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Studying the performance of second-generation PV solar technology under Baghdad climate

Research article

Naseer K. Kasim[1], **Hazim H. Hussain**[2], **Alaa N. Abed**[3]
[1] Ministry of Electricity/Training and Energy Research Office, Baghdad-Iraq
[2,3] Department of Atmospheric Science, College of Science, Mustansiriyah University, Baghdad-Iraq
Correspondence: irss2004@yahoo.com;
https://orcid.org/0000-0001-5268-6719

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Abstract
The second-generation technology studied in this work is CIGS technology. The CIGS cell is manufactured from Copper-Indium Gallium Selenide. This study exhibits the performance assessment of a 5kWp CIGS PV solar system Grid-tied, installed at Al-Mansour Factory/Baghdad-Iraq (latitude 33.3°N, longitude 44.4°E and 41m above the sea level). The current system was monitored and studied throughout 2018. The annual daily average of the final, array and reference yields of the system are 4.866 kWh/kWp, 5.03kWh/kWp and 6.20kWh/kWp respectively. The annual yield of the system's energy is 1769.12kWh/kWp. The annual energy output of the system is 8792.5kWh, while the annual global horizontal solar irradiation received in Baghdad is 1986.4kWh/m^2. The annual daily average of the overall array and system losses are 1.62 kWh/kWp, 1kWh/kWp and 0.167kWh/kWp respectively. The annual average of the inverter, system and array efficiencies are 96.7%, 12.32%, and 12.74% respectively. The performance ratio (PR) and capacity factor (CF) are 81.1% and 20.3% respectively. This study indicates the good performance of CIGS technology under Baghdad-Iraq climate.

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Public Interest Statement

The current study is related to the field of renewable energy. The main objective of this study is to carry out the performance evaluation of the 5kWp PV solar system. This study presents the performance of the second-generation technology.

Introduction

Considering the global warming conditions in general and in Iraq in particular, and given the existence of severe shortage of power supply, it is necessary to introduce renewable energy sources, mainly the PV solar technology to minimize the gap between demand and generation in order to achieve grid stability and to reduce dependency on fossil fuel used in power generation. Moreover, such use is an attempt to decrease the large numbers of local diesel generators utilized for generating electricity when the utility grid is in outage. Diesel generators negatively affect human health and increase environmental pollution. Introducing the PV solar systems in the distribution sector plays a major role in this transition under the great technological development. The transition from wafer silicon PV solar modules (first generation technology) to thin film PV solar modules (second generation technology) is a qualitative leap in the production of photovoltaic solar modules.

Increasing international fears about the eco-system challenges has also raised concern in fuel type that is used daily [1, 2]. Today, fossil fuels are the key sources for power supply. Fossil fuel resources will be depleted because of great global demand. Consequently, clean energy resources are required as alternative resources. Among the eco-friendly fuels, biomass is a very important fuel that is made from vegetable oil and animal fat [3, 4]. The materials of the PV solar modules include: Cadmium Telluride (CdTe), Copper-Indium Gallium-Selenide (CIGS), Crystalline Silicon (Monocrystalline and polycrystalline) and amorphous silicon (a-Si), [5]. Silicon modules constituent the largest part of the market, with an estimation of 90% of the marketplace share of modules, whereas thin films make up less than 10% [6]. The efficiencies of silicon PV solar modules at standard test conditions (1000W/m^2, 25°C and AM: 1.5) are 10.2% for amorphous silicon, 19.8% for a polycrystalline and 24.4% for Monocrystalline [7, 8, 9], while the efficiencies of (CdTe) and (CIGS) are 16.5 and 19.9% respectively [10, 11].

