately 50% to 60% of the total cost of the photovoltaic (PV) module [4]. Solar energy applications are classified into two kinds: solar PV energy and thermal energy. Presently, engineers and scientists are working hard to make clean electricity affordable on a large scale, and have been trying for a long time to develop low-cost, high-efficiency, and easy-to-manufacture solar modules with high productivity [5].

There is more work on the use of solar reflectors in both PV solar and solar thermal energy as well as the use of cooling units with solar reflectors to increase energy output and decrease the temperature of PV modules, but in different ways. More recent work has focused on improving the winter period production of PV modules using solar reflectors [6]. Tabaei et al. [7] found that using aluminum foil reflectors boosts the power output of polycrystalline silicon by 14%. When utilizing aluminum foil reflectors with water film, the maximum power output is 50%. A new way to drive the variable speed input mechanism is an open topic to be investigated. Zubeer et al. [8] designed a water-cooled concentrated PV system to improve the PV solar

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module efficiency. The empirical results showed that the ultimate module temperature of the PV panel, concentrated PV system, and water-cooled concentrated PV system is 57.5, 64.1, and 36.5°C, respectively. In addition, the power output of the water-cooled concentrated PV system and concentrated PV system is improved by 24.4% and 10.65%, respectively. In addition, electrical efficiency is increased from 14.2% to 17% by using reflectors and water-cooling units with the PV panel (water-cooled concentrated PV). Pavlov et al. [9] found that the use of mounted solar reflectors resulted in 35% increases in daily power during clear days at specific times of the year.

Bahaidarah et al. [10] designed a solar system that is cooled by flowing water on the backside of the PV module under the climatic conditions of Al-Dhahran (KSA). The results showed that the PV module's operating temperature dropped by about 20% and its electrical efficiency increased by 9%. Khaled et al. [11] designed a hybrid PV-thermal solar collector system in Duhok city to enhance the PV module efficiency. The cooling method leads to an increase in the electrical efficiency by about 3% as compared with the PV solar collector system. Bahaidarah et al. [12] evaluated the electrical and thermal performance of a PV system's V-trough. The results revealed that the power gain of the PV module when using the cooling technique is about 22.8 % and is 31.5 % when using the cooling units with the V-trough system. According to some studies, the best location in high latitudes is a vertical PV module with horizontal solar reflectors (planar concentrator) [13].

Ahmad et al. [14] developed multi-level fin heat sinks (MLFHS) made of an extruded alumnum material with a novel geometry attached to the back side of the PV module. At solar irradiance and ambient temperature of 941 W/m^2 and 36.17°C, respectively, a significant drop in the PV module temperature of 8.45°C was observed. Under outdoor operating circumstances, the heat sink increased overall power production by up to 9.56%. Solanki and Sangani [15] conducted an experimental investigation in Mumbai, India, in 2007. They discovered that the V-trough system (2-Sun) boosts power output by 44% for passively cooled PV modules [15]. In 2009, planar concentrators of various materials were mounted to the upper and bottom edges of PV solar modules to examine their effectiveness. Experiments are carried out using stainless, aluminum, chrome, and steel solar reflectors to determine the most efficient reflector material capable of producing the greatest power with the least amount of heat. It has been shown that chromium reflectors produce 27.65% more energy than aluminum reflectors and 34.05% more energy than stainless steel reflectors [16].

This research aims to improve the power efficiency of a grid-connected PV system to achieve good economic feasibility. To achieve the goal, the thin film PV module technology and the behavior of the grid-connected PV system are studied, and a PV solar system is designed and equipped with facilities for reducing the excess heat generated by the PV modules. In this study, the cooling method is used to reduce the excess heat and help enhance the efficiency of the PV solar modules. In addition, since the lifetime of the PV modules is inversely related to temperature, PV module deterioration is minimized by cooling.

2. PV Solar System Description

The present PV system is located in Baghdad/Al-Taji town at latitude 33.3°N and longitude 44.4°E, as shown in Fig. 1. As illustrated in Fig. 2, the present PV solar system consists of 30 modules designed in 5 strings with 6 series-connected modules. The data sheet for the PV modules and the information on the PV system are shown in Table 1.

