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Experimental and Theoretical Study to Improve the Performance of Solar Cells by Evaporative Cooling in Iraq

Qusay Kamil[1,*], Najim Abd[2]

[1] Department of Technical Power Mechanics, Northern Technical University, Kirkuk, 36001, Iraq
[2] Department of Mechanical Engineering, Baghdad University, Baghdad, 10001, Iraq

ABSTRACT

The operating temperature of photovoltaic panels represents an important parameter that influences their conversion efficiency. High operating temperatures determine a decrease of maximum output power in the same conditions of solar radiation in order to overcome this critical issue, it is necessary to maintain the panels relatively at low surface temperatures as much possible as while using appropriate cooling systems. The current implementation assesses experimentally and simulation (by Mat lab) the performance of a PV system using a forced-air cooling system by an evaporative cooler from June to October of summer weather in Iraq. The results reveal that the highest values of the solar intensity and the ambient air temperature are obtained in July. Employing the forced-air cooling system reduces the average temperature on the front sides of the PV panel during July by 12%. In addition, the forced-air cooling system enhances noticeably the electrical power output of the PV panel by 13.2%, 15 %, 8.21%,6.6%and 5.5% during June, July, August, September, and October, respectively. The results also found a further improvement in the electrical efficiency of the panels by 11.11%, 14.4%, 9.35%,7%. and 6.2% during June, July, August, September, and October, respectively.

Keywords:
Efficiency, Evaporative Cooler, Photovoltaic Panels, Solar Radiation

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1. Introduction

A photovoltaic (PV) panel that is considered the cleanest and most abundant source amongst renewable energy resources, converts a limited wavelength of incoming solar irradiation directly into electrical energy with a low electrical efficiency nearly around 12–15%, depending upon the design of the PV panel and its geographical and operating conditions. The electrical power is generated from a limited portion of incident solar energy passing through PV panels, regulators, battery, cabling, and then through an inverter to supply AC electricity. However, the remaining solar energy is accumulated as thermal energy, causing the crucial issue of rising the panel surface temperature and unfortunately decreasing its electrical efficiency [1–4]. PV is still the cheapest method of electrical generation from renewable source so far [5]. The high temperature of PV panels is one of the main problems that reduce the electrical energy production by 0.4–0.5% per 1 ◦C compared to that obtained at 25 ◦C. Therefore, the concept of "PV cooling" became one of the most important research points. Reducing the temperature of the surface of the photovoltaic cell is an effective way to reduce

* *Corresponding author.*
E-mail address: qusay_hwj@ntu.edu.iq

the rate of thermal degradation and improve its efficiency. The temperature of the photovoltaic panels can be reduced in two ways, either the traditional method, which is natural cooling, using water or air or by using nano-fluid cooling introduced by Choi and Eastman [6] in 1995. Therefore, the aim of the present work is to study experimentally and simulate by MATLAB the performance of the PV solar system via forced-air cooling technique BY air cooler in hot climate summer conditions with high solar intensity during the summer months of June, July, and August, September, and October. The current implementation is to improve the PV solar cell using forced-air cooling and the conventional PV system without air cooling. This study is carried out by keeping the air flow rate constant. The average values of panels' surface temperature, electrical power generation, and the electrical efficiency.

2. Methodology

To understand the working principle of a solar cell, it is appropriate to make a model which is electrically equivalent. The ideal practically photovoltaic cells simplest model is given in Fig. 1 and consists of a constant current source and parallel connected diode. Constant current source works like a generator to push the electrons to the external circuit. Photocurrent I is generated due to the photovoltaic effect. Photocurrent depends on the intensity of the available sunlight Iph of a current source is directly proportional to solar radiation. It means that with an increase of intensity of available sunlight Iph must be increased. Id is the reverse saturation current of a solar cell [7].

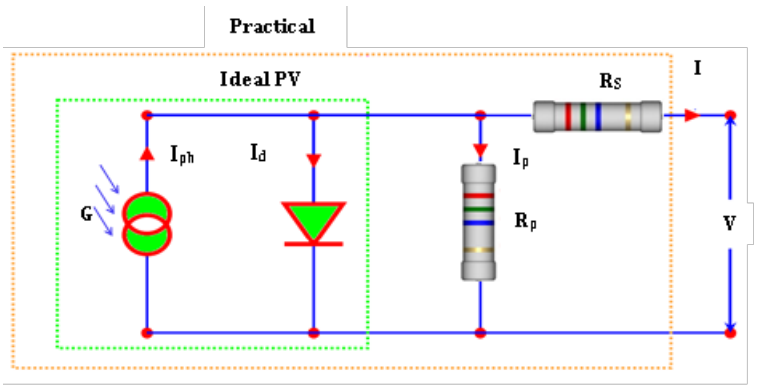

Fig. 1. Comparison of experimental measurement and Numerical

From the schematic of a solar cell equivalent circuit, it is exemplified that the output current of a photovoltaic cell is the difference of photogene rated current, diode current, and shunt resistance current Iph given in equation 1 [8].

