OPTIMIZED CLEANING AND COOLING FOR PHOTOVOLTAIC MODULES BASED ON THE OUTPUT PERFORMANCE

by

Layth MOHSIN[a]***, Ahmad SAKHRIEH***[a,b]*** *, Ahmad ABOUSHI***[c]***, Amer HAMDAN***[c]***,***
Eman ABDELHAFEZ[c]***, and Mohammed HAMDAN***[a]

[a] Mechanical Engineering Department, The University of Jordan, Amman, Jordan
[b] Department of Mechanical and Industrial Engineering,
American University of Ras Al Khaimah, Ras Al Khaimah, United Arab Emirates
[c] Mechanical Engineering Department, Al-Zaytoonah Private Universuity of Jordan,
Amman, Jordan

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This study aimed to design and implement a smart automatic cleaning and cooling system for photovoltaic modules to be activated based on power drop resulting from dust accumulation and high temperature conditions. This was tested by installing two side by side identical photovoltaic modules. The first module was equipped with the prototype cleaning system while the second one was considered as standard. An optimized cleaning and cooling procedure was adopted using data acquisition system. The operational performance of both panels was recorded and analyzed. An increase in energy yield of 8.7% was obtained as a result of minimizing the operational disturbances of dust accumulation and high surface temperature of the photovoltaic panel.

Key words: *smart cleaning and cooling, dust effect, temperature effect, photovoltaic*

Introduction

Middle Eastern countries have dusty climates in addition to the high temperature conditions especially in summer. Both of these disturbances affect the performance of photovoltaic (PV) power devices and reduce the desired energy yields. Thus, cleaning and cooling processes seem to be crucial in this regards. The high water consumption needed for the cleaning process of PV panels, in addition to the possible negative effect of unintentionally wrong cleaning and cooling procedures call for more suitable solutions, especially in the presence of scarce water resources. In light of this, an optimized cleaning and cooling procedure was adopted in this work based on the source of power loss. This was achieved by using a data acquisition system incorporated with high pressurized nozzles and wipers.

Reducing energy losses and increasing the amount of electricity generated per Watt peak [W_p] of installed PV capacity is very important. The PV cleaning and cooling is one of the methods that can be used to achieve this goal. The PV cleaning and/or cooling were studied and assessed by several researches. In this context, many studies have been delivered in last few years. A number of researchers have worked on cooling the PV panels with different approaches. These approaches include passive and active cooling techniques. Air and water

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* Corresponding author, e-mail: ahmad.sakhrieh@aurak.ac.ae

were used as cooling fluids. In the case of using air as cooling fluid fins are usually used to enhance convection heat transfer by extending the heat transfer area. Mazon *et al.* [1] focused on the use of air as a cooling fluid to cool down PV panels placed onto the roof of a greenhouse. In their work they obtained a low operating temperature which corrected and reversed the effects produced by high temperature on efficiency.

As a good cooling media, water has been widely used for PV cooling in various forms. Bahaidarah *et al.* [2] used PV back surface water cooling for hot climatic conditions. In their work, the effect of cooling the module by incorporating a heat exchanger (cooling panel) at its rear surface is investigated numerically and experimentally. Using active back water cooling, the module temperature dropped significantly to about 20% leading to an increase in the PV panel efficiency by 9%. Drews *et al.* [3] studied the long-term performance modeling of a proposed solar-water pumping system. Cooling of the PV panel is achieved by introducing water trickling configuration on the upper surface of the panel. They showed that due to the heat loss by convection between water and the PV panel's upper surface, an increase of about 15% in system output is achieved at peak radiation conditions.

Nousia *et al.* [4] presented test results on hybrid solar systems, consisting of PV modules and thermal collectors (hybrid PV/T systems). By proper circulation of a fluid with low inlet temperature, heat is extracted from the PV modules keeping the electrical efficiency at satisfactory values. Royne and Dey [5] proposed a cooling device based on jet impingement for cooling of densely packed PV cells under high concentration. The device consists of an array of jets where the cooling fluid is drained around the sides in the direction normal to the surface.

