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A Novel Proposed Improvement on Performance of a Photovoltaic/Water Pumping System: Energy and Environmental Analysis

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A B S T R A C T

Nowadays, the world is moving toward using renewable and sustainable energy sources, as much as possible. Photovoltaic (PV) technology is one of the most popular alternatives. PVs are widely used to supply electricity for pumping systems to irrigate the farmlands. It has been proved by many scholars that PV cell temperature is a crucial factor in cell's efficiency. In this study, a novel arrangement of a PV/pumping system has been considered, in order to enhance the pumping performance. To make it feasible, a small part of the pumped water is directed to a box-type passage at the backside of the PV module, and then connect to the water pipe and drain to the farmland. Two various flow rates of 5 and 10 L/min were tested. The results showed two proposed cases have a bit difference in their outputs. Accordingly, the temperature of modified cases did not pass beyond 36°C while, the temperature of the conventional module reaches to 72°C. This temperature reduction leads to about 50% higher electrical efficiency. From the output power point of view, more than 45% increase was observed. Also, an environment evaluation is performed and it was found that the present improvement can reduce emission of 34.57 tons CO_2, annually.

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NOMENCLATURE

A	Area (m^2)	**Subscript**	
G	Solar irradiation (W m^{-2})	amb	Ambient
I	Current (A)	cell	Cell
P	Power (W)	cons	Consumption
PV	Photovoltaic	i	Input
PV/T	Photovoltaic thermal	o	Output
PVWPS	Photovoltaic water pumping system	mp	Maximum power
T	Temperature (°C)	oc	Open circuit
t	Working time	sc	Short circuit
L	Liter	el	Electrical
V	Voltage (V)	pump	Pump
η	Energy efficiency (%)		

INTRODUCTION

For a long time, combustion of fossil fuels was the leading method to generate electricity, in the world. But now, this kind of energy resource is known as the most polluted factor in environment.

In recent years, the trend of using renewable and green energies is growing quickly. Various countries, according

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to their climatic and geographical conditions, moving toward their own available energies. Photovoltaic (PV) technology is one of the most popular types of green energies. Low need to maintenance, quick startup, financial justification, are the reasons that PV systems have received too much attentions. One of the applications of PV energy is to use in water pumping systems. The system can be used in locations where electricity is not available. Generally, increasing in temperature of PV cells is a challenge which facing to this technology, so that the electricity production of a PV cell is reduced by increasing its temperature. So, it is necessary to keep PV cell temperature as low as possible. In many papers, the temperature coefficient of crystalline silicon photovoltaic cells has been assessed and reduction of 0.45% to 0.5% in their electrical efficiency was seen for one-degree Celsius increase in their surface temperature [1, 2]. Different techniques have been investigated experimentally and numerically by scholars, to alleviate this problem e.g. mounting fins [3, 4], using phase change materials [5, 6], water film [7], air blowing [8, 9], and nanofluid circulation [10-12].

Extensive researches have been carried out in the field of water and improving the water technologies e.g. atmospheric water generator [13], waste water treatment [14-16], water desalination [17-19], and optimizing water consumption in agriculture [20]. Some other scholars focused on using different kinds of power plants for desalinating water e.g. using gas turbine power plant [21], solar energy [22], geothermal energy [23] biomass [24] and photovoltaic/thermal [25], for either potable or irrigation water.

In order to supply the water requirements for the engineering and technology department, New Delhi, India, Jamil et al. [26] suggested a photovoltaic water pumping system (PVWPS). In that study, both financial and technical assessment of PVWPS was done and compared with a diesel water pumping system. It was revealed from economic analysis that the payback period of PVWPS is 4 years. By considering 20 years as lifetime of PV systems, a large amount of gasoline will not be consumed. In another similar study, Rezae and Gholamian [27] had done an investigation using RETScreen software on PVWPS for irrigation purpose. The case study was Gorgan farm, Iran. It was concluded that initial cost for installing PVWPS is very high, but the cost is returned in a justifiable time. A review of design and installation methods of PVWPS was performed by Khatib [28] in Palestine and the proved to be feasible. Abu-Aligah [29] has a financial comparison on photovoltaic water pumping system vs diesel water pumping system. He investigated many variables in both diesel and PV pumping systems. It was proposed that in the case of no need to water pumping during night, the PV pumping system should be installed without battery. By this means the initial cost drops to 33%. Moreover, the life cycle cost was evaluated for bothcases and found that the break-even point is less than 2.5 years. So, using PVWPS is financially justifiable.

