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Research Article

Temperature effect in the energy degradation of photovoltaic power system

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ABSTRACT

The modelling of output power for the photovoltaic system is essential for system design and local resource prediction. Accurate photovoltaic power modelling the foremost vital issue is systems efficiency analysis. The temperature plays the main role in the energy degradation of the photovoltaic systems, especially in the host sites. In this paper, experimental and theoretical investigation into the photovoltaic module energy degradation due to temperature effects. This work objectives to investigate the photovoltaic power generated due to the ambient temperature effect. The presented results show that the ambient temperature has positive effects on the photovoltaic module energy production during the winter period and negative effects during the summer period. For the proposed photovoltaic system with a capacity of 2.97 kWp the expected theoretical annual energy production by about 554.01 kWh while the annual experiment production was l493.73 kWh. The novelty of the work is to estimate the energy losses due to the ambient temperature effect on the photovoltaic energy production.

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INTRODUCTION

The growing demand for electrical energy leads us to search for an alternative energy resource. Solar energy, considered as direct energy from the Sun, is one of the most considerable exploitable renewable energy resources. Globally, the annual energy consumption is possibly created by the sun in approximately an hour [1]. Solar energy is available for free on any site on the earth as well as clean, sustainable and renewable. Yet, many places still struggle worldwide to meet their energy needs. The PV module could harness and convert energy from the sun into electricity [2-4]. Meanwhile, PV systems are not sufficient enough to achieve what is required, because of the influence of many environmental and climatic factors, such as air temperature and pollution, wind speed, and incident irradiation angel. In addition, other factors are the solar radiation spectrum, snow and shadows. So researchers and scholars are still struggling to increase the efficiency of PV cells [5-7]. Typically, all types of PV cells are made to work under standard test conditions (STCs) (solar radiation of

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1000 W/m^2, wind speed of 1 m/s, cell temperature of 25 °C and air mass of 1.5). The PV operating conditions are different from standard test conditions and vary in different zones. High ambient and cell temperatures more STC considered critical to the reliability of the PV module performance. The efficiency of the PV cell depends on the cell type and operating temperature as follows: Polycrystalline silicon (16.0-17.0%), Monocrystalline silicon (20.0%) and thin-film amorphous silicon (7.0%) [8]. There is a positive relationship between the photovoltaic temperature and the current increase and a negative correlation between the voltage and the final effective electrical power [9].

In previous studies, several articles have investigated the influence of PV system performance on cell temperature. Also, there are several correlations have been developed for the production of cell temperature based on environmental and climate parameters. The most explicit and implicit correlations for predicting PV cell/module temperature were reviewed by Skoplaki and Palyvos [10]. Another review of the PV energy production and temperature effects for diffident sites has been prepared by Dubey et al. [11]. Based on the energy balance equations, Hassan [12] have prepared a module for predicting the cell temperature by using experimental measurement. Their results show that the yearly energy waste because of temperature impacts about 23% for a 1 kW PV system. Five linear and nonlinear modules for predicting PV module temperature were tested by Pantic et al. [13]. The work was done based on experimental measurements using a monocrystalline silicon module under moderate-continental climate conditions. Their results showed that nonlinear models have better accuracy than linear models for the prediction of the module temperature at various environmental conditions. Santiago et al. [14] used twenty models to predict the PV cell temperature, and the module output power with temperature effect and module efficiency. The selected models have different complicity from the point of relationship between PV cell temperature and environmental factors. The results showed all models have better predictability during the summer months than in winter for stability of solar radiation and ambient temperatures. It also shows similar results for the module's output power. The linear models showed better fits with the experimental measurements at the lower solar radiation intensity and the module efficiency. The linear models confirmed the experimentally supplied data. Jaszczur et al conducted a PV model comprehensive analysis by using in-situ experimental calculations and computer simulation to model airflow and heat transfer of the model PV through a 3-dimensional simulation to determine the rate of heat dissipation and the model temperature [15-17]. The results concluded the development of a new model with high complicity, such as the environmental aspects, the ambient temperature, the incident solar and wind speed, and the Ross coefficient for prediction of PV module temperature. Garcı´a et al. [18] examined photovoltaic performance and temperature in "Nominal Operation Cell Temperature" NOCT technology for various directions and a variety of photovoltaic module tilted angles. In addition, Mattei et al. [19] investigated the temperature and electrical efficiency of the polycrystalline PV module through NOCT technology, energy balance and a variety of heat transfer correlations. In this work, the best model is the energy balance using the solar transmittance and absorption coefficient at 0.81 as Ju et al. showed [20]. They improved a method for estimating the temperature of solar cells that could work under high concentration conditions if the solar cell temperature ranges between 10–120^{o}C. The finding showed that the improved model could be used in a variety of operating conditions. Armstrong and Hurley tested the thermal behaviour of the photovoltaic module at various wind speeds [21]. They showed a parasite variation in the convective and radiative heat waste in the module at various speeds of wind. Siddiqui et al. [22] studied three-dimensional numerical models which were capable of predicting the thermal and electrical performance of the photovoltaic module for various conditions of the environment and operation. There were efficiency between 8.47% and 10.5%, with about a linear growth in producing energy. Kaplani and Kaplanis [23] analysed the photovoltaic module wind incident angle and accurately evaluated the wind velocity. It also asseded stream incidence angle on the front and back of the photovoltaic module. In addition, there is a positive correlation between the photovoltaic temperature slightly with the wind incidence angle. This happens in particular at high wind velocities. Styszko et al. [24] examined the impact of the chemical composition of the dust particles on the PV module temperature and performance.

