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Experimental Investigation of an Irrigation Water-Based Cooling System for Photovoltaic Water Pumping Applications in Desert Environments

Part I: Thermal Performance Analysis

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Abstract

Photovoltaic (PV) water pumping systems have emerged as a reliable and environmentally sustainable solution for agricultural irrigation and water supply in remote regions. However, the performance of PV modules in arid and desert environments is significantly affected by elevated cell temperatures caused by intense solar radiation and high ambient temperatures. Although various cooling techniques have been proposed, many require additional energy consumption or impractical water use. This study proposes and experimentally investigates an innovative cooling approach in which a portion of the pumped irrigation water is diverted through a cooling circuit attached to the rear surface of the PV module and then reinjected into the irrigation stream. The proposed configuration provides effective thermal management without additional pumping energy or water losses. A theoretical model was developed to evaluate the influence of solar radiation and cell temperature on PV performance, and an experimental test rig was constructed and operated under desert climatic conditions in Biskra, Algeria. The results showed a significant reduction in PV cell temperature of up to 23°C under peak operating conditions. Consequently, the cooling process enhanced the electrical performance of the PV module, increasing power output by approximately 15–20% and improving conversion efficiency by about 1.7%. The proposed system represents a practical, low-cost, and water-conserving solution for improving photovoltaic water pumping performance in hot and water-scarce regions.

دراسة تجريبية لنظام تبريد يعتمد على مياه الري لتحسين أداء تطبيقات ضخ المياه بالطاقة الكهروضوئية في البيئة الصحراوية – الجزء الأول: تحليل الأداء الحراري

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الملخص: تُعد أنظمة ضخ المياه بالطاقة الكهروضوئية من الحلول الموثوقة والمستدامة بيئياً لتطبيقات الري الزراعي وتوفير المياه في المناطق النائية. إلا أن أداء الألواح الكهروضوئية في البيئات الجافة والصحراوية يتأثر بشكل ملحوظ بارتفاع درجة حرارة الخلايا الناتج عن شدة الإشعاع الشمسي وارتفاع درجات الحرارة المحيطة. وعلى الرغم من تعدد تقنيات التبريد المقترحة في الأدبيات العلمية، فإن العديد منها يتطلب استهلاكاً إضافياً للطاقة أو استخداماً غير عملي للمياه. تقدم هذه الدراسة وتتحقق تجريبياً من منهجية مبتكرة لتبريد الألواح الكهروضوئية، حيث يتم تحويل جزء من مياه الري المضخوخة عبر دائرة تبريد مثبتة على السطح الخلفي للوح الكهروضوئي، ثم إعادتها إلى مجرى الري. وتوفر هذه المنظومة إدارة حرارية فعالة دون الحاجة إلى طاقة إضافية للضخ أو التسبب في أي فاقد للمياه. ولتقييم تأثير الإشعاع الشمسي ودرجة حرارة الخلايا على أداء المنظومة الكهروضوئية، تم تطوير نموذج نظري، كما تم تصميم وبناء منصة تجريبية وتشغيلها تحت الظروف المناخية الصحراوية في مدينة بسكرة بالجزائر. أظهرت النتائج انخفاضاً ملحوظاً في درجة حرارة الخلايا الكهروضوئية وصل إلى 23 درجة مئوية تحت ظروف التشغيل القصوى. وانعكس ذلك إيجابياً على الأداء الكهربائي للمنظومة، حيث ارتفعت القدرة الكهربائية المنتجة بنسبة تراوحت بين 15–20%، مع تحسن في كفاءة التحويل الكهروضوئي بحوالي 1.7%. وتؤكد النتائج أن النظام المقترح يمثل حلاً عملياً منخفض التكلفة ومرشداً لاستهلاك المياه، ويسهم في تحسين أداء أنظمة ضخ المياه بالطاقة الكهروضوئية في المناطق الحارة وشحيحة الموارد المائية

الكلمات المفتاحية: الطاقة الشمسية، الضخ الكهروضوئي، الألواح الكهروضوئية، التبريد المائي النشط، الكفاءة.