Fig. 1 Present PV solar system

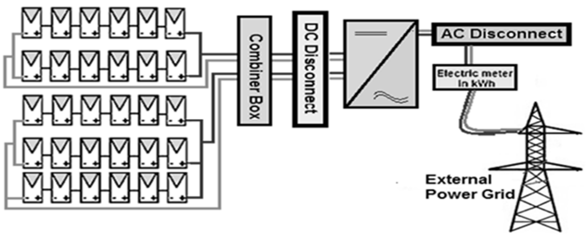

Fig. 2 Block circuit of the present PV solar system

Table 1 PV system information and PV module data sheet

System information	Value	Module data sheet	Value
Inverter model	SMA SB-5000T-21	Module model	TS-165C2 CIGS
Modules number	30	Max power (P max)	165 W
Inverter size	5.30 kWp	Open circuit voltage (Voc)	88.7 V
Inverter efficiency	97%	Short circuit current (I_{sc})	2.66 A
System size	5 kWp	Max power voltage (V_{mpp})	68.5 V
PV modules tilt angle	30°	Max power current (I_{mpp})	2.41 A
Temperature coefficient of P max	-0.30% / °C	Max reverse current (I_R)	6.5 A
Array area	32 m^2	Operating temperature	-40°C to 85°C

3. Solar Reflectors and PV Solar Modules

The present PV system in this work is divided into two clusters. The first cluster comprises 12 PV modules and is classified as an improved cluster, while the second cluster comprises 18 PV modules and is classified as a reference cluster. The improved cluster (PV modules) is then compared to the reference cluster (PV modules) to determine the increment percentage (gain) in PV solar system electrical parameters. The improved cluster receives more solar radiation (from the solar reflectors and the sun) than the reference cluster. As shown in Fig. 3, the solar reflectors are attached in front of the improved cluster, whereas the second cluster (18 PV modules) remains without solar reflectors. In the current PV system, the inverter has two inputs: the reference cluster input contains 18 PV modules (2970 Wp), and the improved cluster input contains 12 PV modules (1980 Wp). The data is obtained via a speedwire that connects an inverter to the computer. As shown in Fig. 4, an inverter shows data in two clusters (A and B). Cluster (A) represents the improved cluster data, whereas cluster (B) represents the reference cluster data. In the current system, an inverter is made up of two inverters that use maximum point tracker (MPPT) technology [17].

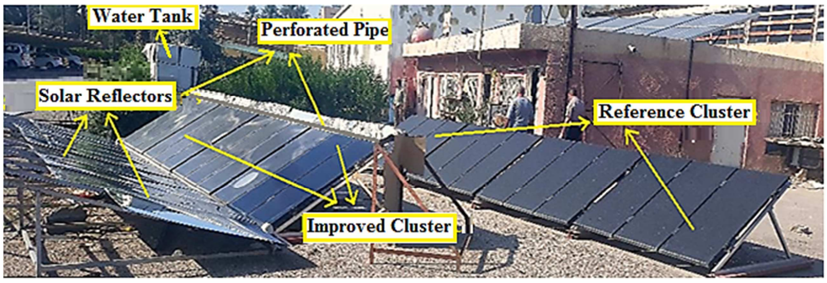

Fig. 3 The improved and reference PV solar module clusters

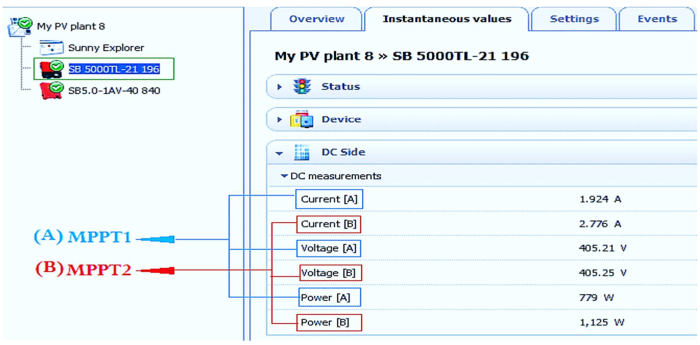

Fig. 4 Screenshot of the inverter data shown on PC

4. Preparation for the study

The present experiment has been carried out in Baghdad/Al-Mansour Company (latitude 33.3°N and longitude 44.4°E). Efficiency, electrical power, and performance ratio (PR) have all been improved, as have solar radiation, PV module temperature, and ambient temperature. Temperatures of reference and improved PV modules (clusters) are recorded.