Internationally, numerous research studies investigated the PV solar systems performance assessment. For instance, in Iraq, Obaid, et al., conducted a study on the Performance Assessment of HIT PV Solar system under Iraq-Baghdad climate in 2019 and they found out that the performance ranged from 83% to 67% and that the system efficiency extended from 14.8 % to 11.47% when the efficiency at STC was 17%, [12]. Farida, et al., studied the performance evaluation of 9540W poly crystalline PV solar system in Algeria, and found out that the monthly average system efficiency ranges between 7% and 10% when the efficiency at STC is 12% and the yearly average performance ratio is 71%, [13]. In Morocco, Amine, et al., carried out a study on the Performance Indicators For Grid-Connected PV Systems in Casablanca based on the data collected for two years (2015 - 2016). The study compared three technologies: mono crystalline, polycrystalline and amorphous silicon; the findings indicated that the annual monthly average of performance ratio for monocrystalline, polycrystalline and amorphous silicon are 76.7%,75.6% and 73.1% respectively, while the efficiencies were 11.7%, 11.4% and 7.21% respectively, [14]. Akash, et al., studied performance assessment and simulation of grid-tied PV solar system for residential buildings in India and found that the performance ratio of the PV solar system ranges from 70% to 88% [15]. Li, et al., studied the On-grid PV system in the city of Hong Kong and concluded that the energy payback duration is calculated to be about 8.9 years [16]. Jawad, et al., evaluated the PV solar modules in 5 different places in the Baghdad city and illustrated that PV solar modules which are located in agrarian places are less affected by dust, while the densely populated places are more affected by pollution [17]. Adaramola, et al., studied the effect of relative humidity on the performance ratio of the PV solar system; the outcomes displayed that the PV solar module power productivity increases with the decrease in relative humidity [18]. The research objective is to assess the performance of grid-tied thin film CIGS PV solar system during a one-year period under Baghdad climate conditions.

PV Solar System Details

The PV solar system is installed in Baghdad /Al-Mansour factory, at latitude 33.3°N and longitude 44.4°E

Table .1 PV solar system specifications

Module model	**TS-165C2 CIGS**
Number of modules	30
Inverter model	SMA SB-5000T-21
Inverter Size	5.30 kWp
Inverter efficiency	97%
Module efficiency	15.3%
System Size	5 kWp
Tilt Angle	15° summer /45° winter
Array Area (PV solar modules Area)	32.6 m^2

Figure 1: View of current PV sol system

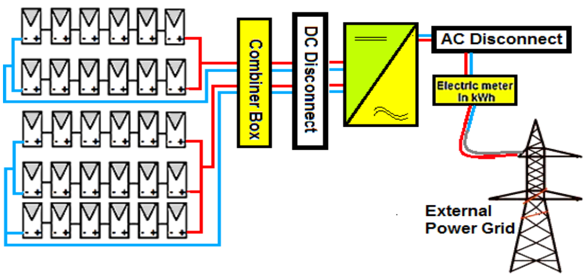

Figure 2: Single line diagram of current PV solar system

Performance Assessment

Assessment parameters comprise those that are Energy produced, the Performance Ratio, Capacity Factor, overall losses (System and Array losses), Efficiencies (Inverter, Array and System Efficiencies) and yields (Reference, Final and Array yields).

A. Energy Produced

The energy produced represents the magnitude AC energy output from the PV solar system during a specified duration. The hourly, daily and monthly energy output is given respectively as follows: [17, 19]

$$E_{AC,h} = \sum_{t=1}^{60} EAC,t \quad ...(1)$$

$$E_{AC,d} = \sum_{h=1}^{24} EAC,h \quad ...(2)$$

$$E_{AC,m} = \sum_{d=1}^{N} EAC,d \quad ...(3)$$

Where: $E_{AC,t}$ is AC energy produced at minutes; $E_{AC,h}$ is AC energy produced at hour; $E_{AC,d}$ is AC Energy produced on daily basis; $E_{AC,m}$ is AC energy produced at monthly and N refers to the day numbers in the month.

B. System Yields

The system energy yields are classified into three categories: Array yield, Final yield and Reference yields. The Array Yield (Y_A) is the DC energy production of the PV solar array with specific duration divided by the nominal power of the PV solar system [20]. It is calculated in kWh/kWp,[18] as follows:

$$Y_A = \frac{E_{DC}}{P_{PV.rated}} \ (kWh/kW_P) \quad ...(4)$$

Where E_{DC} is the DC energy produced (output) in the unit of (kWh).

The Final yield (Y_F) denotes the AC energy produced by the PV solar system for a specific time over the rated (nominal) power of the PV solar system [21]. It is presented as:

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} (kWh/kW_P) \quad ... (5)$$

Where E_{AC} is the AC energy product in the unit of (kWh).

