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ARTICLE

Performance Analysis of a Rooftop Hybrid Connected Solar PV System

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ABSTRACT

In the present work, a 5-kW hybrid PV solar system was installed on the roof of a house in Diyala, Iraq (33.77° N, 45.14° E elevation 44 m). The system consists of two strings, where each string consists of nine polycrystalline PV modules with 355 Wp in series, and the two strings are in parallel. The energy storage system (ESS) consists of two parallel strings, each with four 12 V and 150 Ah tubular deep cycle batteries in series. A hybrid inverter of 5 kW rated power was operated in different modes. The results showed that May's monthly energy consumption was about 822.9 and 1085 kWh, respectively. The percentage distribution of the DC energy produced was about 1% system energy losses, 27.9% was used to charge the ESS, 34.3% was used to feed the grid, and the remaining 37.64% was used to share the load. The energy percentage sharing the load was 16.67% from ESS, 33.33% from the PV system, and 50% purchased. The average daily reference, array, and final yields were 6.07, 4.327, and 3.991 h/day, respectively. The average array and load efficiencies were 12.3% and 92.24%, with the performance ratio at 65.4%.

KEYWORDS

Solar energy; PV system; final yield; photovoltaic installations; performance ratio; hybrid PV system

Nomenclature

A_a	Array area (m^2)
$E_{A,\tau}$	Net energy from the PV array (kWh)
$E_{FS,\tau}$	Energy from the storage system (kWh)
$E_{FSN,\tau}$	Net delivered from the storage system (kWh)
$E_{FU,\tau}$	Energy supplied by the utility grid (kWh)
$E_{FUN,\tau}$	Net energy supplied to the utility grid (kWh)
$E_{i,\tau}$	Energy produced at the corresponding time (τ) (kWh)
$E_{in,\tau}$	Total energy input by the PV system (kWh)
$E_{L,\tau}$	Net energy to the load (kWh)
$E_{TS,\tau}$	Energy supplied to the storage system (kWh)
$E_{TSN,\tau}$	Net energy supplied to the storage system (kWh)
$E_{TU,\tau}$	Energy delivered to the utility grid (kWh)
$E_{TUN,\tau}$	Net energy delivered from the utility grid (kWh)
$E_{use,\tau}$	Energy output by the PV system (kWh)
$F_{A,\tau}$	Fraction of the energy from all sources

G_I	Global irradiance on the plane of the array (W/m^2)
$G_{I,ref}$	Reference solar radiation (W/m^2)
P_i	Power generated/consumed (kW)
P_{rated}	PV rated power (kW)
R_P	The performance ratio
Y_A	Array yield (kWh/day.kW)
Y_f	The final PV yield (kWh/day.kW)

Greek symbols

τ_τ	Actual reporting interval of time
η_{Load}	Efficiency transmitted to the load
$\eta_{A,mean}$	Mean array efficiency