Many investigations have been conducted by Jaszczur et al. [25-28] to evaluate the efficacy degradation of polycrystalline PV modules due to temperature and natural dust deposition. Their results abstracted a new mathematical correlation consisting of four variables for predicting module temperature. Ceran et al. [29] framed a hybrid power system on the basis of a PV array in a handhold application. The results illustrated that the ambient temperature participated in increasing the PV array power production in cold periods and degreasing the power production in hot periods.

Palej et al. [30] analysed and optimised hybrid power systems consisting of PV modules and turbines of wind with grid connection for single household application. Based on results, the efficiency of PV modules is lost slowly when the module temperature rises. The study of PV cell characteristics is essential for understanding how solar cell functions and respond to various factors. Sharma and Goyal [31] examined the influence of temperature and solar insolation on the characteristics of PV cells. Analysing the effects of solar insolation and temperature on PV cell characteristics. The authors used mathematical modelling and fabrication for a single diode solar cell model. The results displayed that the influence of the cell temperature and solar irradiance changes on electrical parameters: short-circuit current, Fill-Factor, open-circuit voltage, and conversion efficiency has been degraded by increasing cell temperature higher than 25 °C for monocrystalline silicon. Shi et al. [32] investigated the stability of grid-connected PV system at cell temperature and solar irradiance variation. The study targeted to obtain the relationship between cell temperature, solar irradiance and system operating points. The authors built a small signal multivariable model combining cell temperature and solar irradiance as variables. The obtained results illustrated stability of PV power delivered to the grid has high influenced by PV cell temperature. Which, due to the system operating point changes often, it's difficult to characterize the system performance using a traditional equivalent circuit paradigm. The authors resolve this concern, by presents a multivariable small-signal admittance model for PV generation that incorporates solar irradiance into the standard PV generator admittance model. Ouédraogo et al. [33] indicated that the effect of the PV cell temperature dependence of individual energetic process efficiencies (Thermalization efficiency, Absorption efficiency, Fill factor, and Thermodynamic performance) as well as average conversion efficiencies of a polycrystalline silicon solar cell over a range of temperature of 10–50 °C. All of these specific efficiencies show a reduction as the cell temperature rises. The PV cell thermodynamic performance and fill factor,are more susceptible to temperature increases than thermalization efficiencies and absorption.

In this work, the PV module temperature was investigated by using experimental and numerical simulation to analyse the environmental temperature impact on the PV module efficiency and producing energy. The analysis was performed under local measurement of weather conditions and confirmed by the measurement of in-situ on the study photovoltaic system.

EXPERIMENTAL SET-UP AND NUMERICAL MODEL

The experimental calculations were performed by polycrystalline DAH Solar Module 330W PV module (60,6*10)

Figure 1. Temperature experimental measurements for the PV system connecting with inverter.

$$\theta_z = \cos^{-1}(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta)$$

