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An Electrical, Thermal and Optical Analysis for Photovoltaic Module using MATLAB

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Abstract: Employing renewable energy decreases global warming dramatically. Photovoltaic (PV) electricity is an important renewable energy source for a bright future. Using programming to predict generated power and losses may assist the researcher in improving the response of solar cells. In brief, applying cooling systems with solar cells can play a vital role in enhancing their performance especially in hot locations. This article describes a systematic approach for measuring generated power, the temperature influence on PV electric energy output, and the optical losses. The approach calculation is done by developing a robust simulation model for synchronism with the MATLAB Simulink tool. Furthermore, the system has been validated by experimental and theoretical articles that have been published. Finally, this research compares the benefits of utilizing a cooling strategy for Baghdad city during the summer season.

Keywords: Electrical & Thermal of PV, temperature influence on solar panel, Optical losses, cooling beneficial.

I. Introduction

Developing a renewable energy system is one of the most important tasks nowadays. The importance of generating renewable energy is becoming more prominent globally because of global warming. Solar energy investment greatly contributes to environmental protection [1]. The majority of global energy use comprises electricity consumption by households [2]. Therefore, solar panels for households can significantly reduce the consumption of environmentally hazardous technologies. This sort of energy must be developed and financed to contribute to the transition to clean energy [3]. However, the hot ambient temperature is a key downside of solar panel technology. The ambient temperature considerably affects the generated power of photovoltaic (PV) panels [4]. Consequently, researchers are investigating a variety of solutions to minimize the heat impact on solar panels. For example, one study investigates a procedure that depends on increasing the heat exchange surface of the solar panel by creating fins and using a moist pad cooling technique [5].

Cooling systems are considered one of the main techniques that can be used to support most electrical systems. In fact, the temperature aspect is computed accurately for any device. Cooling systems can be classified mainly into two categories: active and passive. Specifically, the active category involves water and other fluids. This method is applied generally in most solar panels and hybrid PV/T networks [6]. Enasel et al. state that active water cooling is the cheapest method and is very effective. However, it is limited because it requires a continuous power source for cooling the water [7]. Meanwhile, the passive category includes air cooling techniques. They describe that passive cooling methods are less effective because the activity of air is very low compared with water [7]. A cooling strategy can decrease the temperature of a solar cell and improve the output power by approximately 33%. For instance, Abd Al-Qader utilizes an aluminum dispersant to cool the solar panels [8]. The aluminum absorbs the waste heat from the solar cell and then dissipates it into the surrounding air. As a result, the cell temperature drops, and the solar performance improves. Amori and Al-Damook used forced air to cool the PV panels by utilizing an air fan [9]. The forced air contributes to heat exchange with the hot panel surface. Consequently, the cell temperature decreases, resulting in an improvement in the output power of the PV. Abdulmunem examines the effect of Phase Change Material (PCM) in hot climates to mitigate the high temperature of PV cells [10]. The cell temperature significantly decreased from 61°C to 46.2°C. Therefore, the output power and performance of the solar panels have both improved dramatically as a result of this cooling approach. Thermal pipes are used in [11] to absorb waste heat from PVs using circulating water. This strategy leads to a decrease in cell temperature and an increase in the solar panels' output from 8% to 9.8% [11]. Similarly, Kallio and Siroux mention that the gain in generating electrical power of PV reaches about 7.7% in Strasbourg by applying cooling systems for solar panels [12]. It is clear that there are many research efforts to mitigate the impact of high ambient temperature. The major goal of this paper is to propose a mathematical evaluation of PV's electrical, optical, and thermal performance using MATLAB Simulink. This tool conducts systems analysis, modeling, and monitoring in order to mimic reality. Simulation systems result in significant cost, effort, and time savings. This would help scientists and manufacturers investigate the impact of cooling solutions prior to initial deployment.