The Reference Yield (Y_R) represents the in-collimated plane solar irradiation divided by the reference irradiance that equals 1000W/m^2[22]. It is represented as:

$$Y_R = \frac{H_T}{H_R} \ (kWh/kWp) \quad ...(6)$$

Where H_T and H_R are the in-collimated plane solar irradiation and the reference Irradiance respectively. The final yield denotes the number of hours per day, month or year at which the PV solar system works at its rated power. The array yield denotes the number of hours per day, month or year at which the PV solar array works at its rated (nominal) power. The Reference yield denotes the number of hours per day, month or year whereby the solar irradiance is 1000 W/m^2.

C. System and Array Energy Losses

The Array losses (L_A) refer to losses through the actual work duration. L_A denotes the disability of the array to totally convert the available solar insolation to electricity [23]. The array losses represent the difference between the Y_R and the Y_A. They are given as:

$$L_A = Y_R - Y_A (kWh/kW_P) \quad ...(7)$$

System losses (L_S) are losses caused by converting the DC energy to AC energy (DC to AC) by an inverter. They are given as:

$$L_S = Y_A - Y_F \ (kWh/kW_P) \quad ...(8)$$

D. System Efficiencies

The PV solar system efficiency is represented as three efficiencies: system, array and inverter efficiencies. These efficiencies are estimated on annual, monthly, daily and hourly bases. The system efficiency (ηsys) and array efficiency (ηPV) are based on the AC energy product and the DC energy product respectively. The array efficiency represents the ratio (daily, monthly or annually). The DC energy product to the overall (daily, monthly or annually) in-collimated plane irradiation multiplied by the area of the PV solar array [23,24] is illustrated as:

$$\eta_{PV} = \frac{E_{DC}}{H_t * A_m} * 100\% \quad ...(9)$$

where A_m is the array area (m^2) and H_t is the in-collimated plane solar irradiation.

The system efficiency represents the ratio (daily,monthly or annual) AC energy product to the overall (daily, monthly or annually) in-collimated plane irradiation multiplied by the area of the PV solar system [23,25] as follows:

$$\eta_{SYS} = \frac{E_{AC}}{H_t * A_m} * 100\% \quad ...(10)$$

The inverter efficiency is given as:

$$\eta_{INV} = \frac{100 * E_{AC}}{E_{DC}} \% \quad ...(11)$$

E. Performance Ratio (PR)

PR is a very important parameter which apears all the losses affecting the rated (nominal) power of the PV solar system. The PR value displays how close it approaches perfect performance through real work duration permiting comparison among the different PV solar systems regardless of the tilt angle, azimuth angle and their nominal power [26,27]. PR is given as:

$$P_R = \frac{Y_F}{Y_r}\% \quad ...(12)$$

F. Capacity Factor (CF)

CF is a parameter utilized to assess the energy produced by the PV solar system [16] . CF is calculated as the ratio of AC energy produced by the PV solar system divided by a specified period (year or month) multiplied by the nominal value of the installed PV solar system. The annual capacity factor is given as [28,29,30].

$$C_F = \frac{E_{AC}}{P_{PV,rated}*8760} \quad ...(13)$$

Result and Discussion

Fig.3 demonstrates the monthly energy output of the PV solar system and the in-collimated plane solar insolation (irradiation). The lowest value of energy output was 567.9kWh in December, 2018 because of the bad weather conditions like rain and clouds and the lower solar radiation intensity, whereas the highest energy output was 876.159kWh in June because of the clear sky conditions and the highest solar radiation intensity. The solar irradiation which reached the PV solar system ranged from 4454.138kWh in December, 2018 to 7553.4kWh in June, 2018. For all the months of 2018, the produced energy was 8792.46kWh, while the annual average of energy produced was 732.7kWh. The total energy output throughout the year over the nominal power value of the PV solar system (normalization or total final yield during the year) is 1769.12kWh/kWp. The monthly average of the maximum temperature varies from 44°C in July to 16.8°C in January, whereas the annual average of the maximum temperature is 30°C. Although the rise in ambient temperature in June which in turn reduces the energy output of the PV solar system, this month comprises the highest value of energy output because of the largest numbers of sun rising hours (about15 hours) and highest solar radiation intensity. The lowest value of energy output is in December because of the fewest number of sun rising hours (about 9 hours) and the lowest solar radiation intensity.