1 Introduction

Renewable energy offers environment-friendly energy. In 2016 and 2017, about 305 GW of new renewable power was added to global energy production [1]. A stand-alone, on-grid, and hybrid connection solar energy system is a promising technology in developing countries. These typical solar PV systems consist of solar PV modules, DC/AC inverters, and batteries. Hybrid systems also contain energy storage devices (ESS), such as batteries or fuel cells, and operate parallel with the grid power system. Schallenberg-Rodriguez [2] introduced a methodology to analyze a roof PV solar system in the Canary Islands. The results showed that the PV system produced energy higher than the demand energy at low prices. In addition, cost resource curves and the comparison of the daily and monthly profiles have been studied. Attari et al. [3] presented and evaluated a 5-kW rooftop PV system in Tangier, Morocco, during the extended period from January to December 2015. A total of 20 panels each of 250 Wp were used to build the PV system. The parameters under study were the energy output, module efficiency, module temperature, and the system's performance ratio. Ibrahim et al. [4] investigated the hybrid PV-wind system modeling. The grid-connected hybrid system was proposed to power a large plant of a variable load. The MATLAB Simulink software was used to model the proposed system. The effect of environmental conditions on the dynamic performance PV-wind system was studied. de Lima et al. [5] studied the performance of a grid-connected 2.2 kWp PV system in Brazil. The performance of the PV system during the extended period from June 2013 to May 2014 was introduced. Li [6] established the performance of an 8-kW grid-connected PV system. Different module technologies were examined as well as the system performance under summer and winter conditions were introduced. The system efficiency, array, final array, and reference yields were studied as well as the losses for the monthly average capture and the system losses were analyzed. Mathew et al. [7] studied and compared the performance of a 250 MW on-grid PV system. The different PV technologies, namely crystalline silicon and thin-film technologies, were studied. PVsytst software was used to simulate the performance of the system. The energy yields from each PV technology type and the lifetime was analyzed. Bhuvaneswari et al. [8] assessed the performance of a 15 kW rooftop off-grid-connected PV system. The system was monitored three days a week over one year. The system capacity utilization and the filling factor were studied. In the southern region of Iraq, Ali et al. [9] used the geographic information system software to simulate a 10-kW grid-connected PV system and studied the effect of using such a system on CO_2 production. Nurdiana et al. [10] studied an on-grid PV system whose capacity was 10 kW. A total of 40 PV modules of 265 Wp were used to build the system. The system was monitored for eight months, from July 2019 to February 2020. The capacity factor, average daily energy output, energy efficiency, and average daily energy output were studied. Table 1 summarizes the previous work mentioned in the introduction.

Table 1: Summarization of the literature review

Author/Date	Country (Lat., Long.)	Type and size of the PV system	Key variables
Schallenberg-Rodriguez (2014) [2]	Canary Islands, Spain (28.29° N, 16.62° W)	Grid-connected-3 kWp rooftop (Theoretical work)	The available roof area, economic assessment daily and monthly energy production
Attari et al. (2016) [3]	Tangier, Morocco (35.75° N, 5.83° W)	Grid-connected 5-kW rooftop (Experimental work)	Energy output, final yield, modules temperature, efficiency module, (PR)
Ibrahim et al. (2017) [4]	Cairo, Egypt (30° 1° N and 31° 41° E)	Grid-connected hybrid PV-wind system (500 kW PV system + 9 MW DFIG (Theoretical work)	The effect of environmental conditions on the dynamic performance PV-wind system was studied
de Lima et al. (2017) [5]	Northeast region of Brazil (10.06° S, 42.55° W)	Grid-connected 2.2 kWp (Experimental work)	Average daily reference, array, final yields, the annual average daily array, and system losses
Li (2018) [6]	Nanjing, China (32.05° N, 118.79° E)	Grid-connected/8-kWp (Experimental work)	The system efficiency, array, final array, and reference yields
Mathew et al. (2018) [7]	Chandigarh, India (30.73° N, 76.77° E)	Grid-connected/250 MW (Theoretical)	Specific energy production, RP, capacity utilization factor, array efficiency, inverter efficiency, energy injected into the grid

(Continued)

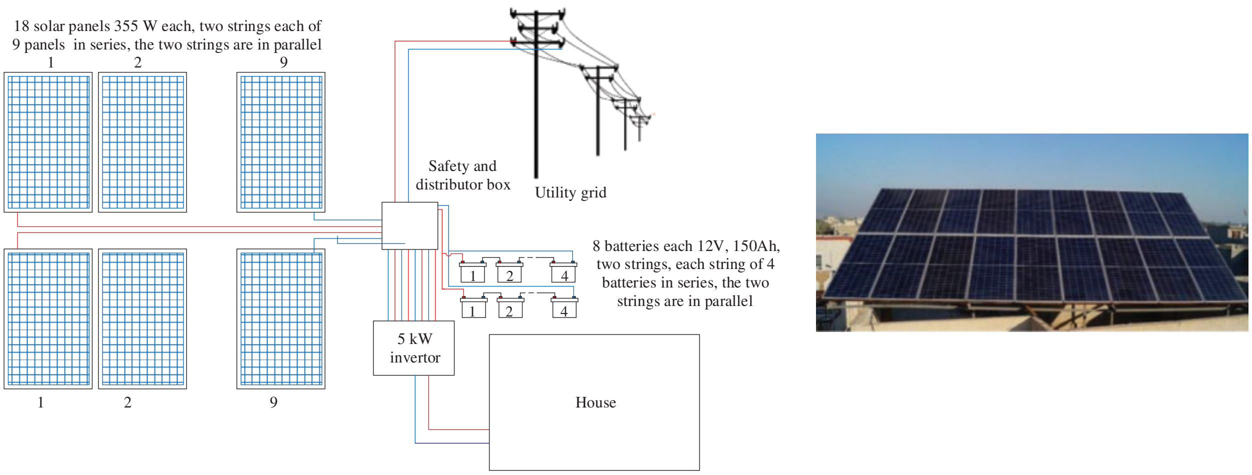
Table 1 (continued)