All electrical parameters of the reference and improved clusters are recorded. The data for each cluster is gathered from an inverter, which shows the PV system data independently in (A and B) format, as previously described. The current research starts from 7:30 AM to 6:00 PM on 14 April 2020, when the weather is clear. The cooling process starts from 10:00 AM to 12:00 PM on the day of work. The tank water temperature, which is 29°C at 10:00 AM, rises to 33°C at 12:00 PM. The temperature of the PV modules causes this rise in tank water temperature, as the water absorbs heat from these PV modules and then returns to the water tank. The cooling process is stopped for two hours to study the temperature gradient of the PV modules to determine how long the cooling process can last. After two hours, the cooling process begins again for one hour.

The cooling unit is shown in Figs. 5 and 6. The cooling unit, like with the solar reflectors, is added to the first cluster (improved cluster). When the water tank tap is opened, water flows toward the PV modules inside the perforated pipe that extends along with the improved cluster (PV modules). Water then drips onto these PV modules, being collected in the gutter and eventually collected in underground water storage. The water pump then pumps water back into the tank, and this cycle continues constantly for the specific time. Water loss during the cooling process is minimal in this experiment.

Although the water tank is enclosed in a cardboard box, it is heated by ambient heat and direct solar radiation. Most of the heat is eliminated by water flowing along the gutter, then to storage, and finally to the water tank, as shown in Figs. 5 and 6. Figs. 5 and 6 show the schematic setup and the real setup of the cooling-solar reflector assembly, respectively. The solenoid valve device displayed in Fig. 5 is utilized to control water flow when the electricity is cut off. This valve closes the water tap when the electricity is cut off, which is important because when the electricity is cut off, the submersible water pump stops and no longer lifts water to the tank. The electricity has not been cut off in the current research.