$$\mathbf{I} = \mathrm{I_{ph}} - \mathrm{I_d} - \mathrm{I_p} \tag{1}$$

The photocurrent depends on both irradiance and temperature [9]:

$$\mathbf{I_{ph}} = \frac{\mathrm{G}}{\mathrm{G_{ref.}}}(\mathrm{I_{ph_{ref.}}} + \mu_{sc} \,.\, \Delta\mathrm{T}) \tag{2}$$

G: Irradiance (W/m2), Gref : Irradiance at STC = (1000 W/m2), ΔT = (Tc -Tc,ref) (°K), Tc,ref : Cell temperature at STC = 25 + 273 = 298 K, μSC : Coefficient temperature of short circuit current (A/K), provided by the manufacturer, Iph,ref : Photocurrent (A) at STC[10].

Diode current from Shockley diode equation is [7]:

$$\mathbf{I_d} = I_0 \,[\exp\,(\,q(\frac{V_d}{AkT}) \,-\, 1] \quad (3)$$

On the other hand, the cell saturation current (I0) varies with the cell temperature, which is described as [7]:

$$\mathbf{I_0} = I_{rs}(\frac{T}{T_{ref.}})^3 . e^{\left[\frac{qE_G}{AK}.(\frac{1}{T_{ref.}}-\frac{1}{T})\right]} \quad (4)$$

where: $\mathbf{I_{rs}}$ is the cells revers saturation current at a reference temperature and a solar radiation, $\mathbf{E_G}$ is the bang-gap energy of the semiconductor used in the cell ($\mathbf{E_G}$= 1.12eV for silicon).

The voltage across these components governed the flow of currents:

$$\mathbf{V_d} = V + IR_s \quad (5)$$

where Vd is the voltage across shunt resistance and diode, V is the output terminal voltage and a voltage across the series resistance is IRS .

Current flows through shunt resistance can be calculated from ohms law

$$\mathbf{I_p} = \frac{V_d}{R_p} \quad (6)$$

By substituting these values in equation 1:

$$\mathbf{I} = I_{ph} - I_0 \,[\exp\,(\,q(\frac{V_d}{AkT}) \,-\, 1] - \frac{V_d}{R_p} \quad (7)$$

q: Electron charge (1.602 ×10-19 C), A: Ideal factor of the diode, K: Boltzmann's constant (1.38 x 10-23 Joule/ºK), and T: Actual temperature of cell (°K).

2.1 Open circuit voltage

The maximum voltage taken from the solar cell (RL = ∞) is known as open circuit voltage (Voc)[11].

$$V_{oc} = \frac{nKT}{q}\ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad (8)$$

2.2 Fill factor

The measure of a photovoltaic cell quality is fill factor (FF), which is derived by equating the maximum power ($Pmax$) to the theoretical power (Pt).Where power (Pt) would be output at both the open circuit voltage (Voc) and short-circuit current (ISC)[12] .

$$\mathbf{FF} = \frac{P_{max}}{P_t} = \frac{V_{max}I_{max}}{V_{oc}I_{sc}} \quad (9)$$

2.3 Maximum power

The output power of a solar cell is given in watts and is equal to the product of voltage times the current and is defined as[13]:

$$\mathbf{P_{out}} = V_{out} I_{out} \quad (10)$$

The device will provide maximum power for maximum values of voltage and current.

$$\mathbf{P_{max}} = V_{max} I_{max} \quad (11)$$

In terms of fill factor maximum power is by putting equation 9 in 11 we get

$$\mathbf{P_{max}} = V_{oc} I_{sc} FF \quad (12)$$

2.4 Power conversion efficiency

Power conversion efficiency is the most frequently used parameter to relate the performance of two solar cells and is termed as η_{CE}[14].

$$\boldsymbol{\eta}_{\mathbf{CE}} = \frac{P_{max}}{P_{in}} \quad (13)$$

$$\mathbf{P_{in}} = G \, . \, A_{pv} \quad (14)$$

Therefore, from equations 13 and 14 the product of theoretical power ($\mathbf{P_{in}}$) and fill factor (FF), divided by the power of the energy input from the sun is the power conversion efficiency [15]. Mathematically expressed in equation 15.

$$\boldsymbol{\eta}_{\mathbf{CE}} = \frac{V_{max} . I_{max}}{G . A_{pv}} \quad (15)$$

3. Matlab/Simulink Model

The mathematical model of a module is implemented using MATLAB/SIMULINK. It is difficult to arrive an analytical solution for a set of model parameter because of implicit and nonlinear nature of equations. Hence the manufacturer's specification is used to evaluate the behavioral characteristics I-V and P-V. Data sheet gives the following operational data of PV modules: the open-circuit voltage (VOC), the short-circuit current (ISC), current at maximum power (IMP), voltage at maximum power (VMP), and the temperature coefficients of open-circuit voltage and short-circuit current , maximum power (P_{max}).The mentioned data are at standard test conditions (STC) which is at solar irradiation of 1000 W/m2 and temperature (T) 25°C. See Figure 2.