There are some studies in cooling photovoltaic modules of a PVWPS. Abdolzadeh and Ameri [30] performed an experimental study to increase the performance of PV cells. They proposed water spraying over modules as coolant and compared the results with conventional case. The results showed significantly increase in the system efficiency and the pump flow rate under different heads. The average flow rate was increased from 663 lit/h to 768 lit/h when water spray was used. In another study, Kordzadeh [31] carried out experiments on using a thin film of water on PV modules, in order to decrease its temperature. He reported that at solar noon, the maximum pumping flow rate is reached. By means of the proposed method, the flow rate was increased by 40 L/h.

India is one of the pioneer countries in using PVWPS. In 1992, the first PVWPS was installed in that country and until 2014, about 14,000 PVWPS were founded. Moreover, the Indian government has an objective of one million PVWPS for either irrigation or drinking water by the end of 2021 [32]. More information in solar pumping systems, its advantages, disadvantages, applications, etc. are discussed in literature [32, 33].

As stated in detail, an increase in temperature of PV modules in a PVWPS leads to drop in flow rate of pumped water. The main objective of this paper, is to evaluate a new method to cool PV modules, to improve the performance of PVWPS. Therefore, a novel arrangement of a PV/pumping system has been designed, in order to increase the pumping performance. To make it feasible, a small part of the pumped water is directed to a box-type passage at the backside of the PV module, and then connect to the water pipe and drain to the farmland.

SETUP DESCRIPTION

In order to simulate a PVWPS and performing the experiments on PV cells, an indoor setup was designed, as schematically illustrated in Figure 1. In this setup, a 1 kW tungsten projector was used to simulate the solar irradiance. The distance between projector and PV module was set to a constant value so that a radiation of 630 W/m^2 was created. A poly-crystalline 60 W photovoltaic module, made by Yingli Solar Company, China, was also used, which its technical and physical characteristics are listed in Table 1.

To measure the temperatures of PV panel, ambient, input and output water flow, during time, it is essential to use appropriate thermal sensors. In this regard, DS-18B20 thermometer was selected and its technical properties are presented by Table 2. Moreover, the exact location of thermal sensor behind the PV panel is shown in Figure 2. More information about the setup is available in [34, 35].

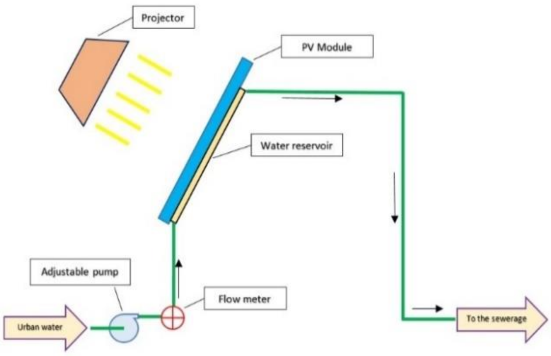

Figure 1. A schematic diagram of the experimental setup

Table 1. Technical characteristics of the PV module

Module characteristics	Value
Power output (P_{Max}) [W]	60
Nominal module efficiency (η_m) [%]	14.4
Voltage at P_{Max} (V_{mpp}) [V]	18.47
Open-circuit voltage (V_{OC}) [V]	22.86
Current at P_{Max} (I_{mpp}) [A]	3.25
Short-circuit current (I_{SC}) [A]	3.44
Operating temperature range [°C]	-40 to +85
Dimension (L /H/W) [cm]	66/63/2.5