II. System Description

In this research, a new holistic approach has been built using the MATLAB/Simulink tool to estimate the response of the photovoltaic system through thermal, optical, and electrical aspects to simulate its working under real weather conditions. The Simulink module system uses blocks from the MATLAB library to represent the electrical and thermal components, and the system has been developed with optical calculations. This design helps greatly in estimating natural conditions and heat temperature to achieve accurate results. The Simulink module system consists of two identical solar panels: one with a cooling system and the other without, as shown in Figure 1. The cooling system uses water to cool the back surface of the PV. This system keeps the temperature of the second panel normal compared with the first panel. Specifically, the cooling water flows on the backside of the PV, where a pump is used to pump the water to the solar panel and then its flow continues to a collector tank. The electrical and thermal systems are described in detail below.

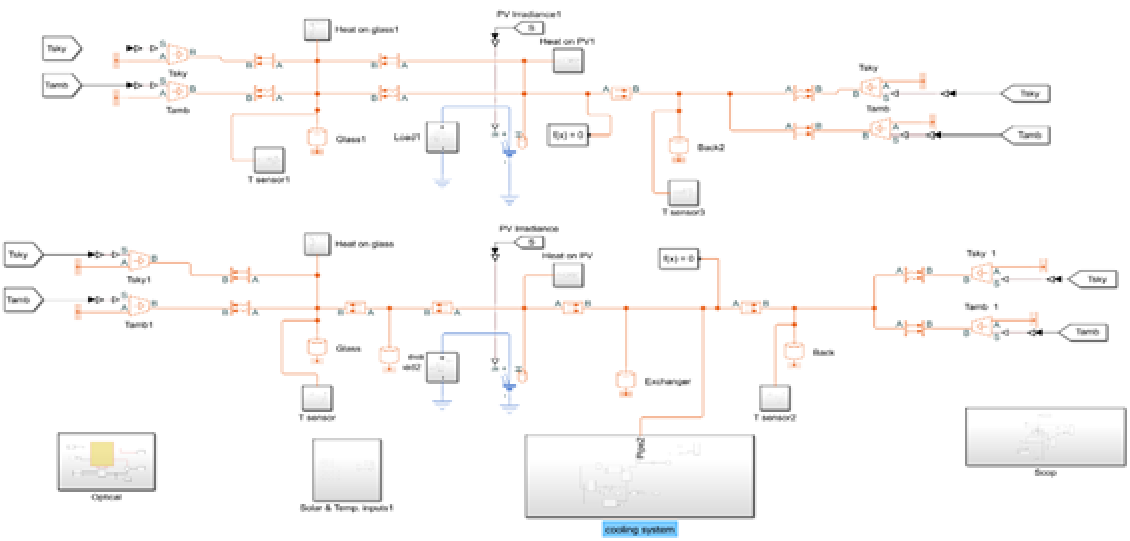

Figure 1 The Simulink configuration of two solar cells with and without cooling system in MATLAB

III. Electrical module

The electrical module has been represented in the Simulink as shown in Figure 2a. The main components of the electrical scheme are solar cells and resistance with measurement sensors. The solar cell has a thermal port that is connected to the thermal system to build one system in Simulink. The equivalent electrical for the solar cell is demonstrated in Figure 2b below.