The dust accumulation on the PV panel surface depends on different parameters like PV panel inclination, kind of installation (stand alone or on tracker), humidity, *etc.* Many researchers studied the performance of panel with dust concentration on the surface. Kimber *et al.* [6] studied the dust effect on large grid connected PV system in state of California, USA, and the ability of recovering part of these losses using distributed power electronics. They showed that the maximum system loss was 6.2%. Moreover, they found that 40% of these losses can be recovered by installing DC to DC converter per string.

The PV module cleaning methods include wet and dry cleaning techniques. In wet cleaning, modules are sprayed with water. Compressed air, brush or rotating brush are used for dry cleaning. For instance, Tejwani and Solanki [7] implemented an automated cleaning system using 360° Sun tracking system for solar PV modules. A mechanism consists of a sliding brushes was developed and the solar panels make a rotation of 360° in a day, which results in sliding of cleaning brushes twice over the panel modules. They found that the system provides 30% more energy output as compared to static PV modules and 15% more energy output as compared to PV module with single axis tracking.

Verma *et al.* [8] carried out the effect of the new hybrid self-cleaning coating for PV modules and the losses caused by accumulated dust at outdoor exposure in Spain and Japan. They found that the dust losses in Spain are greater for the modules without self-cleaning coating. The transmittance losses reached values near the 15%. This value decreases to 13% in modules with self-cleaning coating. Moreover, they showed that in Japan, the power losses of the PV module with coating were 7% less than that without coating after a year exposure.

Combined effect of cooling and cleaning is also presented by several researchers. Elnozahy *et al.* [9] studied the performance of a PV module integrated with standalone building in hot arid areas. The module performance is enhanced by surface cooling and cleaning. They found a decrease of about 45.5% and 39% in the module temperature at front and rear faces, respectively. Consequently, the cooled and cleaned surface module has an efficiency of 11.7% against 9% for the module without cooling and cleaning. Moreover, the maximum output power produced by cooled and cleaned module is 89.4 W against 68.4 W for non-cooled and non-cleaned module.

The performance of PV module is affected by environmental factors including dust accumulation, wind speed and direction. The performance of the PV module is also affected by the geographical location. Several studied were performed recently under outdoor climate conditions in Pakistan [10, 11]. The effect of dust deposition on the performance of PV modules in Taxila, Pakistan was also studied recently [12]. Authors noticed a significant degradation under the effect of dust deposition.

In this work, an optimized, fully controlled cleaning and cooling mechanism was adopted. A system, that will be put into operation when the efficiency of the PV panels drops beyond a threshold value, was designed, installed and then used to improve the performance of a PV panel. Two identical PV panels were installed side by side to study the effect of cooling and cleaning under the same outdoor weather conditions. The electrical characteristics of both PV panels were collected and analyzed for four weeks. The working performance was monitored, analyzed, and illustrated. This research is unique in defining an optimized cleaning and cooling technique based on the power output of the system.

Experimental set-up

In this research, an experimental set-up consisting of two identical PV modules has been developed to study the effect of the suggested cooling and cleaning system is shown in fig. 1. A schematic diagram of the complete set-up is shown in fig. 2.

The experimental set-up consists of the main parts as follows: multi-crystalline PV modules, micro inverters with accessories, weather station, data acquisition system, three wipes of length 0.55 meter each, and water supply system.

Two PV modules each with maximum power of (250 W_P) were used in this study. These modules are integrated with three bypass diodes to protect solar cells from damage caused by shadow effects. The electrical characteristics of the PV modules used in this study are given in tab. 1.

Figure 1. Photograph of PV system and weather station

Two ABB micro-inverters were used to convert the direct current to alternating current. These micro-inverters can be plugged directly to a socket outlet and could harmonize the electrical power generated by the PV system with that of the grid. The AC trunk bus is a 4 mm² cross-section cable homologated for outdoor applications with pre-installed connectors for micro-inverters. The AC accessories complete the range, making it possible to create extension cables, terminations and connections to other cables.