1. Introduction

Nowadays, there is growing interest for renewable and environment-friendly energy sources such as solar energy, on which some kind of sustainable growth may be based. Solar energy is indeed a renewable source of energy, the use of which avoids most of the negative repercussions due to the use of fossil fuels. For North Africa and Middle East countries (MENA), the most promising issue is solar photovoltaic systems, in which energy is produced as a direct result of the conversion of the energy of the solar ray, using the so-called photovoltaic effect [1-3].

In the MENA region, climatic conditions are generally harsh, and ambient temperatures are generally high. This greatly influences the performance of PV systems due to the negative effect of temperature on the efficiency of solar modules, despite these regions being characterized by considerable sunshine. To address this problem, several cooling methods to reduce the negative effects of rising solar cell temperatures are reported in literature, various solutions have been presented and discussed, even so many of them are practically non-viable. The two most widely used cooling methods today are air cooling and water cooling [4-6].

This paper aims to present an effective and innovative methodology for PV pumping systems. Because of water scarcity in desertic regions and initial installation cost of PV pumping systems, it is necessary to fully optimize the use of the pumped water and also maximize energy yields of the solar field using adequate configuration and appropriate control strategies to track the maximum power point (MPPT). In this context, a cooling system has been proposed for possible system setup of agricultural applications and concerns hot regions where the use of some techniques would be wasteful of precious water resources. The proposed scheme suggests deviating a portion of the pumped water to the PV source for cooling and then reinjected back into the irrigation water stream, Figure 1.

This procedure improves system efficiency without any additional energy losses required to pump the cooling water and saves the amount of water that would otherwise be wasted after using it in the spray cooling process for example.

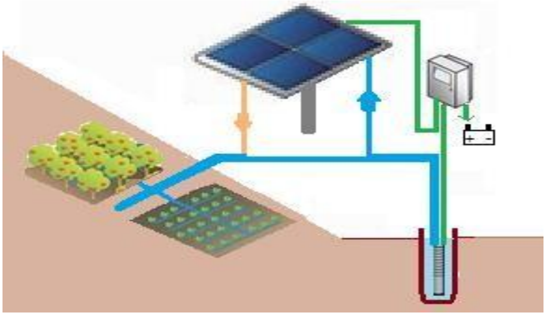

Figure 1. General illustration of a PV pumping system

2. Methodology PV Modules Cooling Techniques

Literature reported several cooling methods to reduce the negative effects of rising photovoltaic cell temperatures. The two most widely used are air cooling and water cooling. Both techniques rely on contact between the surface of the solar module and the cooler, allowing for heat exchange between them. This helps reduce the temperature of the solar cells. These techniques are classified into two categories:

2.1 Passive Cooling:

For air cooling, we distinguish: Natural cooling, which uses natural convection to cool the solar panels. Perforated aluminum heat sinks are attached to the back of the photovoltaic (PV) panels to optimize heat transfer between the panels and the surrounding air. The results showed a significant reduction in operating temperature and an improvement in the electrical efficiency of the panels [7] [8].

Regarding passive water cooling, one of the methods cited in the literature is immersion cooling in water [28]. It has shown an efficiency improvement of 17.8% after immersion to a depth of 1 cm. The disadvantage lies in the impact of immersion on the longevity of the solar modules [9].

On the other hand, the most widely used methods at large scale are the FPV stations where the PV modules float on the water surface. A study conducted by Ocean Sun AS showed a power efficiency increase of 5 to 7% between a system cooled by natural air and one in direct contact with a floating membrane on the water surface [10].