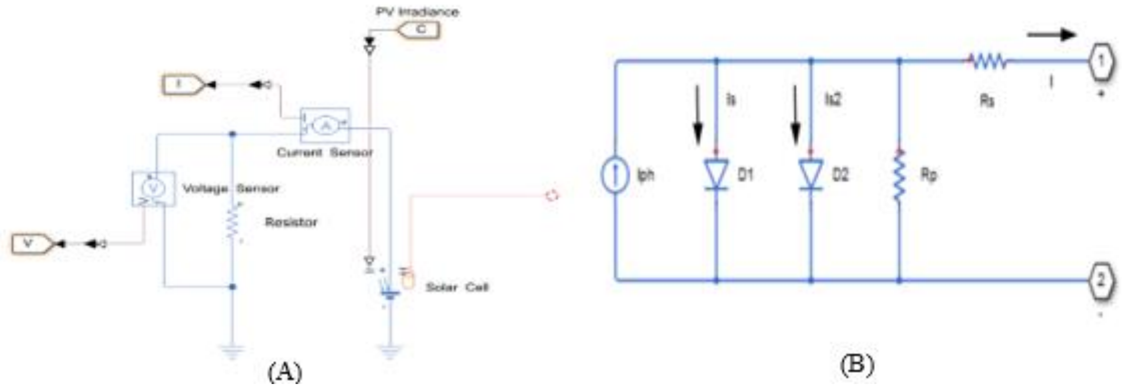

Figure 2 A: The electrical scheme in MATLAB, B: The electrical circuit equivalent of solar cell.

Where the solar current will be calculated according to the following equation [13].

$$I = I_{ph} - I_S * \left(e^{\frac{V+I*Rs}{N*Vt}} - 1\right) - I_S2 * \left(e^{\frac{V+I*Rs}{N2*Vt}} - 1\right) - \frac{V + I * R_S}{R}$$

Where I_{ph} is the sun-induced current, I_{S2}, I_S are the first and second diode saturation current, V_t the thermal power, N the quality factor, V the voltage through the solar cell electric ports. Table 1 illustrates the main values of the photovoltaic module which have been used in the simulation program.

Table 1 Electrical parameter used in the Simulink module [14].

Parameters	Value	Parameters	Value
Type	Monocrystalline	Electrical resistance	8.2
Pmax	240 W	Surface area	1.24 m^2
Is	5.99 A	Solar cell Number	72
Vo	48.7 V	Temperature coefficient	3.5 mA/K

IV. Thermal Module

The suggested methodology comprises of PV module coupled in a single loop to a thermal block to depict heat transmission between different levels of the PV panel and the surrounding environment. As illustrated in Figure 3, thermal blocks are linked by heat transmission blocks that represent radiation, convection, or conduction. The connection permits heat generated in the solar cell to be transferred to other layers, either the rear or front surface of PV, and subsequently to the ambient.

The configuration of Simulink design in MATLAB contains temperature seniors and thermal blocks as well as the ambient temperature blocks.

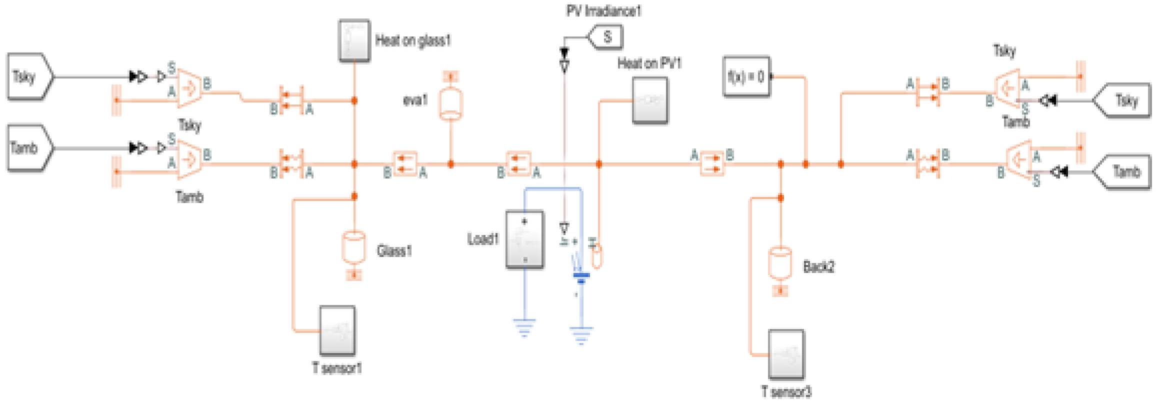

Figure 3 Simulink configuration of thermal module in MATLAB.