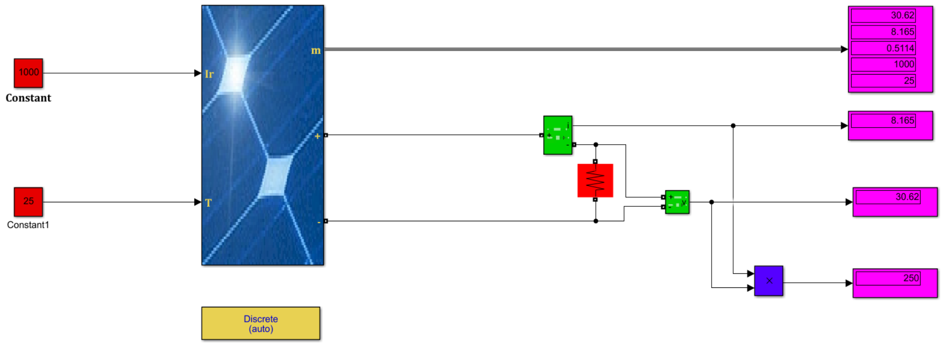

Fig. 2. Complete Simulink model of 250 W Module

4. Experimental Setup Rig

Figure 4 shows the experimental device, which consists of a frame made of wood with dimensions. It passes the cold air coming from the air cooler at a constant speed through an insulated circular duct with a diameter of 10 cm. The cold air cools the back surface of two solar panels placed at an angle (R) made of Monocrystalline material, the capacity of each panel is 250 watts. The rest of the specifications are shown in the table 1. The incident solar radiation is measured by means of a radiation meter (R), and the current and current are measured by a clamp meter. Three k-type thermal sensors are placed at the top, middle, and bottom of the panel, which are used to measure temperatures and take the average of the three temperatures. Another sensor was also placed when exiting to measure the air temperature.

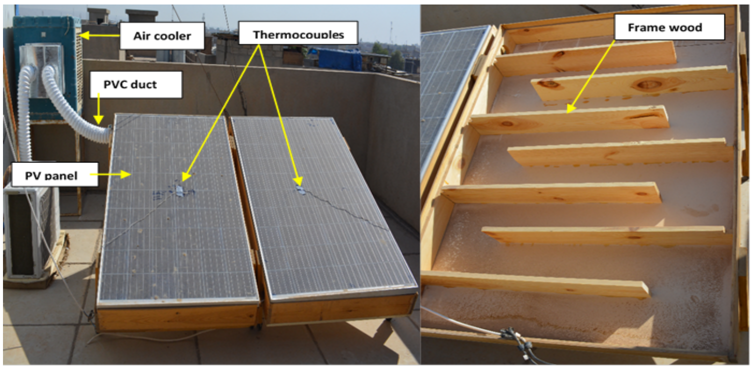

Fig. 4. Experimental device of 250 W Panel

Table 1
Properties of PV Panel

Parameter	Specification
Power	250W
Open circuit Voltage (Voc)	37.74V
Short circuit Current (Isc)	8.74A
Voltage at maximum Power(Vmp)	30.5V
Current at maximum Power(Imp)	8.2A
Temp. Co-eff. Power Pm (PT)	-0.4% / 0K
Temp. Co-eff. Voltage Voc (aT)	-0.34% / 0K
Temp. Co-eff. Current Isc (Ki)	+0.005% / 0K

5. Results

5.1 Performance of a Module at Various Irradiation Levels

Simulated I-V and P-V characteristic of a module is shown in Fig.5 and Fig.6. The simulation is performed at irradiation level of (1000, 800, 600, 400 and 200 W/m2). Keeping all other parameters same. The simulation at 1000W/m2 and temperature of 298 K gives standard test results and this is exactly agreeing with the manufacturers specification. It is found that maximum output power strongly depends on irradiation. However, the open circuit voltage has very small increase as the irradiation is varied. When the solar radiation decreased, the maximum power output that generated by PV panels also decreased. This is because of less availability of photons of semiconductor cells.