Author/Date	Country (Lat., Long.)	Type and size of the PV system	Key variables
Bhuvaneswari et al. (2018) [8]	Vellore District, Tamil Nadu (12.84° N, 78.92° E)	Off-grid 150 kWp rooftop (Experimental)	Monthly average demand and annual RP, Efficiency, FF and capacity utilization factor
Ali et al. (2020) [9]	Southern of Iraq (35.11° N, 45.6953° E)	Grid-connected 10 kWp (Theoretical)	The costs and environmental impact
Nurdiana et al. (2020) [10]	South Tangerang (6.28° S, 106.71° E)	Grid-connected 10 kWp (Theoretical)	The capacity factor, average daily energy output, energy efficiency, and average daily energy output

Previous works focused on the comparative performance of two main types of solar PV systems: on-grid and off-grid solar systems; the hybrid connected PV solar systems did not study extensively in the previous work. This system contains an energy storage system (ESS) to cover the load during nighttime and the shortage of power supply by the grid. In the current work, a 5 kWp hybrid PV solar system integrated with an ESS was installed in Diyala, Iraq, and studied in May 2021. The PV installation parameters under study include output energy, final yield, array efficiency, performance ratio (Rp), array, and system losses.

2 Description of the Current PV Solar System

The present PV solar system of an installed capacity of 5 kW is installed on the roof of a house in Diyala, Iraq (33.77° N, 45.14° E elevation 44 m), as shown in Fig. 1. The system started operating in November 2019 and consists of 18 polycrystalline solar panels, each of 355 Wp, the short circuit current is 9.67 A, and the open-circuit voltage is 47.3 V. The net area of the system installation was 30.6 m^2. The specification of the PV panel is shown in Table 2. The PV system consists of two parallel strings where each string consists of nine modules in series, the specification of the solar array is shown in Table 3. The tilt angle of the strings is 35° towards the south. The ESS consists of two strings used to store the power produced by the solar system. The string consists of four tubular deep cycle batteries in series, each of 12 V and 150 Ah. The two strings are connected in parallel to produce a DC voltage of 48 V. Table 4 shows the specification of the battery. An infinity pure sine wave hybrid inverter of the rated power of 5 kW is used. The inverter can stimulatingly manage power to/from solar, battery, load, and generator, providing multiple inverter parallel operation functions with on- and off-grids; Table 5 shows the inverter specifications.



(a) Schematic diagram of the PV system

(b) The installation of the PV solar modules

Figure 1: Installation of the PV system

Table 2: Specifications of solar panels

Technical data	Specification	
Test conditions	STC*	NOCT**
Rated output (Pmp/Wp)	355	264.62
Rated voltage (Vmp/V)	39.4	36.2
Rated current (Imp/A)	9.01	7.31
Open circuit voltage (Voc/V)	47.3	44.01
Short circuit current (Isc/A)	9.67	7.8
Module efficiency (%)	17.89	
Power tolerance (W)	0 ± 5	

Notes: *Standard test conditions: Irradiance 1000 W/m^2, cell temperature 25°C and AM 1.5. **Normal operating cell temperature: Irradiance 800 W/m^2, ambient temperature 20°C and AM 1.5 wind speed at 1 m/s.