Basic thermal performance equations were utilized to represent the photovoltaic panel as a flat plate with numerous layers, every layer has its thermal properties. The heat is transferred between different layers via conduction which is according to the Fourier law governs the transfer, which is given as follows equation:

$$Q = k * \frac{A}{D} * (TA - TB)$$

Where Q represents Heat flow in material layer, k represents Thermal conductivity of a material. While, A represents surface area, and TA, TB are the bodies temperatures and D is the material thickness. Where the external layers of solar panels transfer heat with the surrounding environment via convection and radiation, which are governed by the Newton-Boltzmann law and expressed as equation:

$$Q = k * A * (TA - TB)$$

$$Q = k * A * (TA^4 - TB^4)$$

Where k represents the convection and radiation coefficients, respectively.

When the solar irradiance fallen on the PV glass some of it will be reflected depend on the transmittance of glass, and the rest of light will pass to the next layer which is the EVA finally to the solar cell. Not all the light arrive to the solar cell will convert to electricity. Small proportion will convert to electrical power, and the rest will be changed to heat. Therefore, the temperature of the solar cell will rise and transfer to other layers before reaching the surrounding environment. The amount of solar incident to the solar cell will be calculated after computing the optical losses. Therefore, at each point of the PV module, the energy balance takes into consideration heat radiation and convection losses to surrounding, and the conductivity to different layers as shown in Figure 4.

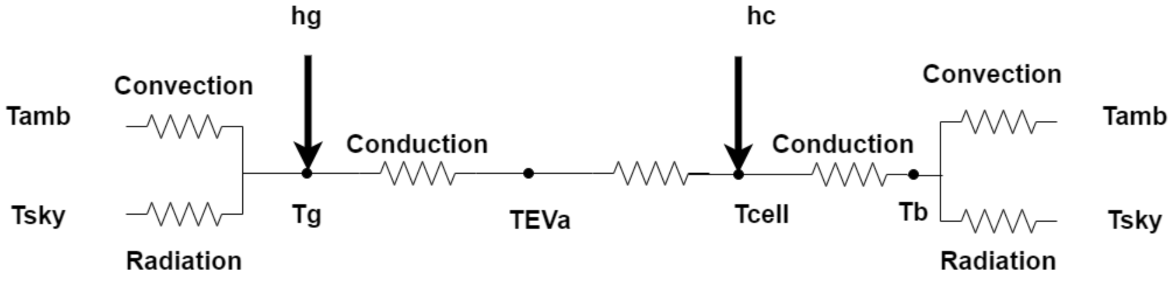

Figure 4 Thermal equivalent of solar penal.

This figure demonstrates how the heat is transferred between different layers. Therefore, the energy balance equation will be:

$$Qcell = Qback + 2 * (Qcov + Qrad)\ Amb + QEVA + Qglass$$

Where the Qcell represents the absorb heat by solar cell due to the solar incident, Qback, QEva, and Qglass represent the heat conduction between the solar cell and other layers of solar panel. While, the Qcov, cand Qrad are the heat convection and radiation between the front and back surface and surrounding ambient.

However, when the system is considering the cooling techniques the equivalent thermal network will be as demonstrated in Figure 5.

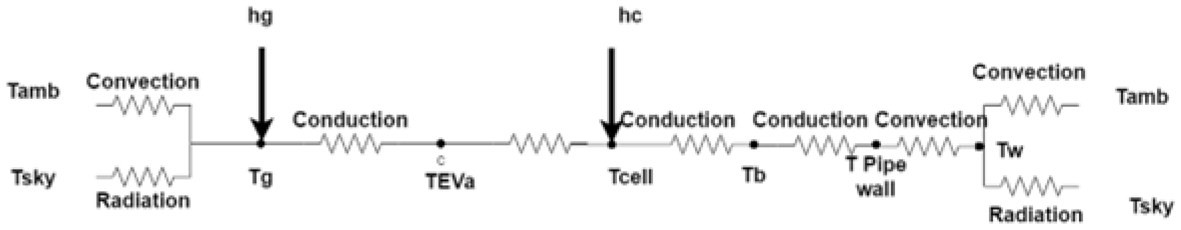

Figure 5 Thermal equivalent of solar penal with cooling technique.