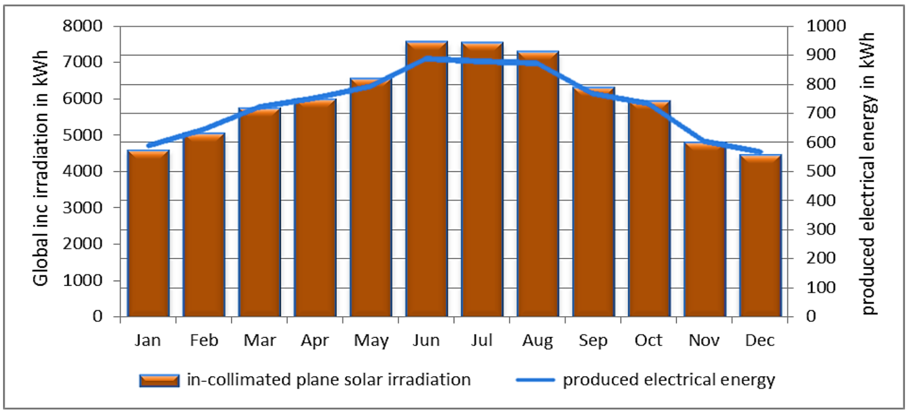

Figure 3: Energy produced and solar insolation

The monthly daily average values of the array yield, the final yield and reference yield are shown in Fig.4. The minimum values are recorded for the winter months (December and January). In December of 2018, the monthly daily average of the array yield, the final yield and yield reference are 3.83 kWh/kWp/day, 3.7 kWh/kWp/day and 4.41 kWh/kWp/day, respectively, while the highest values are in June of 6.2 kWh/kWp/day, 5.97 kWh/kWp/day and 7.72 kWh/kWp/day, respectively. The annual daily average of the array, the final and reference yields throughout the year are 5.03 kWh/kWp/day, 4.86 kWh/kWp/day and 6.03 kWh/kWp/day respectively. For all months, there is a constant variation between final yield (system yield) and array yield. This variation is caused by the conversion losses of DC to AC in an inverter. Regardless of the climatic conditions, an inverter consumes approximately the same monthly energy for the conversion process (indoor installation). Inverter efficiency drops approximately 1% for about each 12°C rise in ambient temperature [31].

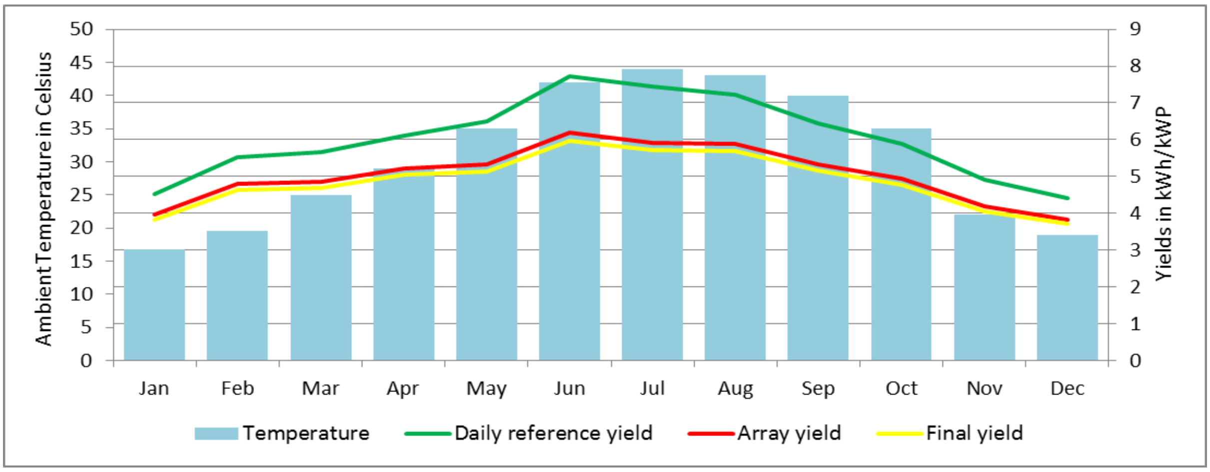

Figure 4: Monthly daily average of yields.