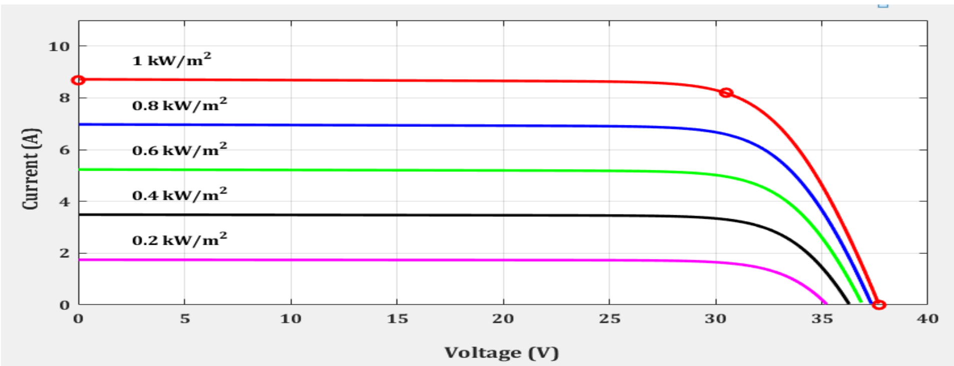

Fig. 5. I-V Characteristics for various conditions of solar Irradiation

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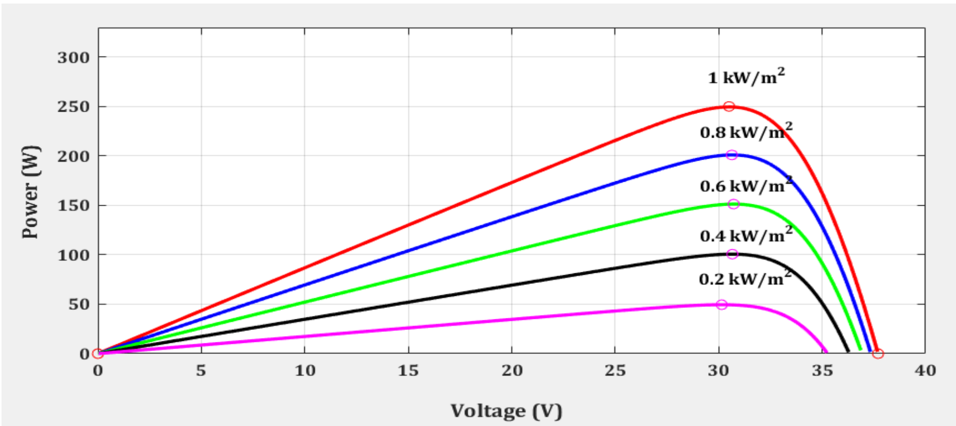


Fig. 6. P-V Characteristics for various conditions of solar Irradiation

5.2 Performance of Module at various temperature levels

Performance of photovoltaic module can be simulated by comparing the graph of the simulation with the reference in different temperature. In this project, the values of temperature are varying from (25, 35, 45, 55 and 65 °C) and the solar irradiance is constantly at 1 kW/m^2. Based on the reference graph, during different temperature the current and power is constant until reaching the maximum point. For simulation, the performance of simulated 250W Photovoltaic also give the same value of current and power. The graphs are shown in Figures 7 and 8.

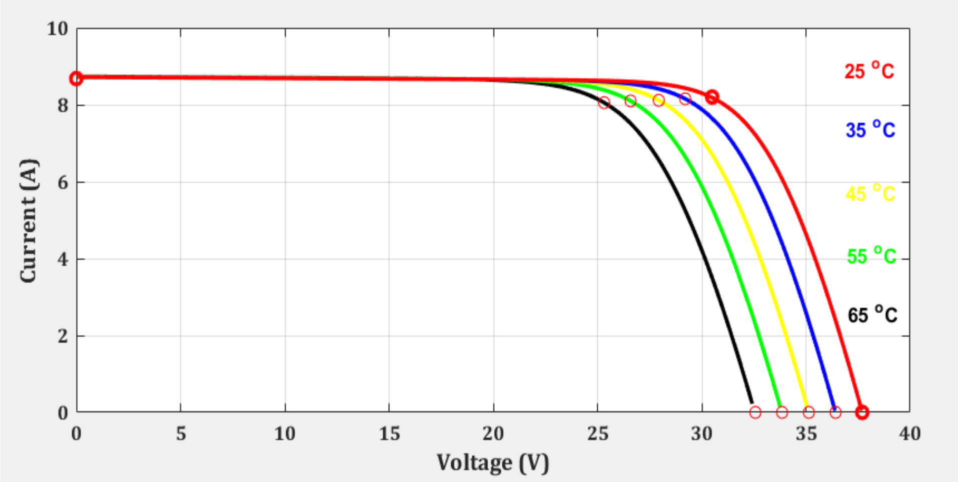


Fig. 7. I-V characteristic at constant solar radiation with different temperature