The energy balance becomes

$$Qcell = Qback + 2 * (Qcov + Qrad)\ Amb + QEVA + Qglass + Qpipe + Qwater$$

The difference with other panel, without cooling, is the heat flow from the back surface to the pipe then from the pipe wall to the water to absorb the unwanted heat.

$$Qpipe = \frac{KAP}{D} * (TH - T)$$

$$Qwater = m * cp(TH - Tin)$$

Where k represents thermal conductivity of the thermal liquid in the pipe. A is the surface area of the pipe wall, D is the hydraulic diameter, TH is the temperature at the pipe wall. Table 2 below has the thermal parameters which have been used in the simulation.

Table 2 The module parameters value used in the Simulink [14].

Parameters	Value
Glass thickness	3 mm
glass thermal conductivity	1 W/m K
glass transmissivity	95%
solar cell absorptivity	85%
Solar cell thermal conductivity	0.036 W/m K
The insulation thickness	50 mm
The insulation thermal conductivity	m K

V. OPTICAL MODULE

Since most solar panels consist of multilayers such as glass, EVA, and the solar cell. The light needs to pass through these different layers. Not all the sunlight arrives at the solar cell surface, transmits through the glass panel, and reaches the cell (Sarkın, Ekren, and Sağlam 2020). As shown in Figure 1, the fallen radiation on a solar panel is divided into three parts some of it will be reflected, absorbed, and transmitted (Goswami 2013).

Mathematical approach was developed using the MATLAB/Simulink tool to predict optical losses and waste heat generated and developed other system. The calculation depends on the analyze the fallen solar irradiance on the solar panel's surface and calculate the losses power.

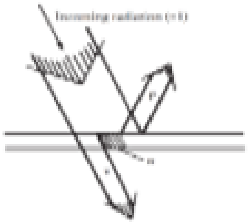

Figure 6the fallen radiation on solar panels.

VI. Proposed System Validation

To validate the suggested method, the outcome was compared to an experimental published paper result in which two identical PV modules were simulated in terms of electrical and thermal behavior. To mimic the experimental characteristics, multiple sun irradiances and ambient temperatures were applied to this PV model for simulation acquisitions. As shown in Figure 5, the simulation results demonstrate a good agreement between the PV power output obtained by simulation and the results of the PV output power in addition to the absorb heat via cooling water compared with the experiment published in the Reference [14].