2.2 Active Cooling (Forced Cooling):

It has been shown that the use of forced air can improve energy efficiency by up to 18.67% [7]. Regarding active water cooling, several techniques are distinguished; each differing in the way the water is used. These include:

- Front-mounted spray cooling of photovoltaic panels: In this case, energy efficiency is increased by up to 15% in extreme weather conditions. Although water-intensive, this method remains a cost-effective and efficient solution for floating solar systems [11] [12].
- Front-to-back spray cooling of photovoltaic panels: This method simultaneously cools both sides of the panel by applying a water spray. Experimental results show a maximum increase in electrical energy production of 16.3%. In addition, the panel temperature was reduced from 54°C to 24°C. This technique also exhibits a self-cleaning effect on the panel surface, which helps improve their long-term efficiency [13].
- Constant water flow on the surface of the solar panel: results showed a significant improvement in the efficiency of the PV module of up to 15% compared to the module without cooling.
- Constant water flow on the back surface of the PV: Unlike the previous procedure, in this case the water flow is applied to the back of the solar module. A study is conducted by. It was reported that a front water film cooling increased the energy production by 22%, while the back cooling improved the production by 29.8%. While the combination of the two cooling methods increased the energy production by 35% compared to the module without cooling [14].

3. Methodology and Practical implementation

3.1 PV module Cooling procedure

The following describes the implementation of a cooling system to improve solar module performance. Active back-end water cooling has been shown to be the most effective solution, compared to air cooling or passive water cooling. Indeed, this method allows for better heat dissipation, which significantly contributes to improving the efficiency of photovoltaic modules. Consequently, this technique is adopted by implementing a cooling system based on direct contact between water and the back of the photovoltaic module to ensure optimal heat exchange. In this experiment, and to better study the effect of heat transfer on module efficiency, the back surface of the module was divided into four zones, each with its own cooling circuit Figure 2. These zones can be connected in series, parallel, or in a mixed connection. This arrangement will subsequently allow for varying the configuration of the solar module's thermal model. These experiments were carried out at Biskra University (Algeria). This city has an agricultural character and is characterized by a hot climate in most months of the year.

The principle involves diverting some of the pumped water to the back of the solar panel, where it absorbs heat, before reintegrating it back into the irrigation circuit. This process allows for rational use of water without any waste.

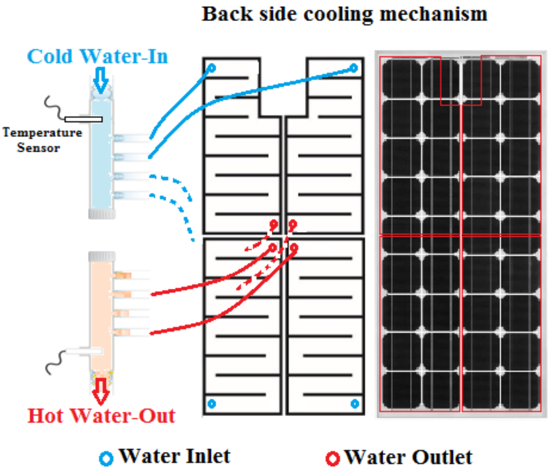

Figure 2. The proposed active cooling system

3.2 Experimental Rig

In the experimental setup, a comprehensive measurement and control system was implemented to monitor and evaluate the performance of solar module. The system incorporates a power stage to optimize the power output of the PV panels to their maximum (MPPT) and a set of sensors and electronic components to measure key environmental and electrical parameters. An 85Wp mono-crystalline solar module is used. It is mounted on a mobile frame that allows either sun tracking or tilt angle adjustment. For the preliminary tests, a 22W, 800L/H Brushless DC type pump is used for pumping (and cooling) and a set of transducers were used to measure a number of parameters as given in table (1):

Table (1): Parameters measured by the transducers

φ (latitude)	32°.
Celle and ambient temperature	LM35
water temperature	DS18B20
optimal current	ACS712
Optimal voltage	B25
Solar radiation	PYR 20

For maximum power tracking, an MPPT Charge Controller SR-MT2410 was used to optimize and match between the solar array and the battery and load pump. The experimental setup of cooling system is given in Figure 3.

For continuous data monitoring, an Arduino board is used as an intermediary for data collection and send them synchronously to the main PC where they are stored in a ready to use Excel data.