Table 3: PV system specifications

	Number	Rated power (W)	Area (m^2)
Modules	18	355	1.984
String	2	3195	17.856
Array	1	6390	35.712

Table 4: Specifications of the lead acid battery

Nominal voltage (V)	12
Rated capacity (Ah)	150
Maximum charging current (A)	10
Cyclic use (V)	14.5
Float use (V)	13.8

Table 5: Specifications of the inverter

Technical data	Specification
Maximum charging/discharging current (A)	120
MPPT range (V)	125–425
Maximum DC input power (W)	6500
Maximum DC input voltage (V)	500
Maximum input current (A)	18 + 9
No. of MPP trackers	2
No. of strings per MPP trackers	2 + 1
Maximum AC current (A)	20.8
Rated AC output (W)	5000

3 Methodology

The hourly global solar radiation on a 35° tilted surface and the ambient temperature for Diyala are generated using Meteonorm V7.3 software, as shown in Fig. 2. According to the IEC Standard 61724 [11], the parameters of the PV system shown in Table 6 and Fig. 3 should be measured to perform the analysis of any PV system.

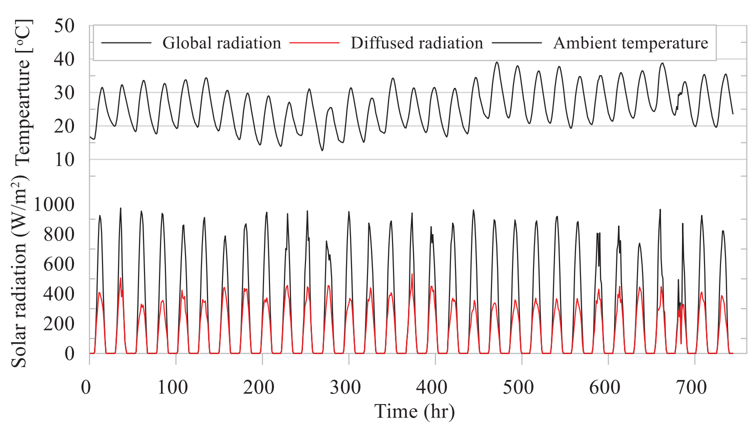


Figure 2: Weather data for Diyala, in May, Iraq (33.77° N, 45.14° E elevation 44 m)

Table 6: The parameters of the PV solar system should be measured

Outdoor		The utility grid	
Variables to be measured	Unit	Variables to be measured	Unit
The global irradiance on the plane of the array (G_I)	W/m^2	The voltage (V_U)	V
Ambient temperature (T_{amb})	°C	The current to the utility grid (I_{TU})	A
The inverter		The power to the utility grid (P_{TU})	kW
The output voltage (V_A)	V	The current from the utility grid (I_{FU})	A
The output current (I_A)	A	The power from the utility grid (P_{FU})	kW
The output power (P_A)	kW	The storage system	
The load		The operating voltage (V_S)	V
The load voltage (V_L)	V	The current to the storage (I_{TS})	A
The load current (I_L)	A	The power to the storage (P_{TS})	kW
		The current from the storage (I_{FS})	A
		The power from the storage (P_{FS})	kW

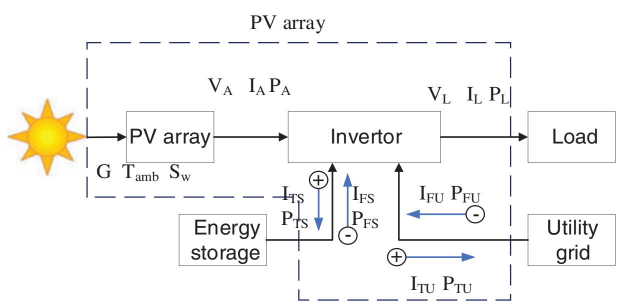


Figure 3: Parameters that should be the measured [11]

The energy quantity for the corresponding measurements of the variable mentioned above during the corresponding time (τ) is [6]:

$$E_{i,\tau} = \tau_\tau . \sum_{\tau} P_i \quad (1)$$

where

$E_{i,\tau}$: The energy produced at the corresponding time (τ) (kWh);

P_i: The power generated/consumed (kW); and

τ_τ: The actual reporting interval of time.