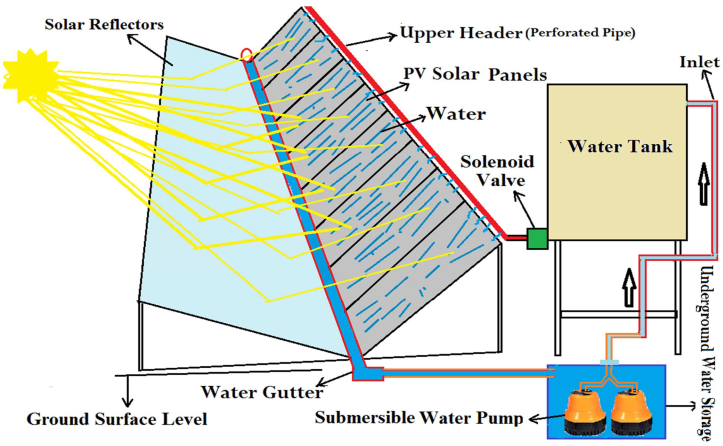

Fig. 5 Schematic setup of the cooling-solar reflector assembly

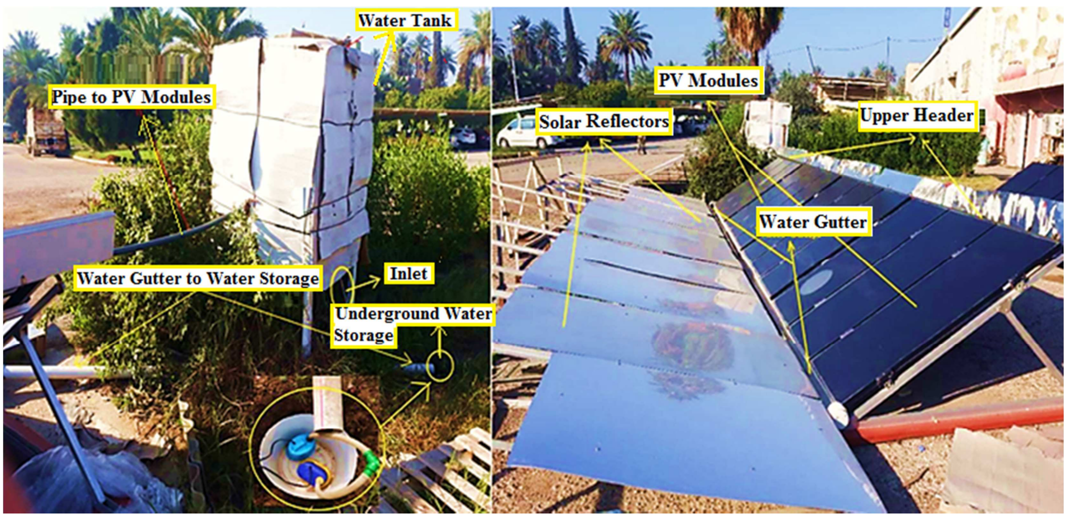

Fig. 6 Real setup of the cooling-solar reflector assembly

The cooling process begins when the tank water tap is opened and water flows through the perforated pipe (upper header). Water falls through the perforations and absorbs the heat from the PV modules. When water falls on the PV modules, it flows down and accumulates in a long gutter that extends along the improved PV modules, and then it flows toward the underground water storage and returns to the water tank via the submersible water pump. When water falls on the PV modules and flows down, it travels 10 meters inside the gutter from the last PV module to the underground water tank. This traveled distance makes the water emit heat, and some water heat is also emitted when it accumulates in the underground water storage, which is buried at a depth of 35 cm below the earth's surface, as illustrated in Figs. 5 and 6.

5. System Performance Evaluation

The reference and improved clusters are evaluated using the previously described performance parameters (PR, efficiency, and power). Power is obtained directly from an inverter via speedwire, while the efficiency, PR, and solar irradiance are estimated using a set of equations. A digital thermometer is used to measure the temperature of the PV modules and the ambient air.

5.1. Efficiency

Efficiency is classified into: array, system, and inverter efficiencies. The array efficiency (η_{PV}) is based on the DC power output, while the system efficiency (η_{sys}) is based on the AC energy output [18-19]. The array efficiency is the ratio of the DC energy output to the in-plane solar irradiation multiplied by the area of PV modules (PV array) [20]. The array efficiency is calculated as follows:

$$\eta_{PV} = \frac{E_{DC}}{H_T A_m} \tag{1}$$

The system efficiency is calculated as follows:

$$\eta_{Sys} = \frac{E_{AC}}{H_T A_m} \tag{2}$$

where H_T is the in-plane solar irradiation, A_m is the solar PV array area, and E_{DC} is the DC energy. The inverter efficiency is calculated as follows [21]:

$$\eta_{INV} = \frac{E_{AC}}{E_{DC}} \tag{3}$$

The inverter efficiency ranges from 96% to 97% because it is indoor [22].

5.2. Performance ratio (PR)

PR is a dimensionless quantity that indicates the overall effect of losses (due to inverter inefficiency and cell temperature, losses in wiring and protection diodes, poor module at low irradiance, partial shading, module mismatch, etc.) on the rated power capacity [23]. It is defined as the ratio of AC energy (E_{AC}) delivered to the grid to the energy production of an ideal loss-less PV system with 25°C cell temperature and the same solar irradiation. PR allows comparison of PV systems regardless of azimuth angle, tilt angle, solar radiation resources and their nominal (rated) power capacity, etc. [24-25]. It is given as follows:

$$PR = \frac{Y_F}{Y_R} \tag{4}$$

where Y_F is the final yield estimated in Eq. (5), and Y_R is the reference yield estimated in Eq. (6).

The final yield (Y_F) is the yearly, monthly, or even daily output AC energy of the PV system divided by the rated power of the connected PV system at standard test conditions (1 kW/m^2 and 25°C cell temperature) [26-27]. The intention to compare a similar solar PV power plant in a specific geographic region leads to the formulation of this representative. Y_F is given as follows:

$$Y_F = \frac{E_{AC}}{P_{PV.rated}} (kWh/kW_P) \tag{5}$$

where E_{AC} is the AC energy output in kWh, and $P_{PV.rated}$ is the system rated power. The reference yield (Y_R) is defined as the ratio of total in-plane solar irradiation (kWh/m^2) to the reference irradiance (1 kW/m^2). This parameter represents an equal number of hours at the reference irradiance and is given by [28-29]:

$$Y_R = \frac{H_T}{H_R} (kWh/kW_P) \tag{6}$$

where H_R and H_T are the reference irradiance and the in-plane solar irradiation (S.Ir), respectively. When the Eqs. (5) and (6) are substituted into Eq. (4), Eq. (7) is attained [30].