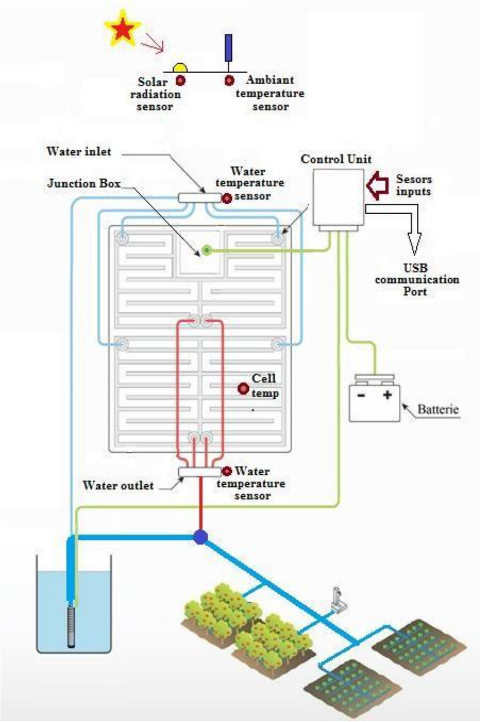

Figure 3. The experimental setup of cooling system

4. Simulation and Experimental tests

Results from both practical and simulation-based work are presented. The solar module under tests is simulated using its characteristic parameters given by the manufacturer. Matlab Simulink and PVSyst software were used in this context to simulate the behavior of the PV module under various working conditions, mainly at different temperatures and variable solar insolation.

The simple one diode electrical model is used, Figure 4.

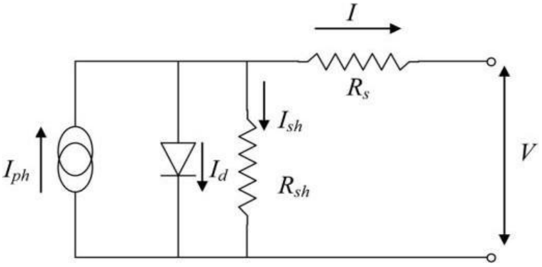

Figure 4. One diode Solar cell model

The I(V)) characteristic of the photovoltaic module is given by:

$$I = I_{PH} - I_o\left[\exp\left(\frac{V + IR_s}{nV_t}\right) - 1\right] - \left(\frac{V + IR_s}{R_{sh}}\right)$$

Where:

$V = (KT)/q$: Thermal voltage at temperature T

K: Boltzmann's constant (1.381×10^{-23} J/K),

T: Effective cell temperature in Kelvin,

q: Electron charge (1.602×10^{-19} C),

n: Junction non-ideality factor,

I_0: Diode saturation current I_{PH}: total Photocurrent

R_{sh}, R_s: shunt and series resistances

I and V: output PV current and voltage

Since PV module performance is strongly influenced by both solar irradiance and cell temperature, simulations were performed to investigate the effect of these parameters on the electrical characteristics of the module. Figure 5 presents the simulated I–V and P–V characteristics of the PV module. The upper plots illustrate the effect of varying solar irradiance at a constant temperature of 25°C, while the lower plots show the influence of cell temperature at a fixed irradiance level. The results clearly demonstrate the increase in power output with increasing irradiance and the degradation in module performance as cell temperature rises.