The mean daily global solar radiation ($\mathbf{H_{i,d}}$) in (kWh/m^2.d) is calculated from the recorded radiation as follows [12]:

$$H_{i,d} = \frac{24.\tau_\tau . \sum_\tau G_I}{1000. \sum_\tau \tau_{AM}} \quad (2)$$

The net energy supplied and delivered to the storage system in each period (τ) are:

$$E_{TSN,\tau} = E_{TS,\tau} - E_{FS,\tau} \quad (3)$$

$$E_{FSN,\tau} = E_{FS,\tau} - E_{TS,\tau} \quad (4)$$

where in a given period (τ):

G_I: The global irradiance on the plane of the array (W/m^2)

$E_{TSN,\tau}$: The net energy supplied to the storage system (kWh)

$E_{TS,\tau}$: The energy supplied to the storage system (kWh)

$E_{FS,\tau}$: The energy delivered from the storage system (kWh)

$E_{FSN,\tau}$: The net delivered from the storage system (kWh)

While for the utility grid, the energy delivered and supplied from the utility is:

$$E_{TUN,\tau} = E_{TU,\tau} - E_{FU,\tau} \quad (5)$$

$$E_{FUN,\tau} = E_{FU,\tau} - E_{TU,\tau} \quad (6)$$

where in a given period (τ):

$E_{TUN,\tau}$: The net energy delivered from the utility grid (kWh);

$E_{TU,\tau}$: The energy delivered to the utility grid (kWh);

$E_{FU,\tau}$: The energy supplied by the utility grid (kWh); and

$E_{FUN,\tau}$: The net energy supplied to the utility grid (kWh).

The total energy input and output by the PV system is [13]:

$$E_{in,\tau} = E_{A,\tau} + E_{FUN,\tau} + E_{FSN,\tau} \quad (7)$$

$$E_{use,\tau} = E_{L,\tau} + E_{TUN,\tau} + E_{TSN,\tau} \quad (8)$$

where over a given period (τ):

$E_{in,\tau}$: The total energy input by the PV system (kWh);

$E_{A,\tau}$: The net energy from the PV array (kWh);

$E_{L,\tau}$: The net energy to the load (kWh); and

$E_{use,\tau}$: The total energy output by the PV system (kWh).

The fraction of the energy from all sources of the solar PV is the ratio between the net energy from the PV array and: the total energy input by the PV system.

$$F_{A,\tau} = \frac{E_{A,\tau}}{E_{in,\tau}} \quad (9)$$

where

$F_{A,\tau}$: The fraction of the energy from all sources.

The load efficiency is the ratio between the total energy output by the PV system and the total energy input by the PV system [14]:

$$\eta_{Load} = \frac{E_{use,\tau}}{E_{in,\tau}} \quad (10)$$

where

η_{Load}: The efficiency transmitted to the load.

This array yield is the number of hours per day that the solar array is operated at its rated power and can be calculated by dividing the net energy from the PV array by the array rated power:

$$Y_f = Y_A.\eta_{Load} \quad (11)$$

where

Y_A: Array yield (kWh/day.kW);

P_{rated}: PV rated power (kW).

The final yield is the ratio of the PV system daily energy output to the installed PV array power:

$$Y_f = Y_A.\eta_{Load} \quad (12)$$

where

Y_f: The final PV yield (kWh/day.kW).

The reference yield is the ratio of the total daily in-plane radiation to the Panel reference radiation [15]:

$$Y_r = \frac{\tau_\tau.\sum_{day} G_I.}{G_{I,ref}} \quad (13)$$

where

$G_{I,ref}$: The reference solar radiation (W/m^2).