$$PR = \frac{E_{AC} H_R}{P_{PV,rated} H_T} \tag{7}$$

PR can also be given in Eq. (8), which is used to estimate PR in this study.

$$PR = \frac{\eta_{Actual}}{\eta_{ref}} \tag{8}$$

The actual power (P_{AC}) and rated power (P_{rated}) are estimated by Eqs. (9) and (10) as follows:

$$P_{AC} = H_R \eta_{Actual} A_m \tag{9}$$

$$P_{rated} = H_R \eta_{ref} A_m \tag{10}$$

The actual efficiency (η_{Actua}) is estimated by Eq. (11) as follows:

$$\eta_{Actual} = \eta_{ref} [1 - \beta(T_m - T_{ref})] \tag{11}$$

where η_{ref} is the rated efficiency (15.2%), A_m is the area of reference and improved PV modules (13.04 m^2 each), β is the temperature coefficient that equals -0.3%/°C, T_{ref} is the reference modules' temperature (25°C), and T_m is the actual PV modules' temperature. From Eq. (10), Eq. (12) is attained as follows.

$$H_R = \frac{P_{AC}}{A_m \eta_{Actual}} \tag{12}$$

where P_{AC}, A_m, and η_{Actual} are the actual power, improved cluster area, and actual efficiency, respectively. Eqs. (12) and (8) are used to estimate the solar irradiance (H_R) and actual efficiency (η_{Actual}) respectively. Power increment percentage (PINCP) is given by Eq. (13) as follows:

$$PINCP = (P_{im} - P_{ref}) / P_{ref} \tag{13}$$

where P_{im} and P_{ref} are the power of the improved and reference clusters respectively.

Since the reference cluster contains 18 PV modules and the improved cluster contains 12 PV modules, before all the calculations, the power of the reference cluster is divided by 18 and multiplied by 12 to accomplish an equalization in power (number of PV modules) between the improved and reference clusters, so that each cluster contains 12 PV modules. The cooling-reflector assembly means the water-cooling unit and solar reflectors.

6. Results and Discussion

Fig. 7 shows the performance increment percentage (PR INCP), as well as the PR of the reference and improved PV modules (clusters). The maximum values of PR INCP (PR gain), reference PR, and improved PR at 12:00 PM are 6.3%, 91.2%, and 97.5%, respectively, where the temperatures of reference PV modules (T_{ref}), improved PV modules (T_{imp}), and ambient air are 32°C, 55°C, and 30°C, respectively. When the cooling process is stopped, the PR of the improved PV modules decreases gradually until it equals the PR of the reference PV modules after 25-33 seconds. This is because when the cooling process stops, the temperature of the improved PV modules increases due to the solar reflectors. This means that solar reflectors reduce the PR by raising the temperature of the PV solar modules while increasing the power output of the PV modules. PR is an important parameter because it reveals all of the impacts of losses on the grid-connected PV system. The PR of a PV system indicates how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation, and their nominal rated power capacity. Fig. 7 shows that the PR increases and decreases when the temperature of the PV modules decreases (during the cooling process) and increases (when the cooling process stops).

Fig. 8 shows the efficiency increment percentage (η INCP), as well as the efficiency of the reference and improved PV modules (clusters). The maximum value of efficiency INCP (the gain) at 10:30 PM is 1%, where the reference and improved PV modules efficiencies are 13.7% and 14.7%, respectively. The temperatures of the reference PV modules (T_{ref}), improved PV modules (T_{imp}), and ambient temperature are 55°C, 32°C, and 30°C, respectively. The maximum efficiency values synchronize with the lowest ambient temperature, namely at the beginning of sunrise and sunset as displayed in Fig. 8, where the efficiencies of the reference and improved PV modules are 14.7% and 14.8%, respectively. The efficiency increases with cooling and decreases when using solar reflectors without cooling because they increase the temperatures of the PV modules, while the efficiency increases when using cooling with solar reflectors, as shown in Fig. 8.