Table 2. Technical characteristics of thermal sensors

Characteristics	Value
Quantity	2
Minimum measurable temperature [°C]	-55
Maximum measurable temperature [°C]	125
Accuracy [°C]	0.1

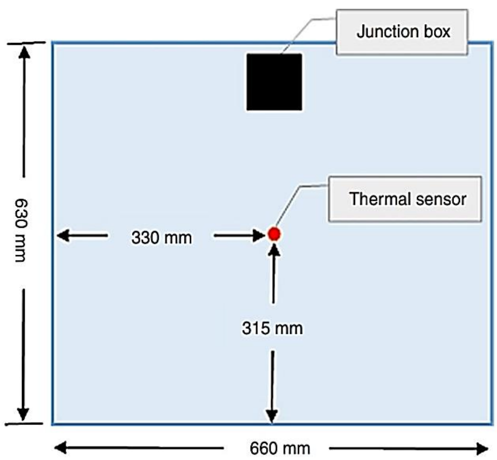

Figure 2. The exact position of thermal sensor, behind the PV module

GOVERNING EQUATION

In this paper, two main parameters are evaluated i.e., variations of output power and electrical efficiency. So, the following equations should be used:

$$P_{out} = V_{mp}\, I_{mp} \quad (1)$$

The geneated power can be calculated by Equation (1). In this relation, I_{mp} and V_{mp} are the electrical current in (A) and voltage in (V), respectively. To calculate the electrical efficiency of the system, it is necessary to define the input power. In a PV system, the input power can be calculated as follows:

$$P_{in} = A\, G \quad (2)$$

In Equation (2), A is the PV module area in (m^2) and G is the solar irradiance in (W/m^2). The efficiency of a system is the ratio of an output parameter to its input. Accordingly, the electrical efficiency of a PV module can be calculated as:

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{A\, G} \quad (3)$$

RESULTS AND DISCUSSION

Temperature variations

As mentioned earlier, the experiments of this study were carried out in an indoor condition, under a constant radiation of 630 W/m^2. At each test, all the variables are maintained constant until the steady state condition is guaranteed, which in the present research, the test time is 120 minutes. Figure 3 shows the transient PV surface temperature for all considered cases. Accordingly, after 80 min, the steady state is observed. In this condition, the temperature of conventional module reaches to 71.5˚C. But, in both two other cases which the module is cooled by the pumped water, the PV temperature does not exceed 35.5˚C. Therefore, reductions of 36˚C and 37.5˚C are encountered for water flow rates of 5 and 10 lit/min, respectively. The important benefit which should be remarked is that this significant temperature drop is achieved with a very low capital cost.

Electrical efficiency variations

Figure 4 illustrates the electrical efficiency of the considered cases. As expected, the electrical efficiency curves for all cases have decreasing trends during time. According to Figure 4, when there is no cooling in the system, the electrical efficiency of the PV module is 10.3%, which shows the lowest value in comparison with the others. Moreover, there is a bit difference of 0.5%, between the two cases of 5 lit/min and 10 lit/min pumping water.