Fig.5 displays the monthly daily average of the array losses, system losses and overall losses with respect to the monthly daily average of reference yield. The maximum value of the monthly daily average of array losses was in July of 1.54 kWh/kWp/day. This can be attributed to the high ambient temperature, whereas the minimum value of 0.56 kWh/kWp/day is observed in January. These values coincide with those of 20.7% and 12.5% of the monthly daily average of reference yields in July and January respectively. The system losses (representing the inverter losses) vary from 0.126 kWh/kWp/day in December to 0.21 kWh/kWp/day in June, as shown in Fig.5. These values coincided with those of 2.7% and 2.7% of the daily reference yields in December and June respectively. The maximum value of overall losses of 1.745 kWh/kWp/day is observed in July and the minimum value of 0.698 kWh/kWp/day is observed in January. These values coincide with those of 23.4% and 15.4% of the daily reference yields for July and January respectively. The annual daily average of the overall, array and system losses is 1.2kWh/kWp/day, 1kWh/kWp/day and 0.17 kWh/kWp/day, respectively. The overall losses equal the array losses plus the system losses.

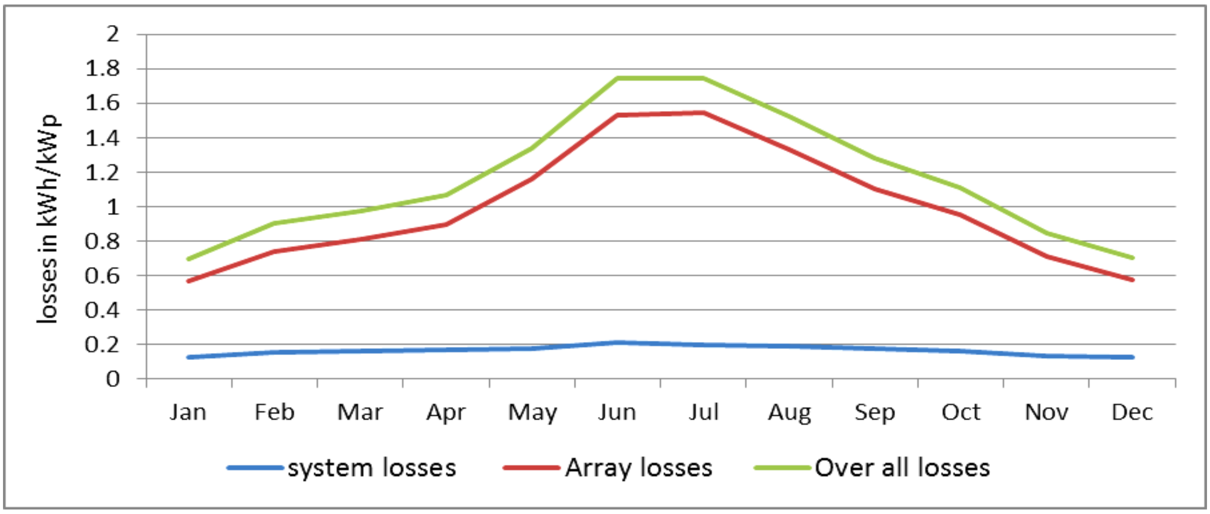

Figure 5: Annual daily average of system, array and overall losses

Fig. 6 demonstrates the monthly average of the system, array and inverter efficiencies throughout the observation period. The annual average values of the inverter, array and system efficiencies are 12.35%, 12.77% and 96.6% respectively. The maximum values of the system, array and inverter efficiencies were 12.79%, 13.26% and 96.7% respectively in January and December. The minimum values of the system, array and inverter efficiencies of 11.68% ,12.14% and 96.6% were in July.