The VSN800 weather station used to automatically monitors site meteorological conditions and PV panel temperature in real-time. It has three types of sensors; photoelectric pyranometer was used to measure the global incident solar irradiance on the PV

Table 1. Electrical characteristics of the PV modules

Company	Philadelphia Solar
Model	PS-P60
Maximum power, P_{max}	250 W
Short circuit current, I_{sc}	8.92 A
Open circuit voltage, V_{oc}	37.66 V
Rated voltage at maximum power, V_{mpp}	29.94 V
Rated current at maximum power, I_{mpp}	8.35 A
Spectrum	AM 1.5
Air temperature	25 °C
Max. solar insolation (irradiance)	1000 W/m^2

panel; weather temperature sensor was used to measure the ambient temperature; and resistance temperature detector sensor was attached to the back rear of PV panel to measure the surface temperature of PV panel.

The data acquisition was used for monitoring and controlling process can take up to 50 kilo sample per second [kSs^{-1}] of measurement readings. It is used to collect the sensor measurements of the meteorological station, to measure the AC current, to measure the AC voltage and to control the operation of water pump and wipers motor

Two AC current transducers type (Chauvin Arnoux) were also used to measure the AC current. The current clamp measures the current through wire and transfers it to an equivalent value in millivolts. To supply the wipers movements for cleaning processes a 90 W AC motor was used. The water supply system consists of: 0.5 hp water pump, 1 m^3 supply tank and a fiber water tank to recycle the water used for the cleaning and/or cooling processes back to the supply water tank. Filters are used to stop dirts. The amount of consumed water is 3.39 L per day. The water is compensated from the 1 m^3 tank. To limit the wiper movement to be not exceeded the upper and lower limits two solid micro switches were installed. The accuracies of the used instruments are listed in tab. 2.

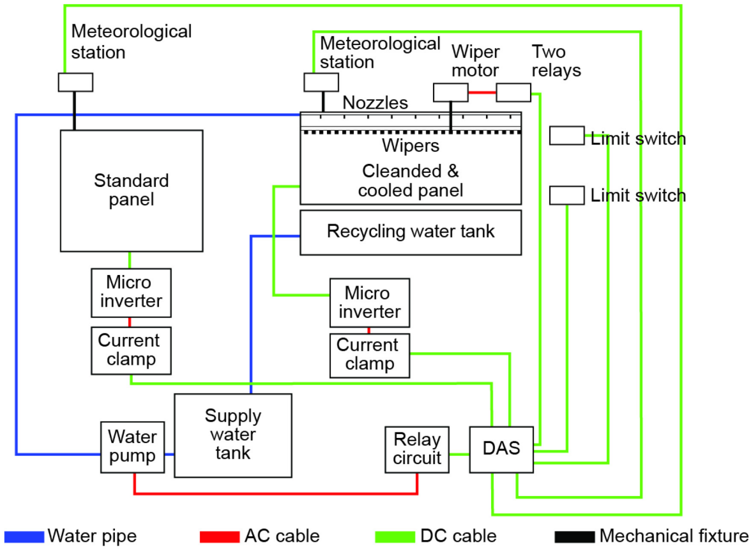

Figure 2. Schematic diagram of the system (*for color image see journal web site*)

Procedure

Two PV modules were installed and mounted facing south with an inclination angle of 26 degrees. The main goal of this work is to measure and compare the electrical characteristics of cooled and cleaned panel with the reference panel. It is aimed to estimate the power gain resulting from optimized cleaning and cooling procedure. The current and power readings were taken each 200 milliseconds and the average values of theses readings were recorded each one minute to be analyzed. The weather conditions, in addition to surface temperature of each panel, were collected and fed into data acquisition system (DAS).

Table 2. Instruments used and their accuracies

Weather station	Accuracy
Pyranometer sensors	±5%
Ambient air temperature sensor	±0.3 °C
PV panel temperature sensor	±0.3 °C
Anemometer	5%
AC current transducers type	2%
Data acquisition system (NI cRIO-907x)	±0.13%

In this study, the cooling procedure will be started when the panel temperature reaches 30 ºC. The power loss resulting from rising the panel surface temperate by 5 ºC above standard test conditions (STC) is estimated to be 2.6% as stated in the PV panel datasheet.