Fig. 9 illustrates the power output of the improved and reference clusters. In this figure, the PINCP bars and the power curve of the improved PV modules have crests and bottoms. The cooling process causes the crests, whereas stopping the cooling process causes the bottoms. The maximum power values of the reference and improved PV modules at 12:00 PM are 1.69 kW and 2.55 kW, respectively, as shown in Fig. 9. The maximum PINCP (power gain) at 12:00 PM is 51.3%. The daily average of PINCP is 32%. This gain is large and has a significant influence on the economic feasibility of installing a PV solar system. Each technique (cooling and solar reflectors) has an impact on a different aspect. The cooling technique increases the voltage by increasing the energy band gap of the semiconductor, reducing the potential barrier resistance. While the solar reflector technique increases the current by increasing electrons, the two techniques together enhance the electrical power of the PV solar system.

Fig. 10 illustrates the solar irradiance increase percentage (S.Ir INCP), as well as the reference and improved PV modules' solar irradiance (S.Ir). The maximum values of S.Ir INCP and the reference and improved PV modules (S.Ir) at 12:00 PM are 43%, 938.7 W/m^2, and 1338.7W/m^2, respectively. The minimum values at 6:00 PM are 3%, 88.6W/m^2, and 88.7W/m^2, respectively. The INCP value (43%) corresponds to 403.6 W/m^2. The daily average of S.Ir INCP is 28%, which corresponds to 272W/m^2. During the time period from 4:00 PM to 6:00 PM and from 7:30 AM to 8:00 AM, the solar irradiance values of the reference and improved PV modules converge, because the solar radiation reflected from the solar reflectors to the PV modules is deflected away from them. In contrast, during midday, when there is no deflection of solar radiation, it is directly reflected on the PV modules. As a result, the improved cluster gets more solar radiation than the reference cluster, resulting in a divergence in S.Ir values between the two clusters.