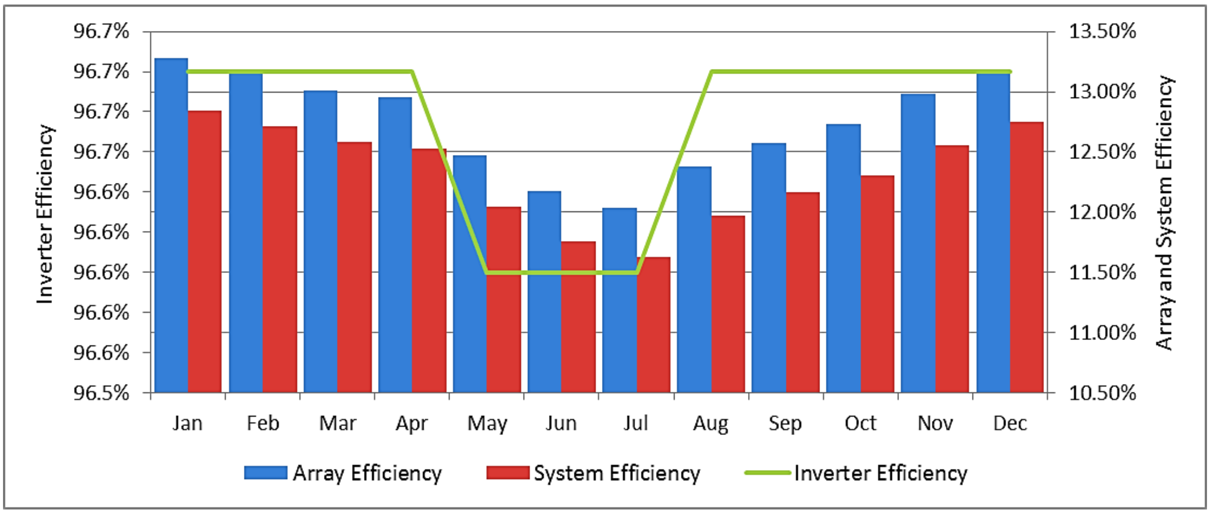

Figure 6: Monthly average of inverter, array and system efficiencies

Fig. 7 exhibits the monthly average of PR and CF. The annual average of PR for the current PV solar system is 81.1%. The maximum PR is in the coldest months (January and December) of 84.11 % and the minimum PR is in the hottest month (July) of 76.61%. PR is an indicator displaying how to approach the real system performance to a perfect performance during the actual work [32]. The PR of the current system drops in May, June, July and August below the average, which can be attributed to the ambient temperature rise in these months.

The annual average capacity factor (CF) is 20.3%. The maximum value of CF is 24.9% in June, while its minimum value is 15.4% in December. CF is an indicator that displays the time magnitude in the percentage at which the PV solar system works in its maximum capacity. Consequently, the current PV solar system works to its highest capacity for approximately 91 days or 2207 h per year (June, July and August), i.e., 20.3% is equivalent to 92 days. The capacity factor has a direct impact on power electricity generation cost of the PV solar system. Therefore, the PR and the CF are very substantial parameters for evaluating the grid-tied PV solar system. Certain techniques are utilized to improve the performance of the PV solar modules such as cooling with optical reflectors [33, 34].

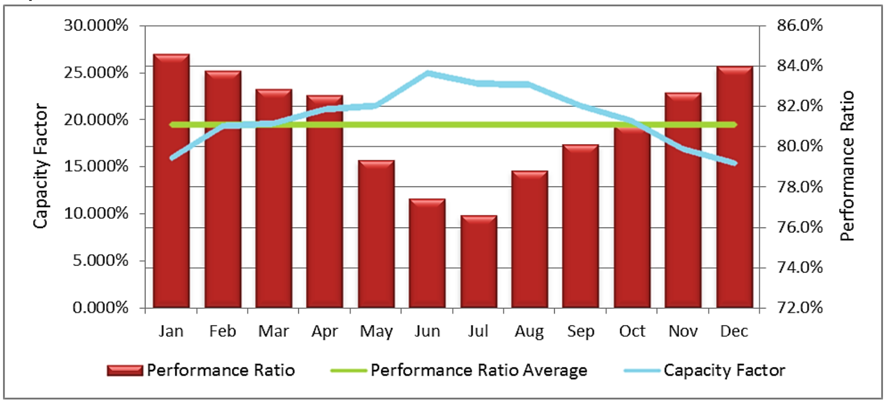

Figure 7: Performance ratio and capacity factor

Conclusion

To sum up, there is a notable difference in the performance ratio between summer and winter, where the higher performance ratio is in winter. The key reason for the improvement in performance in winter is the low ambient temperature. In the summer months, in spite of the increase in solar radiation, the performance is low because of the high ambient temperature. The overall losses of the PV solar system rise in the summer months and decrease in the winter months. Comparing CIGS with Monocrystalline (silicon) technology for the same monthly average of ambient temperature in July for the Baghdad (44°C), it is found that the PR of CIGS PV solar system is higher than the Monocrystalline silicon PV solar system. In terms of the efficiency of the current CIGS system, it is noted that efficiency doesn't significantly drop during the hot months.

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