Table 1. Specifications of PV moduel and solar inverter

PV module [34]	
Type	DAH
Max. power P_{max}	330 W
Tolerance	±5
Voltage at P_{max}	31.6 V
Current at P_{max}	10.92A
Open circuit voltage	38.3V
Short circuit current	11.72A
Operating temperature (*Tc*)	-40 to +85 C°
Temperature coefficient of power (α*p*)	-0.41 % / C°
Module efficient	19.7 %
Solar Inverter [35]	
Type	REVO E 5.5 kw
Rated power	500 W
DC input	48 VDC, 120A
Power Facter	1
AC Output	230V,50Hz,24A,1Phase
Charger AC Input	230V,50Hz,37A,1Phase
DC Output	54VDC,Max. 60A,Defu

with a panel size of (2.97 kW). The cell (power temperature coefficient -0.41 %/°C, cell temperature of nominal operation 49 °C and efficacy at standard experiment condition 19 %). The modules are orientated at a tilt angle β = °30 and an azimuth γ = °0 west. There are two thermocouples that have been connected to the backside of the module number (1) and connected to the data logger. The data is recorded every 5 minutes at resolution for the PV solar system, A hybrid inverter type REVO has been used. The specifications of the PV modules and inverter are described in Table 1. Figure 1 show the PV array, inverter and the energy flow throu the system.

The weather data includes incident solar radiation on the horizontal plane along with the wind speed. This is in addition to the ambient temperature for Baqubah, Diyala with latitude and longitude of 33.7733° N and 45.1495° E, respectively, for the whole year starting 01 January to 31 December 2018 as presented in Figures 2 (a)-(d). Figures 2 (a) and (c) show the monthly average and daily (for two days) solar radiation respectively, and figures 2 (b) and (c) show the monthly average and daily (for two days) ambient temperature respectively.

The preposed PV system set with the grid , which installed to feed houshold by electricity Figures 3 (a) and (b) shows the daily energy cosnumbtion for two selected day April 18, and June 08 of the year 2018, were the daily avarge energy consumbtion recorded by aobut 5.3 kWh/day.

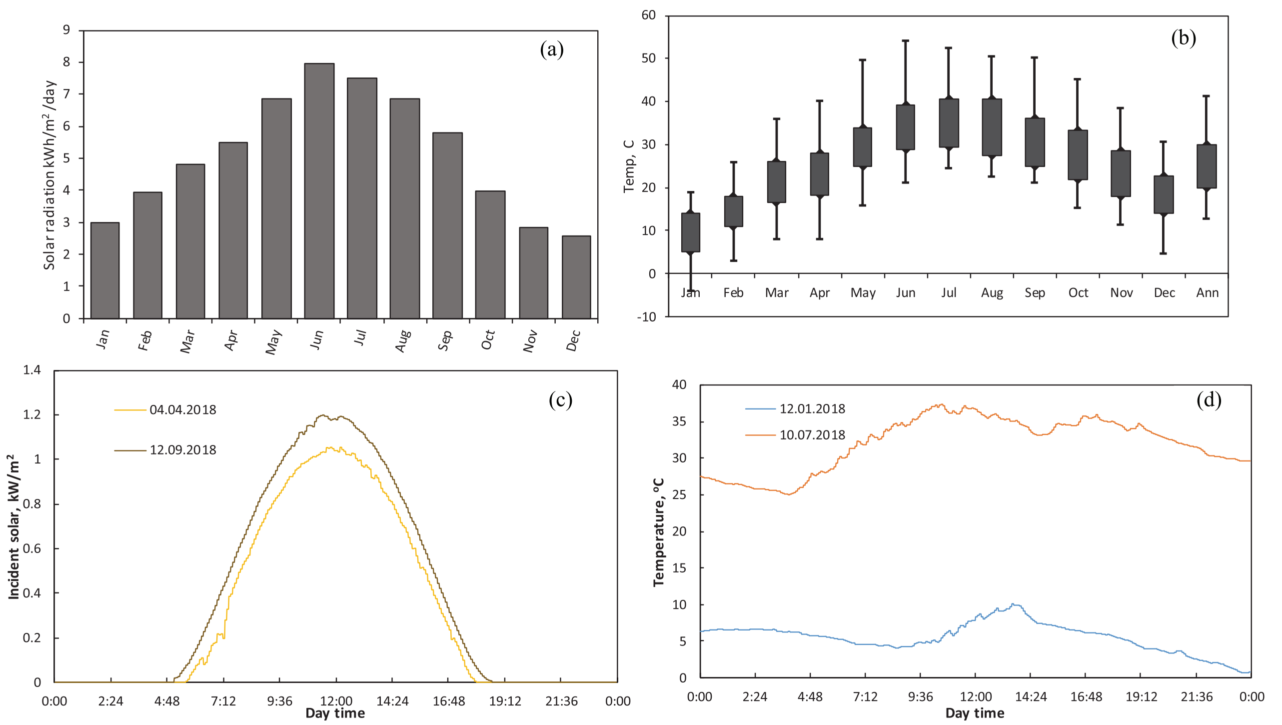

Figure 2. monthly average and daily solar radiation (a) and (c) respectively, monthly average and daily ambient temperature (b) and (d) repeatedly.