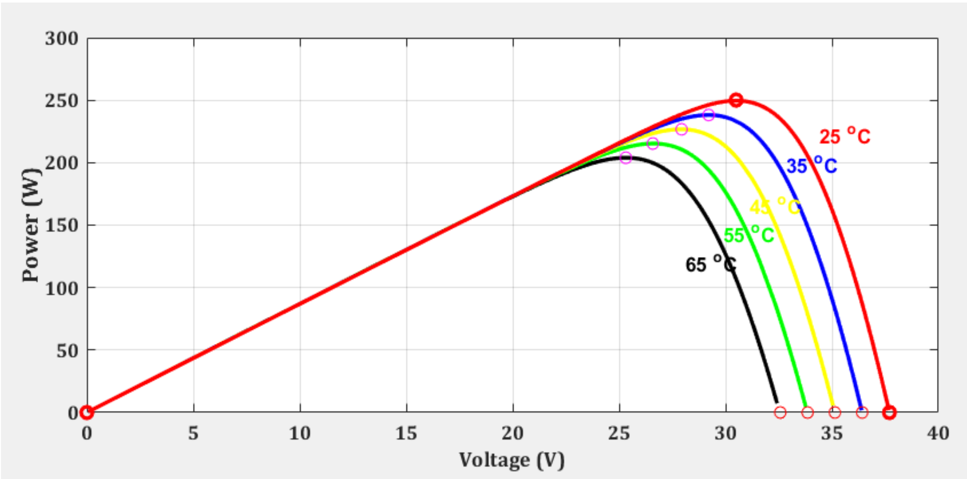


Fig. 8. Effect of temperature on P V characteristics at constant solar radiation

5.3 Electrical Performance of Photovoltaic Panels

The hourly variation of the electrical energy generated by photovoltaic panels for conventional PV plants during June, July, August, September, and October is shown in Fig.s (9,10). The electrical energy generated by the conventional system differs from that of the cooling system for different summer months. The results indicate that in both systems (with and without cooling), the generated electrical energy increases from early morning at 8:00 until it obtains the optimum value at 1:00 in the afternoon due to the increased intensity of the sun. After that, the electrical energy decreases as the solar energy density decreases. Moreover, it is observed that the use of an air cooling system for the photovoltaic panel significantly improves the electrical power obtained. With regard to the forced air cooling system, the results also showed that the highest and lowest values of electrical power were for the month of July and October, respectively, for both systems.