The DAS will handle the values of panel temperatures by a temperature sensor attached to the back rear of PV panel. As the temperature reached 30 ºC, DAS will activate the water pump (0.5 hp) through its switch. The water will flow from water tank into nozzles. The nozzles will spread the water droplets into PV panel front surface. After 20 seconds of continuous cooling procedure, the DAS will turn off the water pump switch. Maximizing the covered water area of PV panel was achieved using 10 nozzles separated by short distance (10 centimeters) and elevated above the front edge of the prototype structure by a suitable distance (20 centimeters). The 0.5 hp water pump can supply up to multiple of PV string.

Zorrilla-Casanova *et al.* [13] stated that dust not only reduces the radiation on the solar cell, but also changes the dependence on the angle of incidence (AOI) of such radiation. In addition, the irradiance losses are not constant throughout the day and are strongly dependent on the sunlight incident angle and the ratio between diffuse and direct radiation. Knisely *et al.* [14] studied the relationship between AOI and short circuit current. The obtained results are shown in fig. 3.

The first three points in fig. 3 showed slightly reduction in I_{sc}. The fourth point clarifies fast drop in I_{sc} as a result of increasing AOI to 18°.

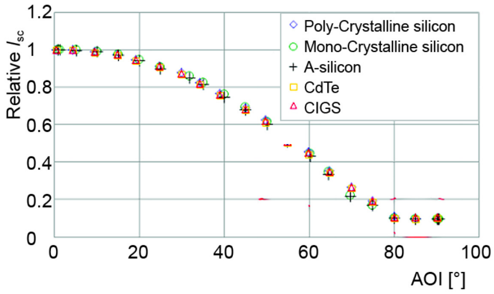

Figure 3. Relative short circuit current *vs.* AOI for five modules (data logger method) [14]

Referring to point four in fig. 3, the optimum point of I_{sc} reduction due to AOI effect has been estimated to be 3.7%. Based on fig. 3. Cleaning process is directly related to the short circuit current which is affected by the AOI due to dust accumulation.

The thickness of dust accumulated on the PV module was not measured in this work. The presented study handles dust and temperature effect on AC side electrical characteristics. The method used based on measuring the actual generated AC current of PV module and compare it with the ideal one calculated using the mathematical eq. (1).

$$I_{\mathrm{AC,\,ideal}} = \frac{E_{\mathrm{G}} A \eta_{\mathrm{panel}} \eta_{\mathrm{inverter}} (1 - P_{\mathrm{L}})}{V_{\mathrm{out}} \cos\theta} \tag{1}$$

where E_G is the measured global irradiance in plane, A – the panel area (= 1.63845 m^2), η_{panel} – the panel efficiency (= 15.3%), $\eta_{inverter}$ – the inverter (= 90% to 96%), P_L – the loss in cables (= 4%), V_{out} – output AC voltage (= 230 V), cosθ – the phase shift between voltage and current (power factor) to be determined by DAS.

When the actual AC current is reduced by 3.7%, compared with the ideal one, the cleaning process will be activated. The cleaning procedure is achieved by activation a water pump for 15 seconds and a wiper motor to clean the front surface of PV panel.

The temperature variation for both panels in addition to the current and power generation have been collected for four weeks, 12 hours a day, and one reading each one minute. The energy yield of both panels was measured. The electricity consumption of the whole automatic cleaning and cooling system was estimated in addition to water consumption. The performance ratios (ratio between actual and target yields) of both panels were calculated. Finally, a feasibility study was conducted based on actual cost in order to show the potential applicability of the system.

Discussion of results

In general, the findings indicated that an increase in the performance ratio by 8% was achieved as a result of implementing the optimized cleaning and cooling procedure. The major finding of the investigation was that the energy yield was increased by 8.7%.

Figure 4 shows average daily temperature variation of both panels. An estimation of average daily temperature variations for both panels indicated how the voltage at maximum power of standard panel is affected due to high temperature impact. The goal of cooling the panel is to maintain the voltage at maximum power within certain limits. The electrical power which was transferred between the generation point and the load side was increased as a result of imitating the voltage at maximum power within certain limits. The maximum power point tracker utilized slight voltage variations to get the maximum power point within a certain oscillation algorithm due to the cooling process.