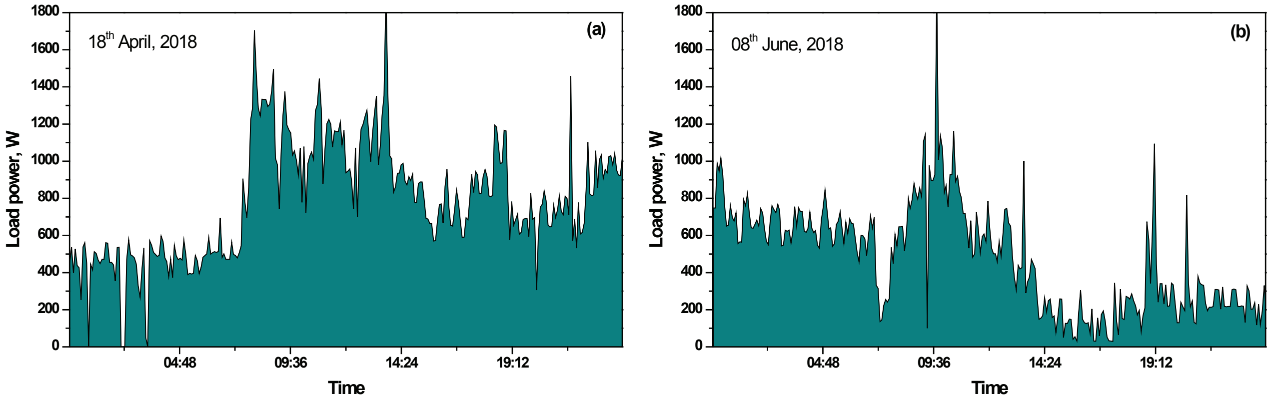

Figure 3. The measured electrical laod for two selected days.

SYSTEM MODELLING AND GOVERNING EQUATIONS

In this investigation, a model for estimation of power generated by the PV model has been presented in this section, where the model is presented for each timestep computing value as written below:

The day time affects the sun's location in the sky is expressed as [36,37]:

$$\omega = (t_s - 12hr).15^\circ / hr \tag{1}$$

where ω is the solar angle (dgree), t_s stands for solar time measurement of civil time:

$$t_s = t_r + \frac{\lambda}{15^\circ / hr} - Z_c + E \tag{2}$$

where t_r represents the local time (in hours), the longitude in degrees, and the time zone are λ *and* Zc respectively. The time unit is hours east of GMT and E stands for the equation of this time.

The time equation is as follows[38,39]:

$$E = 3.82 \begin{pmatrix} 0.000075 + 0.001868 \cos B - 0.032077 \sin B \\ -0.014615 \cos 2B - 0.04089 \sin 2B \end{pmatrix} \tag{3}$$

Here B is:

$$B = 360 \frac{(n - 1)}{365.2425} \tag{4}$$

n is the number day of the year.

The extraterrestrial normal radiation G_{on} (W/m^2) can be given by [40,41] and expressed as:

$$G_{on} = G_{on} \left(1 + 0.033412 \ \cos \frac{360\ n}{365}\right) \tag{5}$$

where G_{sc} is the solar constant 1367 W/m^2.

The extraterrestrial radiation on the horizontal plane G_o (W/m^2) striking the top of the atmosphere [42] can be expressed as:

$$G_o = G_{on} \cos\theta_Z \tag{6}$$

where θ_z is the zenith angle in degree can be written as:

$$\theta_Z = \cos^{-1}(\cos\varphi \cos\ \delta \cos\ \omega + \sin\varphi \sin\delta) \tag{7}$$

[where ϕ and δ are the latitude and the solar solar declination, respectively, in relation to the equator plane written by Cooper (1669) [43]:

$$\delta = 23.45^\circ \sin\left(360^\circ \frac{284 + n}{365}\right) \tag{8}$$

The average extraterrestrial horizontal radiation G_o (W/m^2) can be expressed as:

$$G_o = \frac{12}{\pi} G_{on} \left[\cos\varphi \cos\delta\left(\sin\omega_2 - \sin\omega_1\right) + \frac{\pi\left(\omega_2 - \omega_1\right)}{180^\circ} \sin\varphi \sin\delta\right] \tag{9}$$

The period mediating ω_1 and ω_2 , which are both hour angles, is an hour and ω_2 is the bigger.