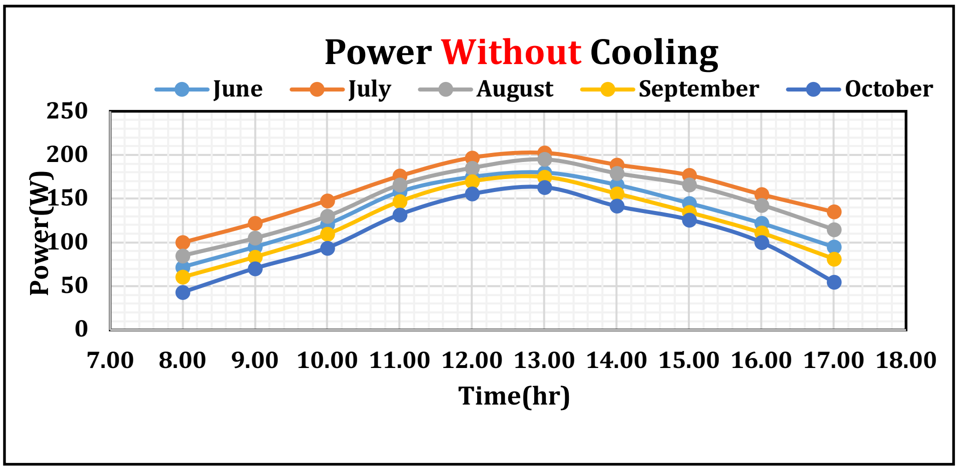


Fig. 9. Electrical Power with daily time for five months

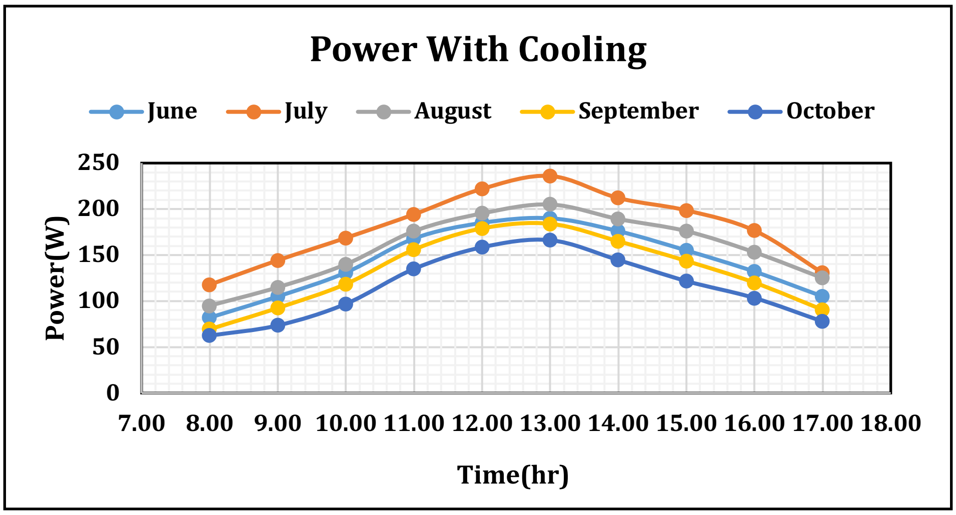


Fig. 10. Electrical Power with cooling at daily time months

Figures 11 and 12 show the hourly electrical efficiency variance of PV panels that depends on the electrical power generated and the solar energy density of conventional PV systems (cooling, no cooling) during June, July, August, September, and October. The highest and lowest value of the electrical efficiency of the two systems was reached during the month of July and October, respectively. This is due to the increase in the intensity of the sun and the temperature of the surrounding air. The use of an air-cooled system greatly enhances electrical efficiency at a high rate, especially in the month of July. This can be described that when the surface temperature of the photovoltaic panel increases, the phonons are excited, thus impeding the regular movement of electrons and thus this resistance degrades the generated electrical energy.

5.4 Percentage improvement of performance for power and electrical efficiency

Figure 13 shows the comparison between the maximum electrical energy generated for each month and the improvement percentage using cooling. It was noted that using the air cooling system for the photovoltaic panel significantly improves the electrical energy generated, and with regard to the forced air cooling system, the average value of electrical energy increases by 13.2%, 15 %, 8.21%,6.6%and 5.5% during June, July, August, September, and October, respectively.