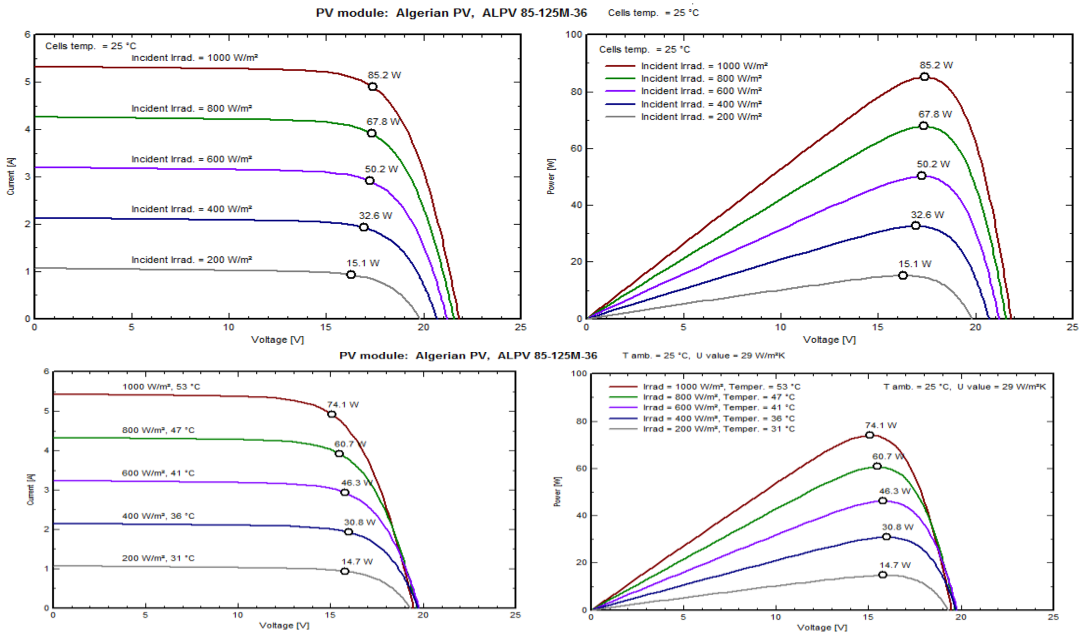

Figure 5. Simulation results of the ALPV 85 solar panel. Without (top) and with (bottom) heating effect of solar radiation

However, in real applications many parameters influence the ideal module operation, especially rising ambient temperature, solar radiations heating effect, wind and humidity effects …etc. In these figures solar radiation heating effect is observed. The cell temperature rises with rising solar radiation which reduces significantly the power yield of the PV module.

The effect of rising cell temperature is clearly seen on Figure 6 obtained by simulation. The module efficiency is given for different solar radiation and increasing solar cell temperature caused mainly by the heating effect of solar radiation in addition to a fixed value of ambient temperature.

This heating effect was investigated practically on the test rig previously described. It is known that Solar cell temperature is affected by a combination of environmental and material factors. mainly ambient temperature, solar irradiance, wind speed, material properties and its mounting structure; in addition, humidity, dust accumulation, and even the size and design of the solar cell itself play a role.

At this stage, no cooling mechanism is used except the cooling effect of wind and humidity which are neglected for the time being.

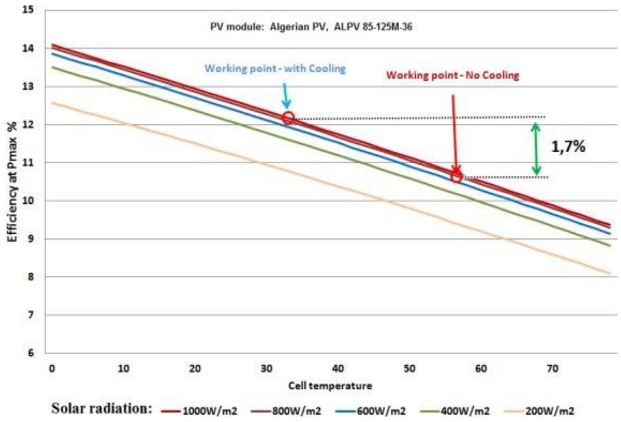

Figure 6. Simulated results of module efficiency versus cell temperature

Figure 7 illustrates cell temperature increase simultaneously as solar radiation increases. While ambient temperature varies from 25 °C in the morning and reaches its maximum of about to 32 °C in the noon, Cell temperature approached 60°C at its maximum at noon and then decreases gradually as solar radiation decreases. This high temperature increase will surely reduce solar module efficiency according to the theoretical curves indicated previously and depicted in Figure 6.