The atmosphere and the clouds could attentunate the sun's solar radiation prior to its arrival on the earth. The earth's surface global horizontal radiation ratio, which is G, to the horizontal extraterrestrial radiation, which stands for clearness index k_T as:

$$k_T = \frac{G}{G_o} \tag{10}$$

where G is averaged over the time step (W/m^2) and G_o is the extraterrestrial horizontal radiation, which is an average over the time step (W/m^2).

The total horizontal radiation consists of two main parts. Direct radiation and diffuse radiation are G_b (W/m^2) and G_d (W/m^2) respectively. The latter comes from all parts of the sky with no shadow to make three elements. The first is isotropic. The second is circumsolar and the third is horizon brightening. The beam and diffuse radiation sum is global solar radiation G (W/m^2) [44] as:

$$G = G_b + G_d \qquad (11)$$

In most cases, they measure only the total solar radiation, neither direct nor diffuse components. The correlation [45] provides a diffuse fraction as a function of the clearness index in this expression:

$$\frac{G_d}{G} = \begin{cases} 1.0 - 0.09k_T & for \quad k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & for\ 0.22 < k_T \le 0.80 \\ 0.165 & for \quad k_T \le 0.80 \end{cases} \qquad (12)$$

In the clear sky at high sun position, the direct radiation is about 85% of the whole radiation hitting the ground with a diffuse radiation (15%) that keeps rising until it reaches 40% while the sun is 10° above the horizon [56].

The PV array surface total radiation is made up of diffuse, beam, and reflected radiation. Here, the former consists of isotropic, brightening of the horizon and circumsolar. The reflected radiation comes from the surrounding ground. There are different models to evaluate the estimation of the PV array's total solar radiation. This work uses the Hay and Davies, Klucher and Reindl (HDKR) model to consider the beam and all diffuse radiation G_T (W/m²) [46]:

$$G_T = \left(G_b + G_d A_i\right) R_b + G_d \left(1 - A_i\right) \left(\frac{1 + \cos\beta}{2}\right) \left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right] + \left(G\rho \ \frac{1 - \cos\beta}{2}\right) \qquad (13)$$

where β and f are the PV array surface slope in degree and the horizon brightening factor respectivly :

$$f = \sqrt{\frac{G_b}{G}}, \quad A_i = \frac{G_b}{G_o}, \quad R_b = \frac{\cos\theta}{\cos\theta_Z} \qquad (14)$$

where A_i and R_b stand for the anisotropy index and the beam radiation ratio on the tilted surface to beam radiation on the horizontal respectively. In addition, θ is the incidence angle in the middle of the surface beam radiation and the normal surface:

$$\begin{aligned} \cos\theta = {} & \sin\delta \sin\varphi \cos\beta - \sin\delta \cos\varphi \sin\beta \cos\gamma \\ & + \cos\delta \cos\varphi \cos\beta \cos\omega + \cos\delta \sin\varphi \sin\beta \cos\gamma \cos\omega \\ & + \cos\delta \sin\beta \sin\gamma \sin\omega \end{aligned} \qquad (15)$$

where γ and ρ are the surface azimuth angle, is the ground reflectance (%).

The PV array output power depends on the total solar radiation (beam, diffusive, and reflected) incident on the PV array surface, generally not horizontal. In each time step, the model should measure the global solar radiation on the PV array outer layer [47]. The PV array output power P_{PV} (W) can be calculated according to the following:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) \left[1 + \alpha_P \left(T_c - T_{c,STC}\right)\right] \qquad (16)$$

where Y_{PV} and f_{PV} are the rated capacity of the PV array (W) and the PV derating issue (%) respectively for the accounting factors that impact the PV array, such as soiling of the panels, wiring waste, shading, cover of snow, and ageing. Also, $G_{T,\ STC}$ and α_p are the incident solar radiation at STC (1000 W/m²) and the temperature coefficient of power (%/°C) repetivey, while T_c stands for the PV cell temperature (°C). $T_{c,\ STC}$ represents the PV cell temperature under STC (25 °C).