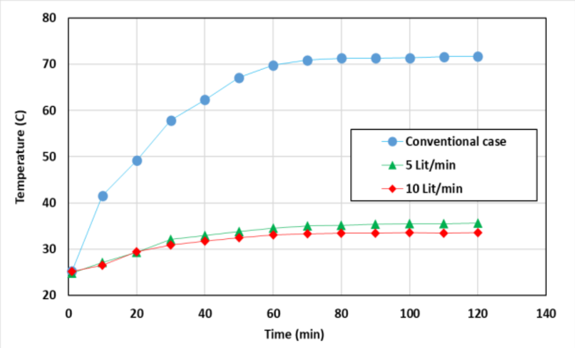

Figure 3. Temperature variations for experimental duration time of 2h

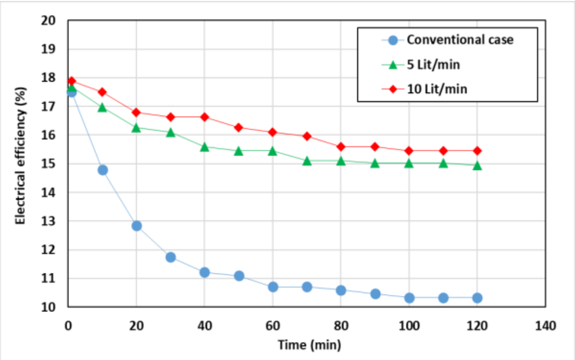

Figure 4. Electrical efficiency variations for experimental duration time of 2 h

Output power variations

The assessment of output power is the most important part of the results, since it directly affects on the performance of a PVWPS. According to Figure 5, the electricity generation is only 35 W, when there is no cooling in the system. Whereas, if the pumped water is employed, a significant improvement is detected in output power. So that, 50.6 W and 52.8 W are obtained, when the pumped water flows through the back side of PV module with the flow rates of 5 L/min and 10 L/min, respectively.

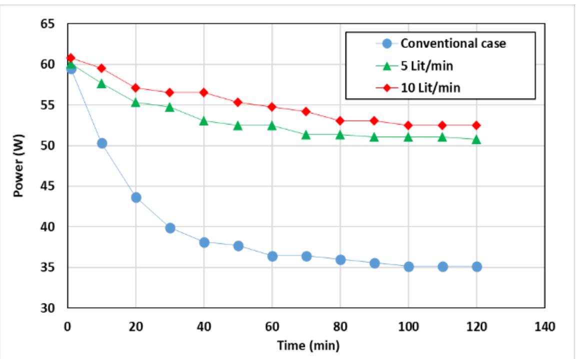

Figure 5. Output power variations for experimental duration time of 2 h

In this study, the power consumed by the pump is intentionally ignored. In calculation of the electrical efficiency, all input and output energies must be counted and the power consumed by the pump is one of the input energies. However, because of the application described in the "Introduction" section, the cooling water is not pumped separately and does not consume supplement energy. Therefore, this advantage make the proposal more feasible.

Environmental assessment

According to the last report by International Renewable Energy Agency (IRENA), although many countries are rapidly moving toward renewable energy sources, still 70% of the global electricity generation is produced by the thermal power plants [36]. The electricity production in oil-rich countries, strongly relies on fossil fuels. For instance, Shahsavari et al. [37] estimated 180 million tons CO_2 emit from the Iranian thermal power plants, annually. They showed that each kWh of electricity generated by solar power plants, leads to prevent 715 g CO_2 emission. This report and also another similar study, Taheri [38], focused on the challenges and importance of investment for moving toward renewable energies in Iran. Therefore, the environmental evaluation of the considered PVWPS seems to be essential. In this section, the environmental impacts of using a diesel pumping system versus a PVWPS are compared. In this regard, a 10 acres farm in Dezful, Iran, which is irrigated by a 15-kW pump was assessed. To reach the aim, it is essential to calculate the annual power consumed by the mentioned system. This value can be calculated by the following relation [39]:

$$E_{cons} = 365\, P\, t \qquad (4)$$

where E_{cons} is the annual energy consumed by the system in MWh, P is the nominal power of the system and finally, t is the number of working hours per day of the pump which is set as 7 hours. So, the output of Equation (4) is the annual electricity consumption by a WPS.

The CO_2 emission factor is different for each country. Stoppato [40] collected the values for many countries. The annual emission factor of 0.902 tCO_2/MWh is considered for a diesel-based system which is alocated for Iran [41]. According to the mentioned descriptions, it is found that, $E_{cons} = 38.325\ MWh$. Therefore, 34.57 tCO_2 is the quantity of CO_2 emission when a diesel pumping system is at work, while if a PVWPS is employed, this amount of CO_2 does not emit to environment in the first year. To have a better sight to this value, some equivalent environmental effects are listed in Table 3. This calculations are obtained by the RETScreen software which is a powerful tool for environmental analysis of both traditional and renewable kinds of systems [42].