To investigate the cooling effect of the proposed procedure, pumped water is injected in the back of the solar module and collected afterword to be reinjected to the main pipe, Figure 3. The recorded results for a time period at midday are depicted in Figure 8. Ambient temperature, initial cooling water temperature at the in-let and the subsequent transmitted water at the outlet are all recorded continuously. As can be seen, the water temperature rises from 28°C to approximately 32 °C absorbing hence heat from the solar panel and cooling subsequently the solar cells to about 33.5°C. Solar cell temperature using the cooling process is compared to the one if the solar panel if not cooled. It is clearly seen that in the normal working conditions, the cell temperature might reach 57°C at 13H while the ambient temperature is only about 29°C. The excessive heat is due to the heating effect of the solar radiations in addition to the ambient temperature effect.

To monitor the daily solar panel thermal behavior during a sunny day, data were collected for a full day and are illustrated at Figure 9. It is shown that the negative effect of the solar radiation heating is more manifest heavily if the module is not cooled. If cooling is adopted, the effect of the ambient temperature is more significant and influential.

In addition, the bell shape of the solar radiation variations is reflected by the solar panel temperature shape with a slight tilt to the left due to the effect of the ambient temperature.

Figure 10 illustrates the daily harvested power along two consecutive days where the climatic conditions were similar (Solar radiation and temperature profiles). It is clearly seen that the power generated under cooling conditions is much higher the one collected in normal conditions (without cooling) with a remarkable increase of 15-20% approximately.

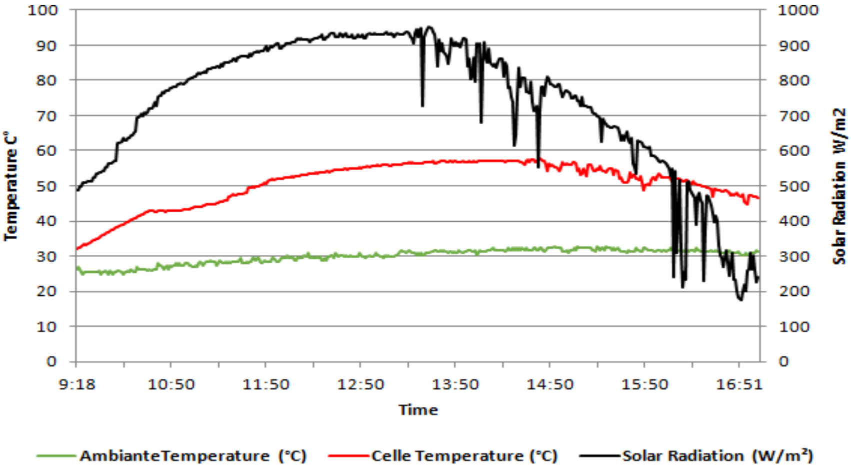

Figure 7. Instantaneous global solar radiation, ambient temperature and cell temperature without cooling.

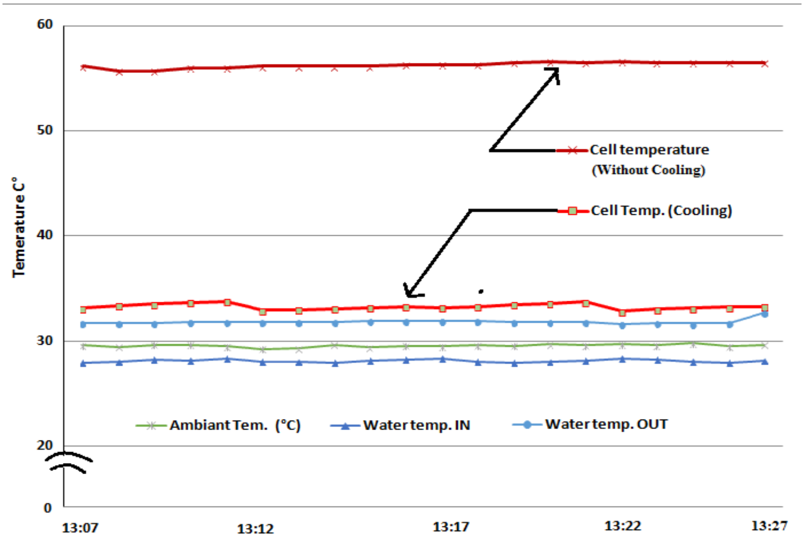

Figure 8. Comparisons on solar panel temperature between cooling and without cooling