RESULTS AND DISCUSSION

This work is done based on experimental and simulation processes based on weather data, incident solar radiation, and ambient temperature. The work includes two main parts: The first one demonstrated the power degradation for a single module because of the PV cell temperature influence, and the second part shows the experiment energy generated for the whole energy system. The incident solar radiation and ambient temperature are in Figure 2 and the mathematical model is illustrated in equations (1-16). Figures 4 (a) and (b) shows the daily energy generated by

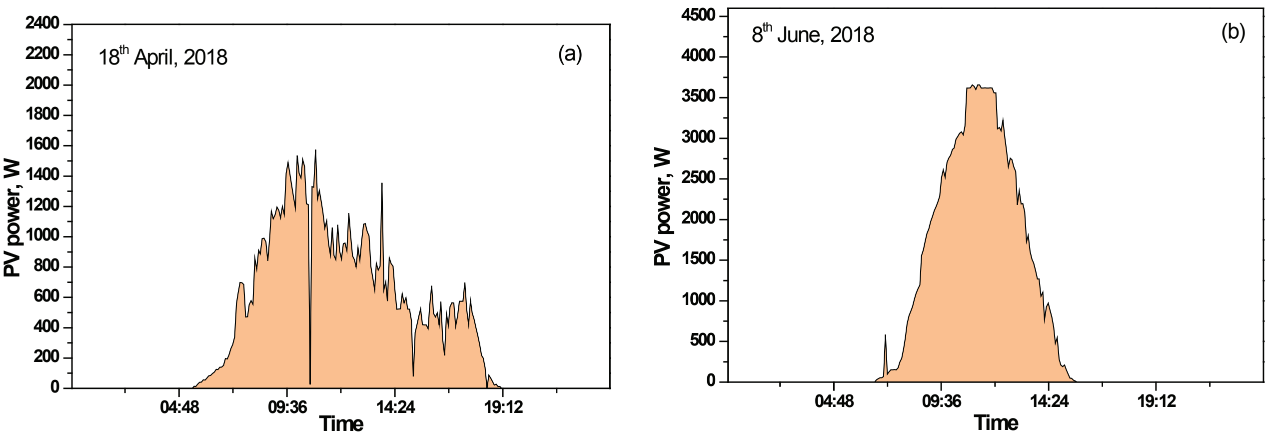

Figure 4. The PV power generated for two selected days.

PV system for t two selected days partly cloudy (April 18), and sunny (June 08) of the year 2018, were the daily avarge energy production recorded by aobut 2.7 kWh/day.

Figures 5 (a) and (d) show the module temperature and ambient temperature with incident solar radiation for two days (sunny day 04.05.2018 in (a) and partly cloudy day 15.03.2018 in (c)), where the power generated on the same days is shown in figures (b) and (d) respectively. The night period and the PV module temperature are similar to the ambient temperature, while in the day time the module temperature is recorded higher than the ambient temperature due to the accumulative heat from incident solar radiation and the ambient temperature.

The daily theoretical and experimental energy generated from the single PV module for the same days (sunny day 04.05.2018 (Figures 6a) and partly cloudy day 15.03.2018 (Figures 6a) with the energy wasted because of the temperature of the module. On the sunny day, the theoretical calculation for the single module was about 2.301 kWh, while the experiments generated 2.043 kWh. The