The performance ratio is the ratio of the final to the reference yields:

$$R_P = \frac{Y_f}{Y_r} \quad (14)$$

The mean array efficiency is:

$$\eta_{A,mean} = \frac{E_{A,\tau}}{A_a.\tau_\tau.\sum_\tau G_I} \quad (15)$$

The overall PV system efficiency over a period (τ) is [16]:

$$\eta_{tot,\tau} = \eta_{A,mean}.\eta_{load} \quad (16)$$

where

R_P: The performance ratio;

$\eta_{A,mean}$: The mean array efficiency;

A_a: The array area (m^2).

4 Result and Discussion

The understudy's average daily profile load is shown in Fig. 4; the types, power, and number of the electrical appliances used by occupants are shown in Table 7. Fig. 5 shows the daily energy production by the PV system and the daily solar energy during May. The daily energy production ranges from 19 to about 33 kWh. The figure shows a significant difference between solar energy and the PV system's energy production due to the low efficiency of the PV array shown in Fig. 6. The performance ratio (R_P) indicates the PV system's overall losses caused by increased array temperature, inefficient utilization of solar energy, and system components failure or inefficient use. Thus, the P_R is the Percentage of net energy delivered by the system after subtracting the losses in energy produced by the PV array, and the P_R for the PV system ranges from 0.4 to 0.7, as shown in Fig. 6. The load efficiency of 0.9 shown in Fig. 6 is the ratio of the energy used to the summation of energy from all sources.

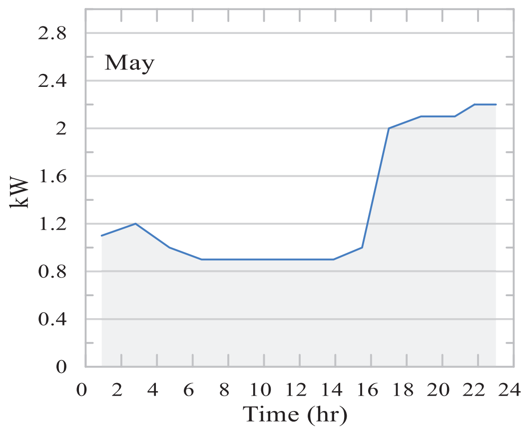


Figure 4: The house load profile

Table 7: The types and the power of the electrical appliances used by occupants

Appliances	Power (W)	Number	Total power (W)
Refrigerator	200	1	200
Chest freezer	200	1	200
Washing machine	800	1	800
Celling fan	250	6	1500
LCD TV	120	4	480
Microwave oven	750	1	750
food processor	400	1	400
LED light	15	10	15
Kitchen hood	150	1	150
Total			4495

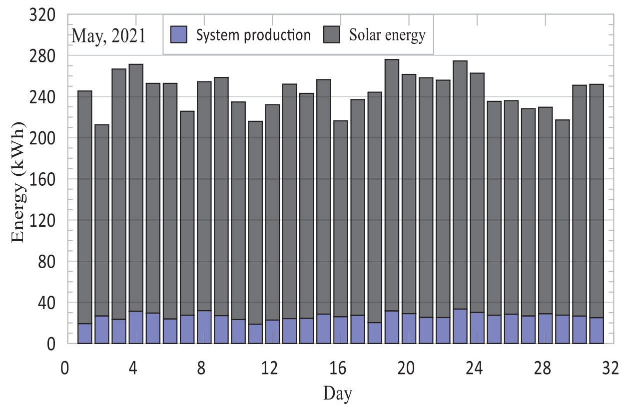


Figure 5: Daily AC energy production and solar energy in May

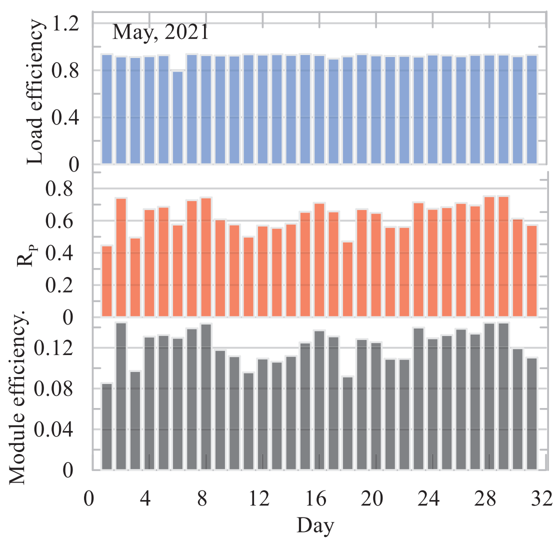


Figure 6: Variation of daily performance ratio, module, and load efficiencies along the month in May