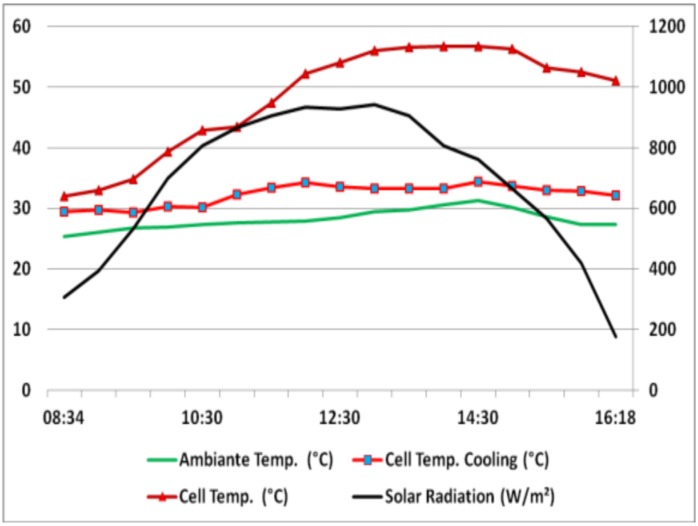

Figure 9. Instantaneous global solar radiation, ambient temperature and cell temperature with and without cooling

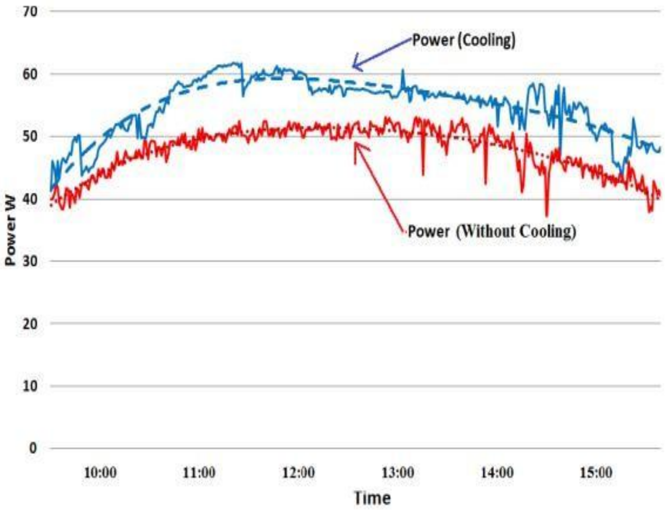

Figure 10. Instantaneous output power between non-cooling and continuous cooling system

5. Conclusion

A cooling system has been proposed for possible system setup of agriculture irrigation system application to cool down the solar panel. The distinguishing result among the solar panels with and without cooling, using an integrated serpentine cooling system at the back of the module is given in Figure 4 revealing the fact about cell temperature and Intensity of radiations. Comparison between temperatures of solar panels with and without cooling made obvious that temperature with water cooling reduces significantly solar module temperature if an appropriate flow rate is observed. For the present test, solar module temperature is reduced by 23°C in a desertic region as shown in figure5, increasing therefore the PV conversion efficiency by 1.7% approximately. This will increase the harvested solar energy consequently and reduce the cost payback time thereafter. This would be investigated in future work as well as a quantitative investigation about water use for cooling and what is the optimal proportion to adopt.

Conflict of Interest

The authors declare that no financial or personal conflicts of interest have influenced the work presented in this paper.

Authors' Contributions

A. Moussi formulated the research concept, designed the experimental methodology, supervised the study, developed the theoretical framework, interpreted the results, and led the writing and revision of the manuscript. Memiche Meriem conducted the experimental work, participated in data collection and processing, performed the simulations and preliminary analyses, and contributed to the preparation of the initial manuscript draft under the supervision of the first author. Both authors reviewed and approved the final version of the manuscript.

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Data Availability

Data are available from the corresponding author upon reasonable request.

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