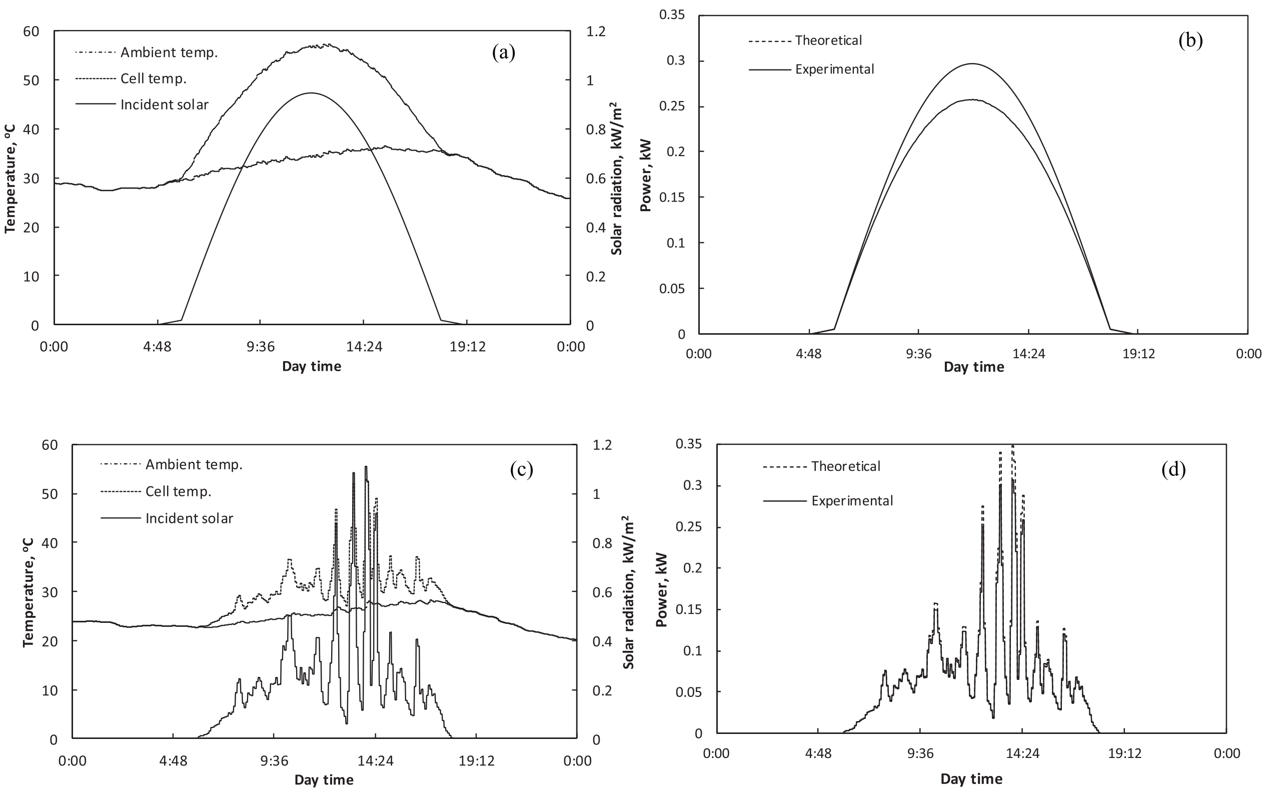

Figure 5. The PV module temperature and experimental with the theoretical energy distribution in a sunny and a partly cloudy.

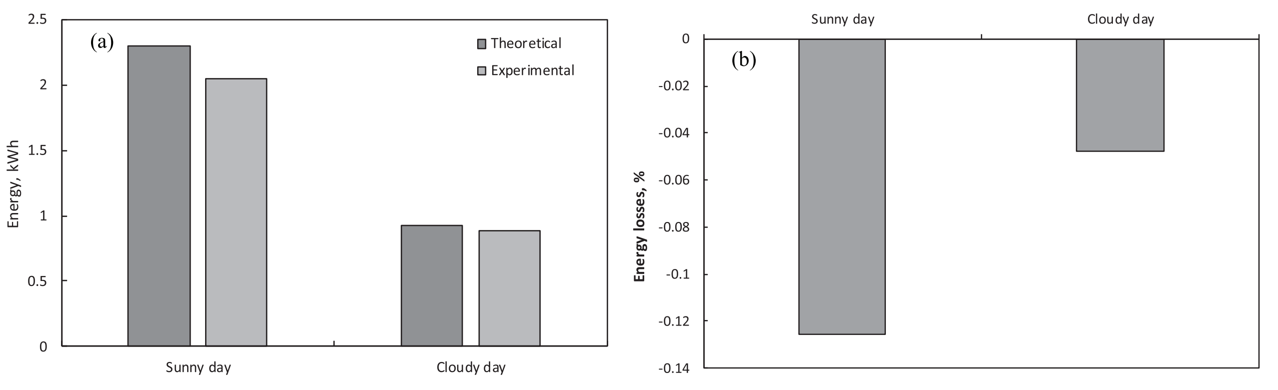

Figure 6. The theoretical and experimental energy production for a single PV module in (a), the energy losses percentage due to the module temperature in (b).