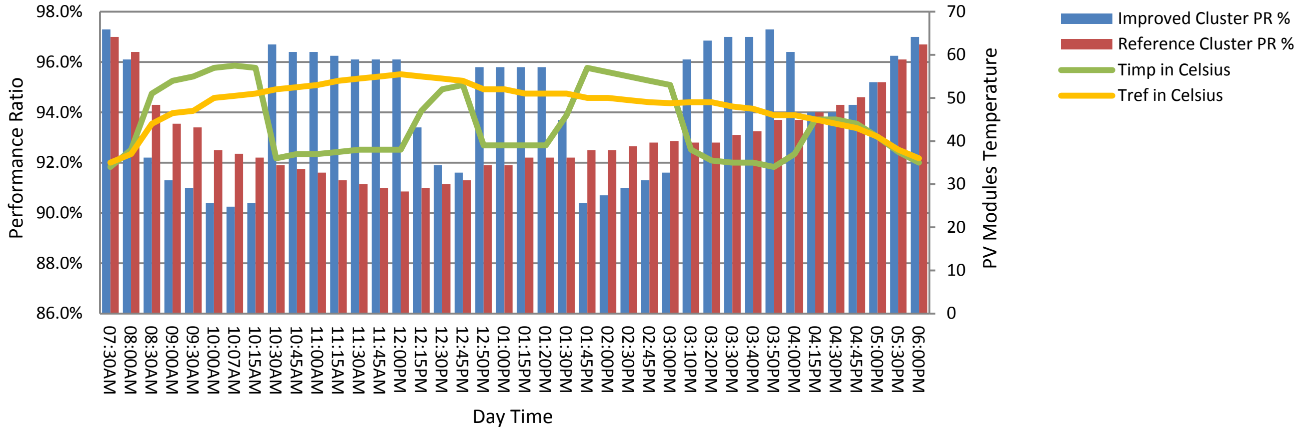

Fig. 7 PR INCP vs PR of the improved and reference clusters

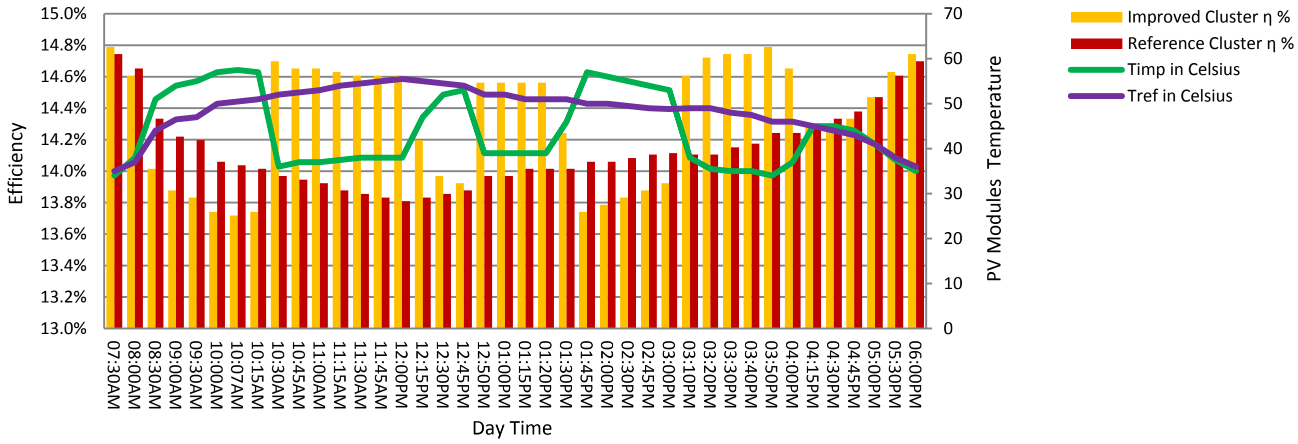

Fig. 8 η INCP vs the efficiency of improved and reference clusters (PV modules)