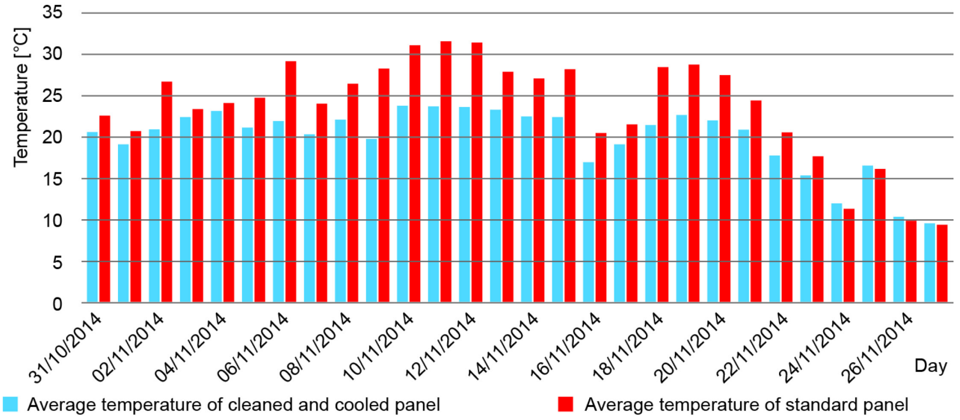

Figure 4. Average daily temperature variation of both panels

The absorption of solar radiation through panels was increased due to periodic cooling process. When the temperature of a PV panel did not exceed 30 °C, the AC current was increased. The net shifting of DC electrical characteristics was conducted on current at AC side as shown in fig. 5.

The main advantage of taking PV panel performance at AC side was that the inverter efficiency increases as voltage at maximum power increased. Moreover, the inverter efficiency is strongly dependent on AC current generation.

The relation between average panel temperature and average daily temperature is shown in fig. 6. The average temperature of the standard panel is higher than that of the cooled and cleaned panel.