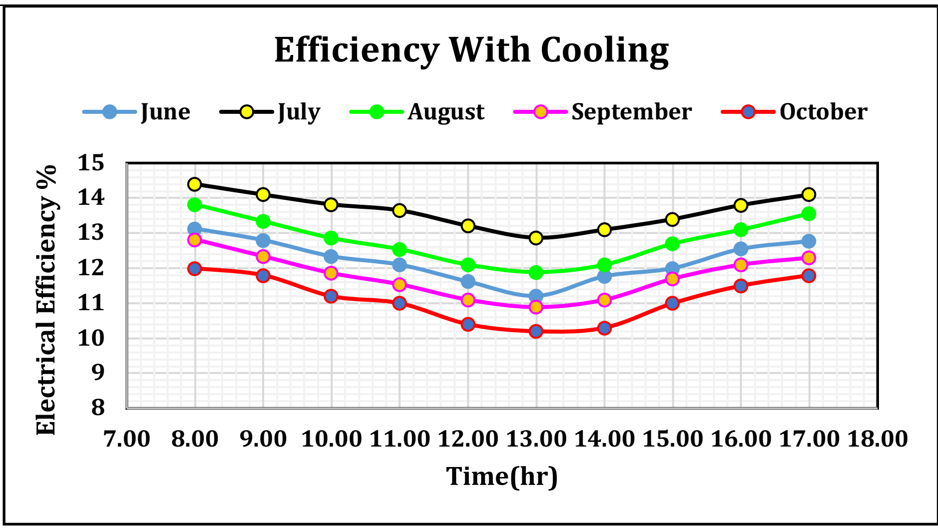


Fig. 11. Efficiency with daily time with cooling system

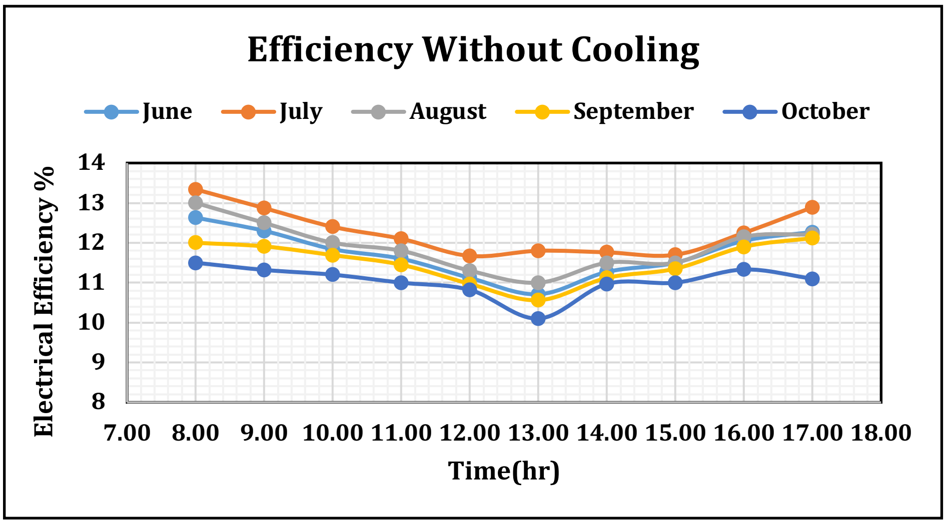


Fig. 12. Efficiency with daily time without cooling system

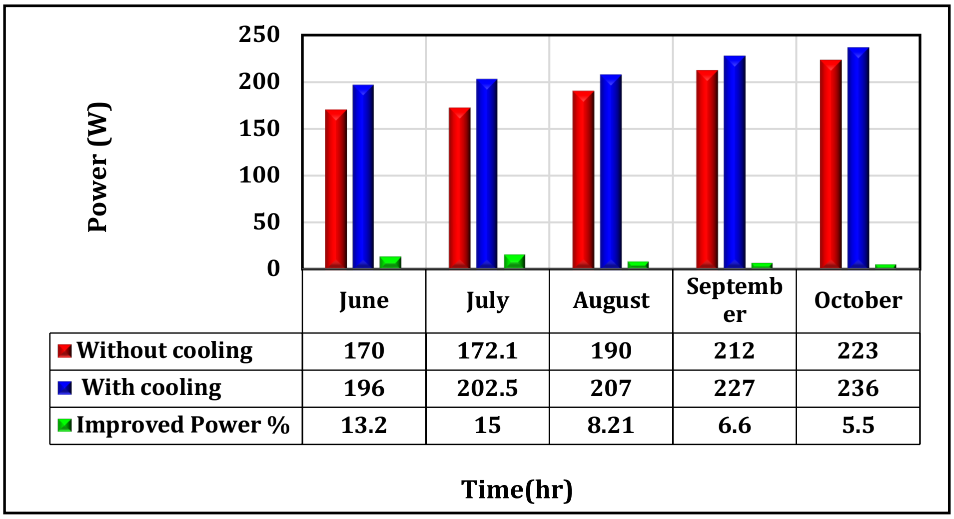
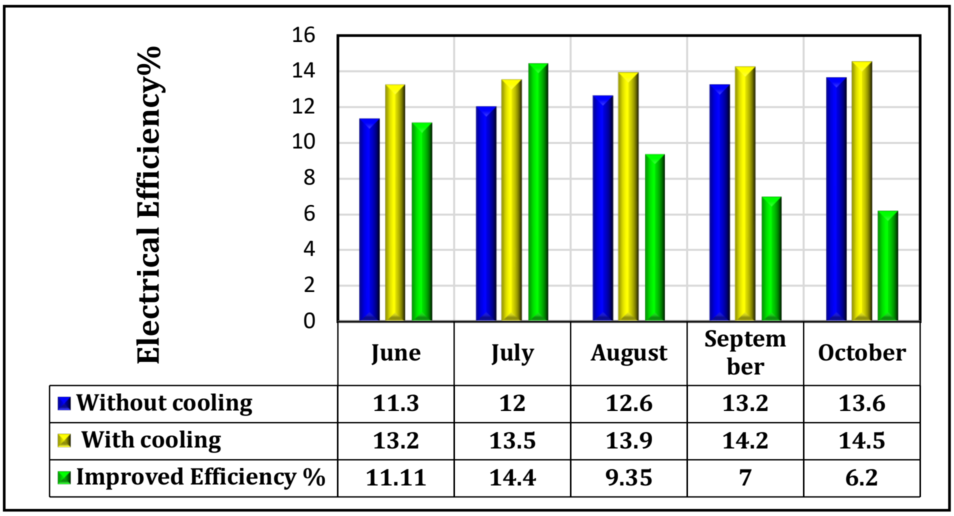


Fig. 13. Improved Power with and without cooling against months

Figure 14 shows the comparison between the maximum electrical efficiency generated per month and the percentage of improvement using cooling. It is observed that the use of the air cooling system for the photovoltaic panel greatly improves the generated electrical efficiency, and with regard to the forced air cooling system, the electrical efficiency value increases by 11.11%, 14.4%, 9.35%, 7%. and 6.2% during June, July, August, September and October, respectively.



	June	July	August	Septem ber	October
Without cooling	11.3	12	12.6	13.2	13.6
With cooling	13.2	13.5	13.9	14.2	14.5
Improved Efficiency %	11.11	14.4	9.35	7	6.2

Fig. 14. Improved efficiency with and without cooling against months

5.5 The effect of the cooling process on the rate of improvement of efficiency and production capacity

The results showed that the improvement of photovoltaic power generation was about 14.1% when implementing the proposed cooling system with previous works.The results also showed that the percentage of electrical efficiency improvement is 14% when comparing the photovoltaic unit with a system without cooling, and the reason for this is that cooling increases the voltage of the panels and thus increases the productive capacity, which in turn improves efficiency.