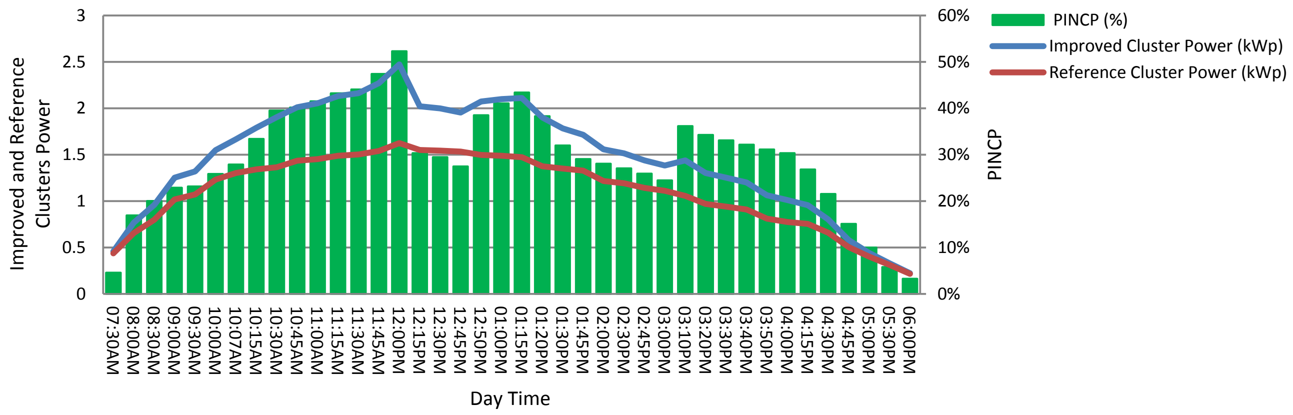

Fig. 9 PINCP vs the power of improved and reference clusters

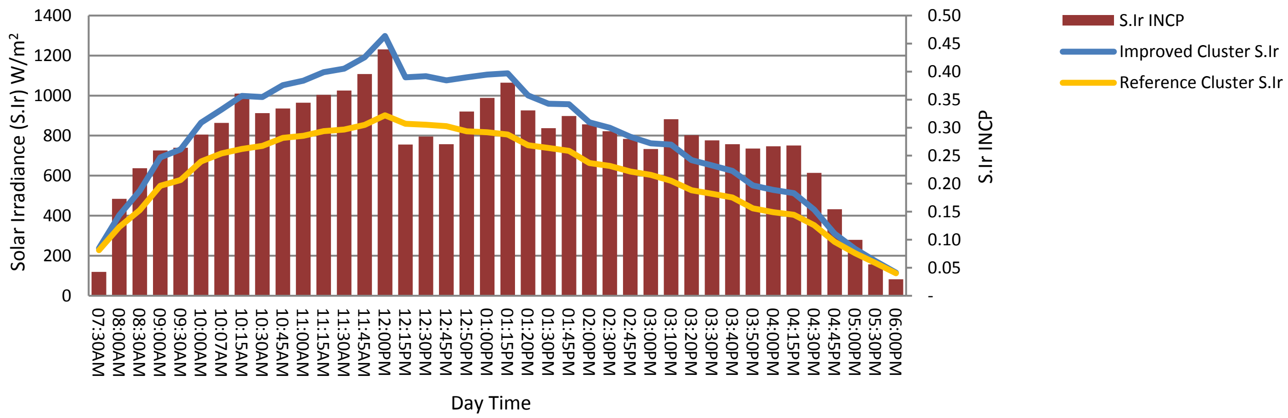

Fig. 10 S.Ir INCP vs the S.Ir of reference and improved clusters

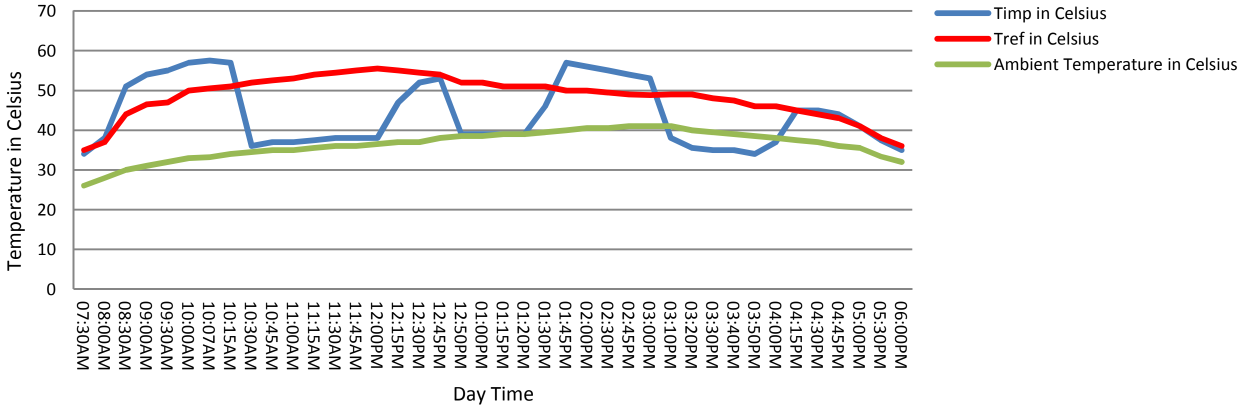

Fig. 11 Ambient temperature, T_{ref}, and T_{imp}

Fig. 11 displays the temperature of the reference PV modules (T_{ref}), the temperature of the improved PV modules (T_{imp}), and ambient temperature. The maximum values of T_{ref} and T_{imp} are recorded at 12:00 PM at 55°C and 32°C, respectively, at an ambient temperature of 30°C. The minimum values are recorded at 6:00 PM at 32°C and 31°C respectively, at the ambient temperature of 26°C. The temperature of improved PV modules drops by 23°C due to cooling. This indicates that, despite the use of solar reflectors, which increases heat, the cooling technique is very effective in removing heat from the PV modules. The cooling unit increases voltage by decreasing resistance. The maximum ambient temperature occurs at 3:00 PM, whereas the maximum PV module temperature occurs at 12:00 PM.

The T_{imp} curve has a top and a bottom. When the cooling process stops, the top appears, and when the cooling process begins, the bottom appears. The temperature of the PV modules drops rapidly at the beginning of the cooling process and slowly rises when the cooling process stops until it stabilizes at the final temperature, as shown in Fig. 11.

7. Conclusions

Because of the use of cooling-solar reflectors, significant gains in performance parameters (efficiency, PR, and power) and solar radiation are made. The power gained (PINCP) is estimated at 32% as a daily average. PR and efficiency are enhanced by 6% and 1%, respectively. As a daily average, the achieved solar irradiance (S.Ir INCP) is estimated to be 31%. The maximum power output gain value is 51%. The cooling technique has a considerable impact on reducing heat generated by PV modules. The water used for cooling has a considerable impact on the cleaning of PV modules. The cooling unit reduces the temperature of the PV modules by 23°C, permitting solar reflectors to be added to the upper and bottom edges of the PV solar modules to increase power output even more. When utilizing solar reflectors without cooling, PR and efficiency decrease because they raise the temperature of the PV modules. Based on the results of this study, it is recommended that researchers improve the performance of PV solar modules by cooling the back side of the PV modules and adding solar reflectors to the upper and bottom edges of the PV modules to increase power output even more.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this study.

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