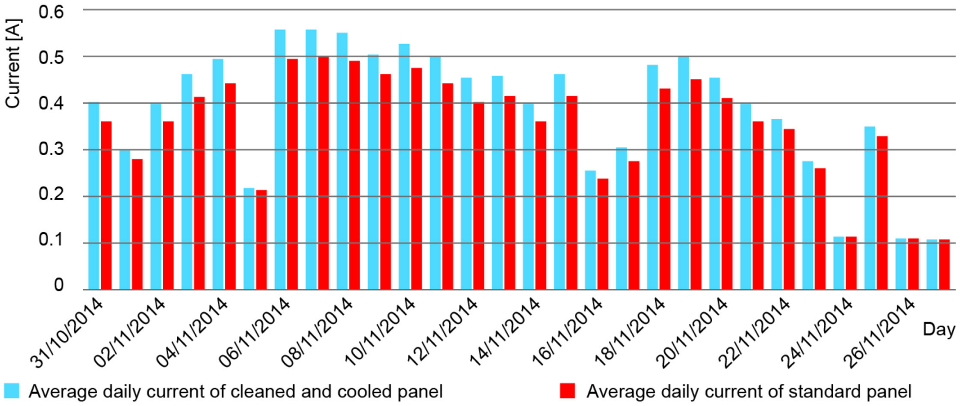

Figure 5. Average daily current of both panels

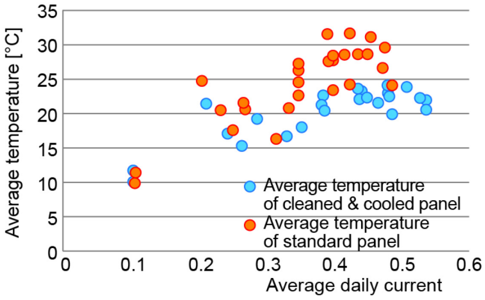

Figure 6. Average daily temperature *vs.* average daily current

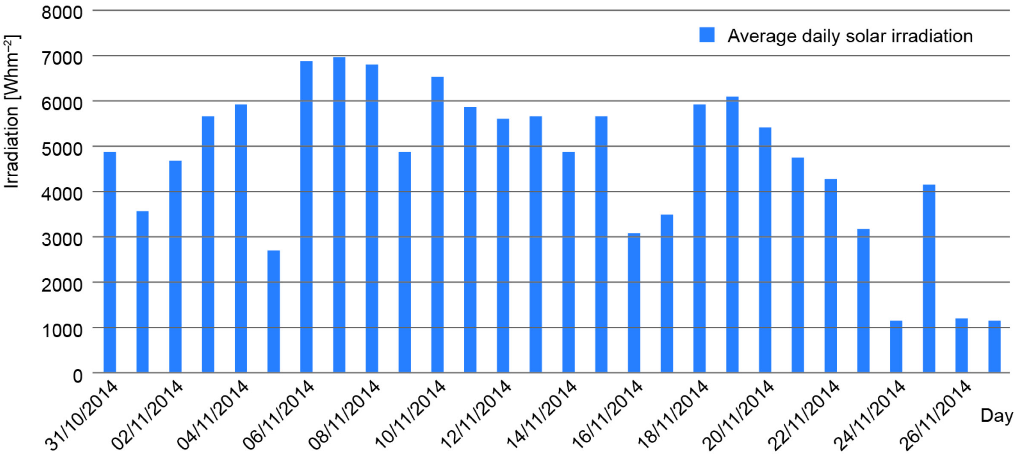

Figure 7. Average daily solar irradiation

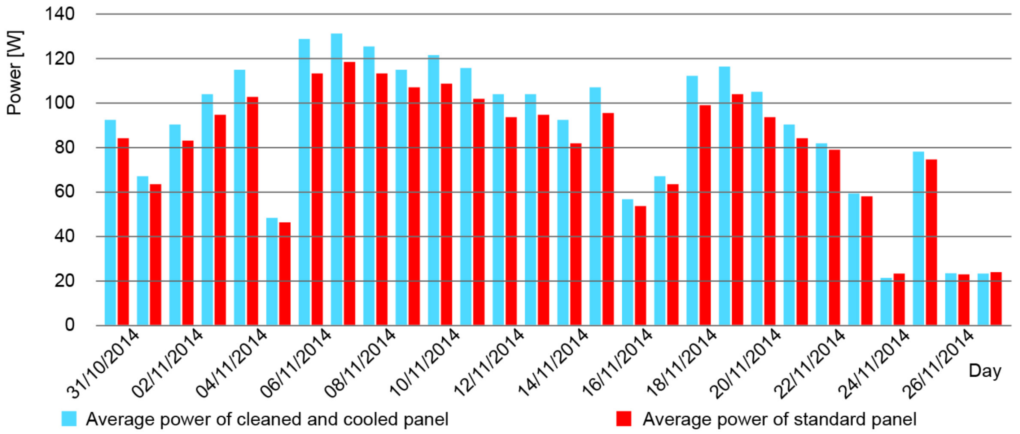

Figure 8. Average daily power generation of both panels

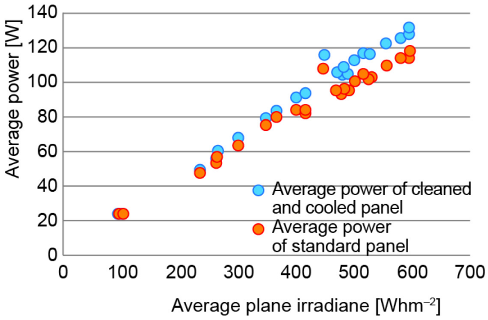

Figure 9. Average power *vs.* average irradiance

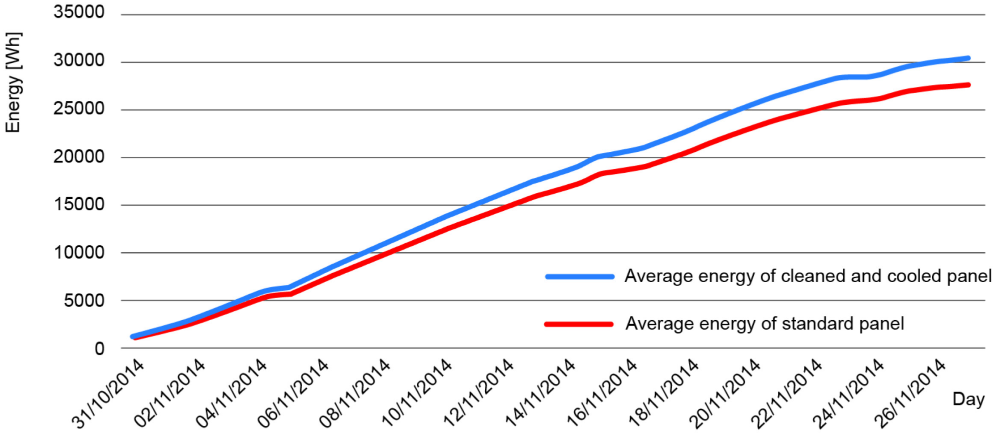

Figure 10. Accumulative energy yield of each panel

Maximizing the supplied DC power generated by PV panel has significant impact on power electronics efficiency, increases the energy yield. The average daily solar irradiation and power generation of both panels were illustrated in figs. 7 and 8, respectively.

Table 3. Energy generation and performance ratios of both panels

Total solar radiation, [kWhm^{-2}]	131.5423
Total energy yield of cleaned and cooled panel, [kWh]	30.0428
Total energy yield of standard panel, [kWh]	27.42374
Energy difference, [kWh]	2.61854
Energy difference ratio	8.716%
Performance ratio of cleaned and cooled panel	91.11%
Performance ratio of standard panel	83.16%
Performance ratio difference	7.95%

Table 4. Assumptions of simple financial model

System size for study, [kW$_p$]	160
Number of PV panels	640
Number of panels a single pump can support	20
Project lifetime, [years]	20
Electricity tariff, [JODkW^{-1}h^{-1}]	0.259
Cost of one m^3 of water, [JOD]	1
Pump cost for 40 panels, [JOD]	35.00
Pipes cost for single panel, [JOD]	10.00
Modified structure cost per panels, [JOD]	25.00
DAS cost for the whole system, [JOD]	10,000.00
Discount rate	10%

The power difference is a result four main parameters. The first one is represented by increasing the supplied DC voltage through cooling. The second parameter is specified by the voltage mismatch resulting from indirect deterioration of DC voltage supplied to maximum power point tracking (MPPT). Reducing voltage mismatch between generation point and load sides was achieved by maintaining