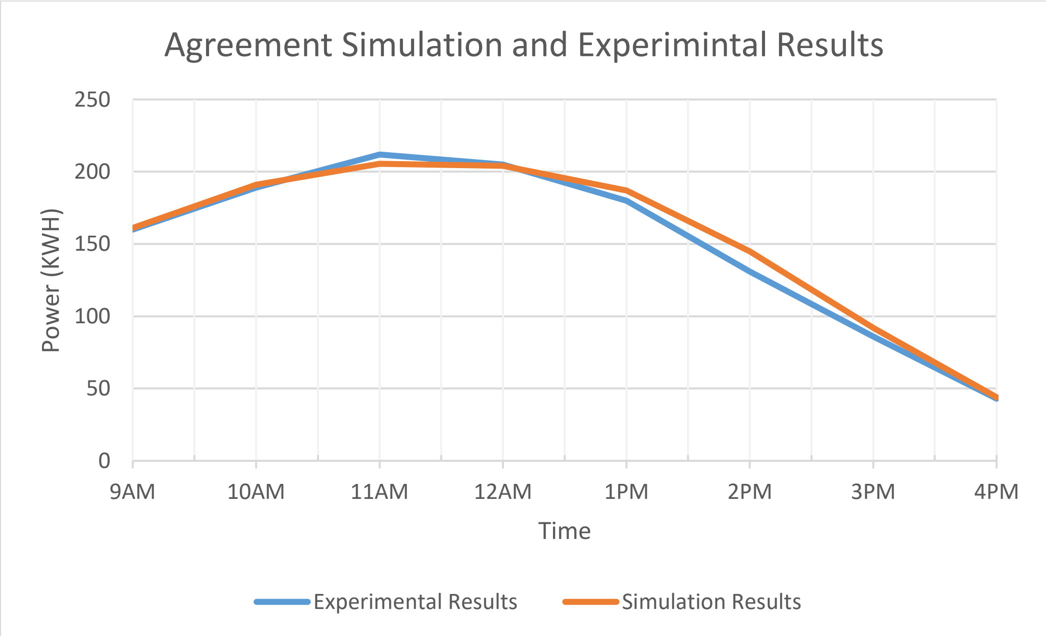

Figure 2 PV power output from the proposed method and Reference [14] during the experimental day.

In addition, a statistical analysis is used to handle a comprehensive validation by calculating the root mean percent deviation square (e) and linear correlation coefficient (r) [15].

$$e = \sqrt{\frac{\sum (e_i)^2}{N}}$$

$$\text{where } e_i = \frac{X_i - Y_i}{X_i} \times 100$$

$$r = \frac{N(\sum X.Y) - (\sum X).(\sum Y)}{\sqrt{N\left(\sum Y^2\right) - (\sum Y)^2}.\sqrt{N\left(\sum X^2\right) - (\sum X)^2}}$$

Table 3 illustrates the comparison between the theoretical analyses of reference [14] and the Simulink outcomes. The root mean square (e) as well as the correlation coefficients (r) for Simulink model showed better results than the theoretical results which are done by the same reference.

Table 3 The comparison of proposed system with theoretical and experimental of reference [14].

Parameter	**[14] e (%)**	**Present model e (%)**	**[14] r**	**Present model r**
T front	5.43	4.56	0.98	0.995
T back	7.4	4.73	0.98	0.98
P	4.1	1.57	0.99	0.98
Q water	6.1	6.54	0.98	0.99

It is clearing that the efficacy of the proposed technique. Utilizing this technique will help to evaluate the performance of a solar cell in a real-life scenario and thus, this will minimize the design costs.

VII. Optical Losses

There are many researches for all types of PV panels demonstrate that using cooling systems with solar cells improve the efficiency and enhance thermal performance of these panels [16]. Therefore, one solar cell with electric and thermal components was used to implement the research technique. It has been considering the standard laboratory condition with constant irradiance 1000 kW/m2 and 25C ambient temperature for a solar panel to implement the research technique. The simulation runs for 8 hours to calculate the one-day behavior of PV performance. Figure 2 illustrates the generated and losses power.