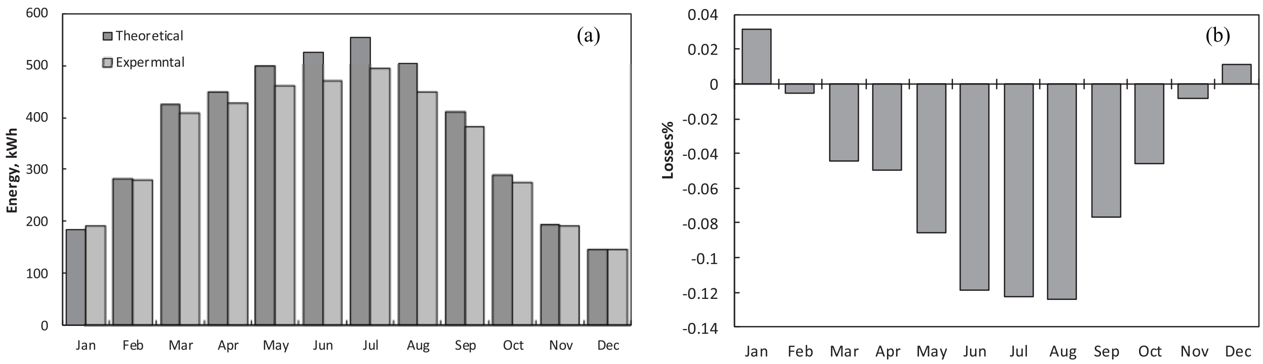

Figure 7. The theoretical and experimental generation of the energy for the PV system, the system energy losses percentage due to temperature in (b).

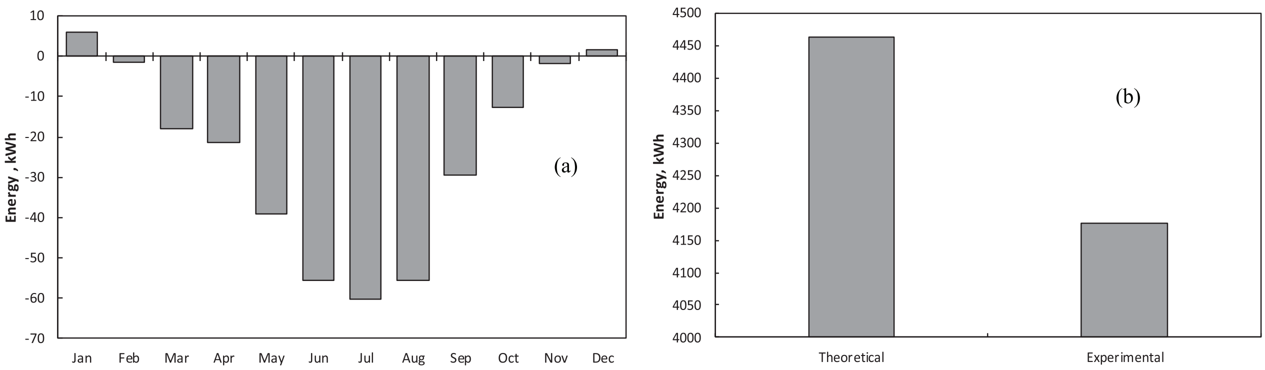

Figure 8. The monthly and yearly energy losses in (a) and (b) respectively.

energy degradation because of the module temperature was recorded at 0.257 kWh. On the partly cloudy day, the theoretical calculations for the single module were about 0.930 kWh, while the experiments generated 0.887 kWh. The degradation of the energy because of the module temperature recorded 0.0425 kWh (see figure 6 (b)).

Figures 7 (a) and (b) illustrate the energy production of a 2.97 kW PV array with a tilt angle of β = 33° and an azimuth angel a = 0 to the south. The simulation process has been considered to be 95%, ground reflection 20%. Figure 7 (a) shows the thermotical and experiential energy generated, where the maximum energy recorded during July (theoretical about 554.012 kWh and experimental is 493.733 kWh) for the long day period and shining hours. The lowest energy generated during December (theoretical about 145.072 kWh and experimental is 146.761 kWh) for the short-day period. Figure 7 (b) illustrated energy losses per month because of the ambient temperature influence, where during the winter periods (January and December) the temperature has a positive effect on the system energy produced, while during the summer period it has a negative effect. The highest degradation was recorded during August (-0.124%).

Figures 8 (a) and (b) show the system energy losses per year and per month because of the module temperature influence respectively. The energy lost per year is about 287.435 kWh.

CONCLUSIONS

By using the model for power generation results, it provides a means for improving the understanding of the performance, reliability, and decision-making when designing the PV power system. By comparing the experimental and theoretical results, they displayed almost big differences in energy production due to the effect of the temperature on the PV modules. In Figure 3, we can observe that the maximum power production for a single day is higher during sunny days than on cloudy days. The degradation of power on sunny days is higher than on cloudy days. The results showed that the module temperature degraded PV power production during the summertime and raised it during the wintertime. According to the theoretical simulation, the total production value of energy for the system size of 2.97 kW located in Baqubah city in Diyala, during 2018 should be 554.012 kWh, while it actually produces only 493.733 kWh.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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