surface panel temperature below 30 °C. The third parameter is represented by increasing the absorption of photons utilizing cleaning procedure. This boosted the current generation and directly increased the power generation by improving the efficiency of inverter. The inverter efficiency was considered as the last parameter which affects the power generation and ultimately energy yield. The relation between the average power and the average irradiance is linear. Figure 9 shows clearly that the average power of the cooled and cleaned panel is higher than that of the standard panel at the same irradiance. The cumulative energy yield of each panel is shown in fig. 10.

Economic analysis

A simple financial analysis was made according to the assumptions listed in tab. 4.

An increase in energy yield has been conducted. This is due to maximizing the performance ratio by cleaning and cooling the PV panel. Increasing performance ration by 7.95% boosted the energy yield to 8.7% as shown in tab. 3. The average daily consumption of water per panel is 3.39 liter.

Running the previous inputs in a financial module to calculate the net present value (NPV) based on 10% interest rate, it has been noted that the NPV value is (2495 JOD) which is positive and feasible to implement this experiment.

Conclusions

The optimized cleaning and cooling procedure was implemented to rectify power drop which was resulted from dust accumulation and high temperature conditions. During the period of the experiment, it was concluded as follows.

- A performance ratio increase equal to 8% was calculated.
- An increase in the energy yield was obtained and it was calculated to be 8.7%.
- The PV panel surface temperature was maintained below 30 °C.
- The supplied DC voltage and current were increased by cooling and cleaning PV panel.
- The MPPT mismatch error was reduced as a result of cooling.
- The inverter efficiency was improved by increasing the supplied DC voltage and AC current.
- Water consumption was found to be reasonable.

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