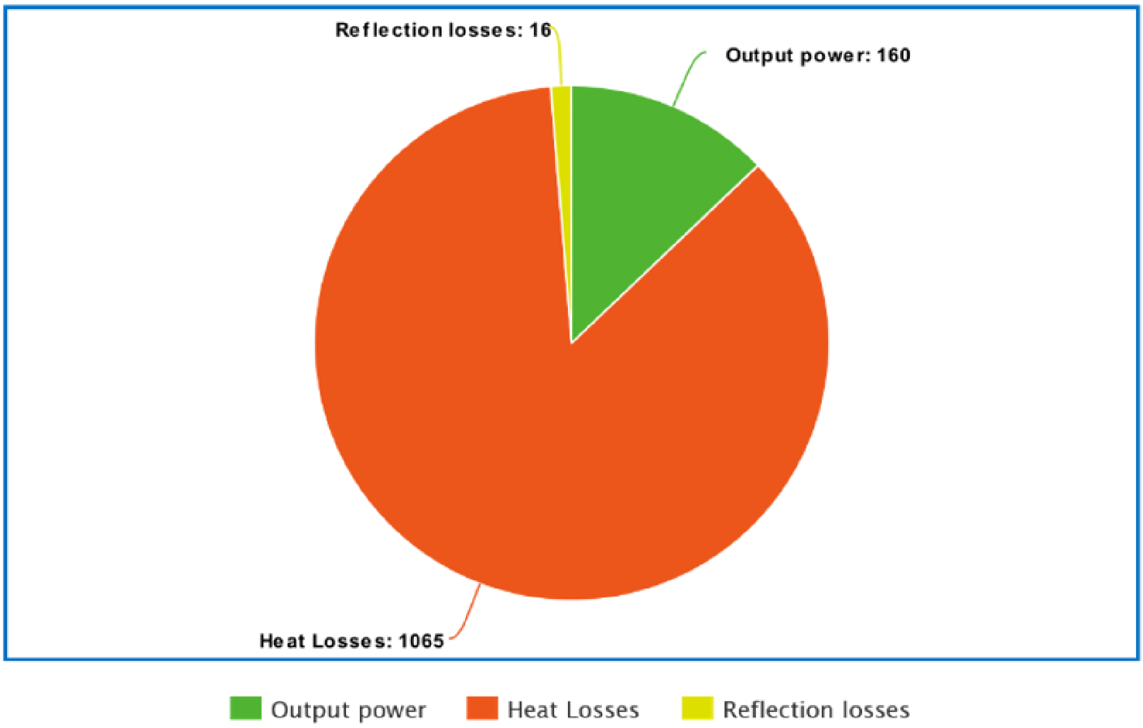

Figure 8 generated and losses power results from Simulink.

The results show significant losses due to heat losses. In addition, the optical losses comparing to the output power is approximately 10% which is not a low amount. Also, after one hour of simulation running the output power of solar cells has decreased because of increasing cell temperature. Approximately 22% of the power output has decreased since the absorb heat increasing. This will indicate for the researcher to estimate the main losses that could impact significantly the solar penal energy.

VIII. Case Study

After validating the system, the proposed framework investigates the benefits of cooling technology in Baghdad, capital of Iraq. This city is known for its semi-arid climate and hot summers as shown in figure below. The study examines the performance of solar cells as well as the cooling system's capability for one year.

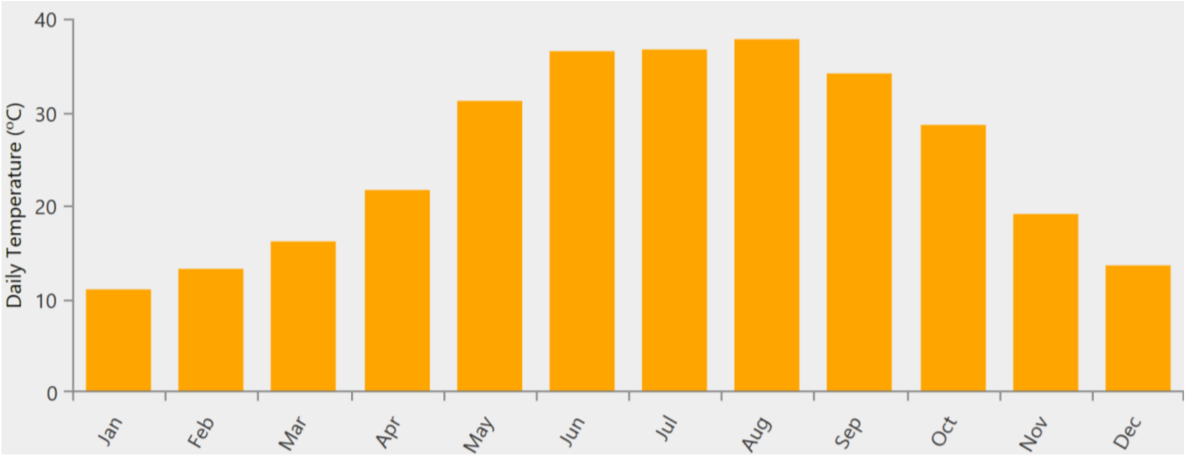

Figure 3 Average daily temperature in Baghdad city

The graphs below show the monthly power output of solar panels with and without cooling. The figure shows clearly the advantages of using a cooling approach in the summer to increase electrical power while keeping the solar cell temperature at a satisfactory limit. The annual increase for a 240w panel is 115.2 kWh, which is approximately 5.2 percent higher than the panel without cooling. During the winter, however, the output power of the panel with the cooling system was equivalent to that of the panel without the cooling system.