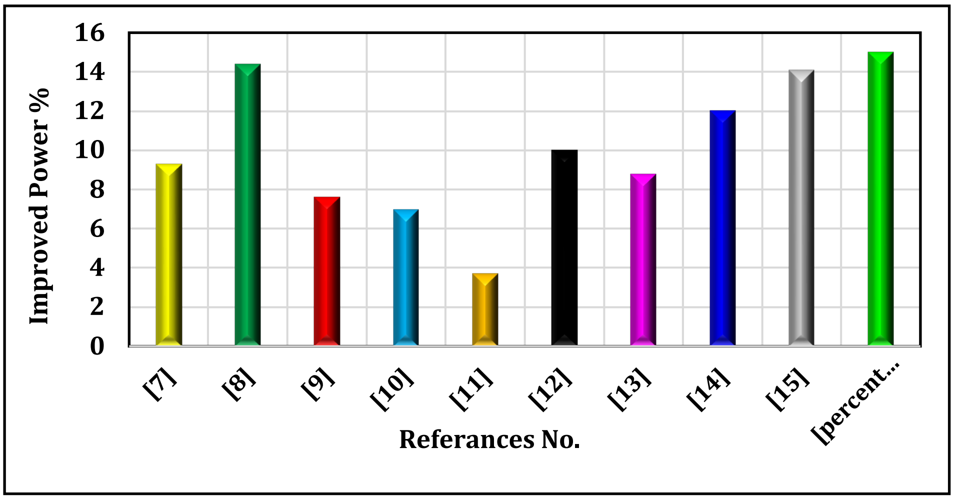


Fig. 15. Comparison Improved Power with some reference

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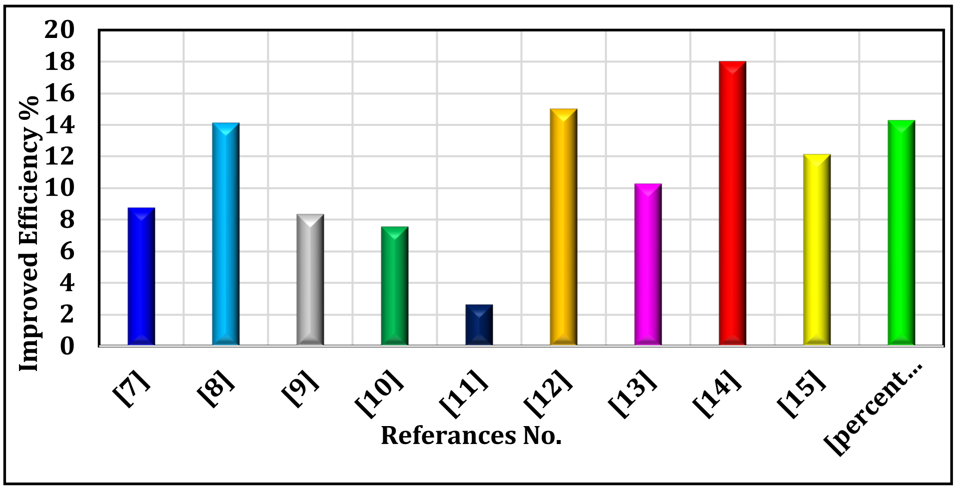

Fig. 16. Comparison Improved Efficiency with some reference

6. Conclusions

Due to the decrease in the efficiency of the solar cells with the increase in temperature due to radiation, Therefore, methods are used to cool these panels, as the cooling of the panels improves the performance of the electrical conversion of cells, and there are several methods for cooling solar cells, and among these methods is the forced-air cooling process adopted by the current study, as the following conclusions were reached:

1. The model describes the relationship between temperature, irradiance, and the power output of a PV cell.
2. Power output and electrical efficiency from the PV plant were also recorded within the period.
3. It is found that maximum output power strongly depends on irradiation. However, the open circuit voltage has a very small increase as the irradiation is varied.
4. The increment in operating temperature of PV panels due to higher solar radiation leads to reduce the electrical power and efficiency
5. Employing the forced-air cooling system reduces the average temperature on the front sides of the PV panel during July by 12%. In addition, the forced-air cooling system enhances noticeably the electrical power output of the PV panel by 13.2%, 15 %, 8.21%,6.6%and 5.5% during June, July, August, September, and October, respectively.
6. The results also found a further improvement in the electrical efficiency of the panels by 11.11%, 14.4%, 9.35%, 7%. and 6.2% during June, July, August, September, and October, respectively.
7. Employing the forced-air cooling system reduces the average temperature on the front sides of the PV panel during July by 12%.

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