As a complementary statement, it must be noted that the reported environmental effects in Table 3, are valid

Table 3. Some equivalent environmental effects of using a PVWPS instead of a gasoline-based system

Environmental effect	Reduction value
Liters of gasoline not consumed	14,847.0
Acres of forest absorbing CO_2	3.2
Cars & light trucks not used	6.3
Barrels of crude oil not consumed	80.4

only for the first commissioning year of the PV system. Depreciation effects in PV cells should be considered for the succeeding years. According to an investigation, made by Ito et al. [43] in year 2011, the output power of crystalline silicon type of PV cells face up to 0.5% drop, annually.

CONCLUSION

PV/pumping systems can be a good replacement for traditional fossil fuel based pumping systems which are widely used in agriculture purposes for farmlands where are far from the electricity network. In this experimantal study, enhancing a PV/pumping system was considered by cooling the module surface using some minor part of the pumped water. In this regard, a novel cooling technique was proposed. All tests were performed in an indoor condition, under irradiation of 630 W/m^2. Two cases of 5 and 10 L/min water flow rates through the back side of the module were tested and compared to the conventional one. Both energy and environmental assessments were performed.

The results show, after the system reached a steady state condition, the maximum value of the PV temperature of the proposed cases was 37.5˚C, while it was 71.5˚C on the conventional one. This temperature drop led to improve its electrical efficiency by 50% in comparison with the case of no cooling. This higher electrical efficiency resulted from 45.7% increase in output power. From the environment point of view, for a farm of 10 acres area, it was found that there is anuual reduction of 34.57 tCO_2 emission, when the proposed PVWPS was applied.

CONFLICT OF INTEREST

The authors confirm that there is no conflict of inerest in this reaserch.

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Persian Abstract

چکیده

امروزه جهان در حال حرکت به سمت استفاده از منابع انرژی تجدیدپذیر و پاک می‌باشد و فناوری فتوولتائیک یکی از محبوب‌ترین روش‌هاست. یکی از کاربردهای این فناوری، استفاده از آن جهت تامین برق مورد نیاز سیستم‌های پمپاژ آب برای زمین‌های کشاورزی است. افزایش دما در سلول‌های فتوولتائیک به دلیل اینکه بر بازدهی الکتریکی آن‌ها تاثیر منفی دارد، از نقاط ضعف این فناوری محسوب می‌شود. این مقاله با ارائه روشی نوین به دنبال غلبه بر این مشکل بوده تا عملکرد سیستم‌های پمپاژ آب را بهبود بخشد. بدین منظور تعدادی تست در محیط شبیه‌سازی شده آزمایشگاهی انجام شد. آزمایش‌ها بدین صورت است که بخشی از آب پمپاژ شده، ابتدا وارد محفظه‌ی تعبیه شده در پشت پنل فتوولتائیک شده و پس از خروج، به سمت زمین کشاورزی هدایت می‌شود. بدین منظور، دو دبی مختلف از جریان آب، شامل ۵ و ۱۰ لیتر بر دقیقه مورد آزمایش قرار گرفتند. نتایج نشان دادند در حالیکه دمای پنل‌ها در دو حالت دارای خنک‌کاری از ۳۶ درجه سانتی‌گراد تجاوز نکرد، دمای پنل عادی به ۷۲ درجه سانتی‌گراد رسیده بود. این اختلاف، موجب شده تا پنل‌های دارای خنک‌کاری با جریان آب، دارای میزان حدودا ۵۰٪ بازدهی الکتریکی و ۴۵٪ برق تولیدی بیش‌تری باشند. در نهایت نیز ارزیابی محیط زیستی برای پنل‌های مورد بررسی، به کمک نرم‌افزار RETScreen انجام شد که نشان‌دهنده‌ی کاهش بیش از ۳۴ تنی در انتشار سالانه کربن دی اکسید بوده است.