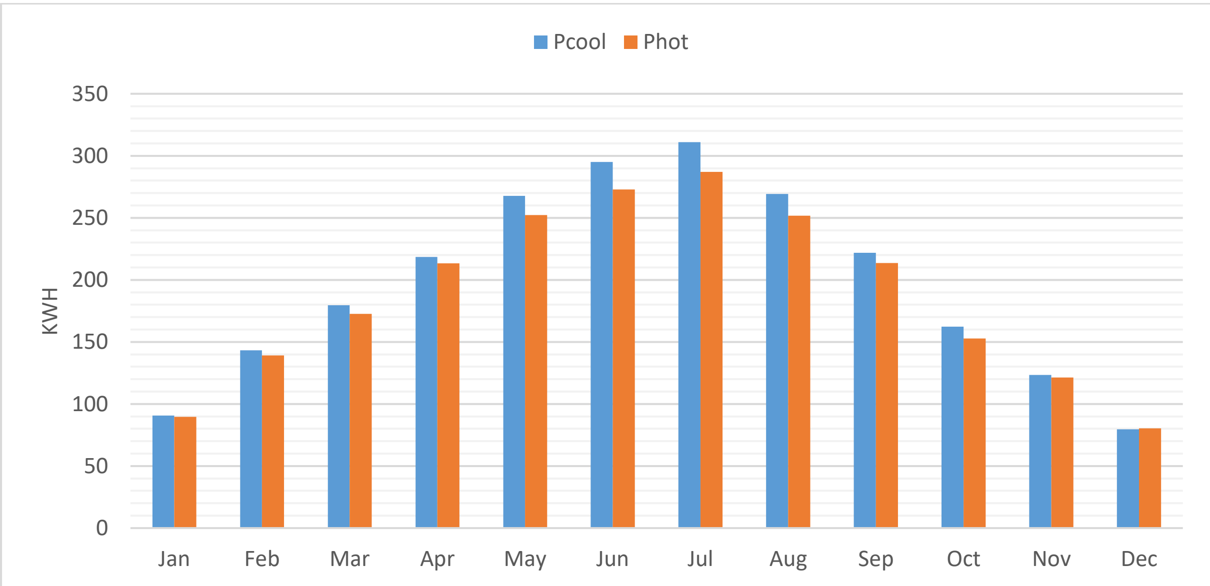

Figure 4 The monthly power output of solar with and without cooling.

IX. Conclusion

The temperature of panels is affecting badly on their generated power. This is because producing photons is proportional Directly with panels temperature and this increases saturation current largely [17]. In fact, Lakshmi and et al. state that increasing one degree in the temperature of panels reduces observed voltage of these panels by 2.2 mv [17]. Furthermore, Mosalam et al. state that the efficiency of solar panels can be increased from 26 % to 37 % with copper-tubes cooling system [18]. Therefore, the fundamental goal of this study is to present mathematical evaluations of PV's electrical and thermal performance using MATLAB Simulink, where it conducts systems analysis, modeling, and monitoring to replicate reality. The study emphasizes the advantages of is using a well-built Simulink in MATLAB to model and simulate reality. The thermo-electrical system was created to mimic the scenario. The model has been validated using previously published results. The system produced a considerable realistic result with a minor deviation error for output power, thermal absorbed power by cooling water, front and rear surface temperature, which were 1.57 %, 6.1, 4.56 %, and 4.73 %, respectively. The built-in system significantly evaluates the thermal, optical, and electrical performance of solar panels. In addition, it has been calculating the benefits of utilizing cooling technique in a hot weather environment. The cooling modifications increase the solar performance by 5.2%. Therefore, the proposed system will assist in lowering the prices, effort, and time required to make any adjustments.

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