Fig. 7 shows three tools that indicate the deviation of the system's performance from the ideal performance, namely, reference, array, and the final yields. The reference yield (Yr) is in the form of 6 h/day, thus the solar radiation at 6 h/day is at reference irradiance levels. Afterward, these hours are reduced to about 4.5 as indicated by the array yield (Ya); hence the final yield (Yf) reduces to about three hours per day. The low-efficiency PV modules cause a high energy loss compared with the inverter's, as shown in Fig. 8. The system loss is due to converting the current from DC to AC and the electric resistance of the wiring system.

Fig. 9 compares the energy supplied to the grid when the system produces excess energy demand and the energy purchased at night and at the beginning and end of the day. The energy purchased is more than that supplied to the grid because ESS is small to cover the shortage of energy-producing at nighttime.

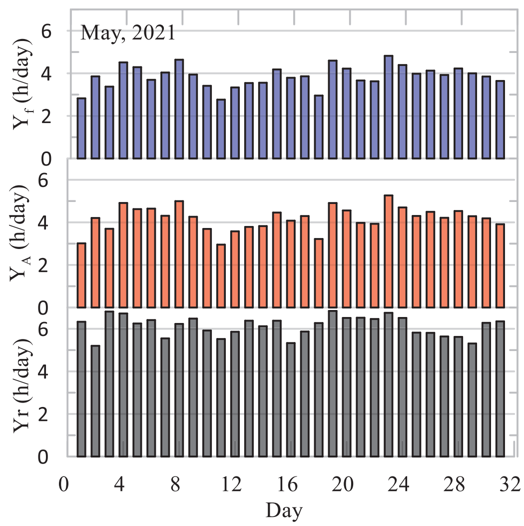


Figure 7: Reference, array, and final yields of the PV system

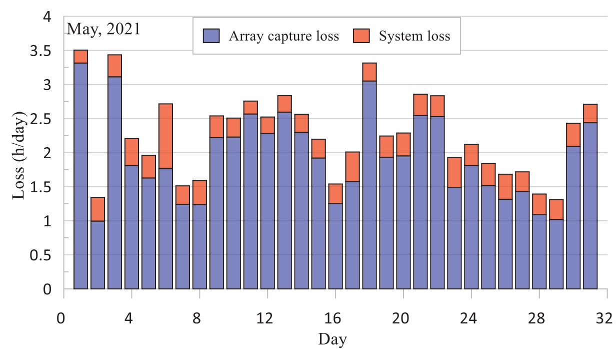


Figure 8: PV and the system energy losses

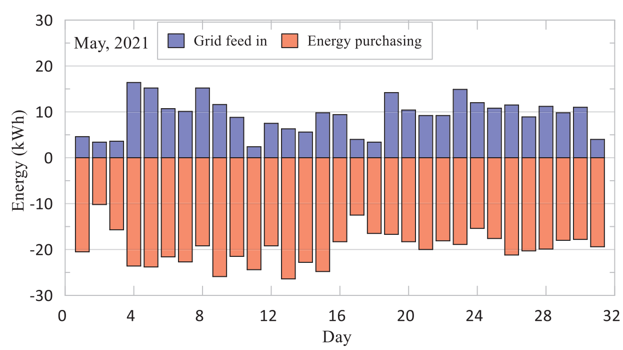


Figure 9: The grid feed-in and the energy purchasing

Fig. 10 shows the charging, discharging energy, and the state of charge (SOC) of the ESS, and the high charging energy follows the high energy discharge by the ESS. The figure indicated a significant difference in discharge energy daily due to the utility grid's shortage and irregular energy supply. The SOC is always up to 90%; the low SOC at the beginning and mid-month is due to clouds.

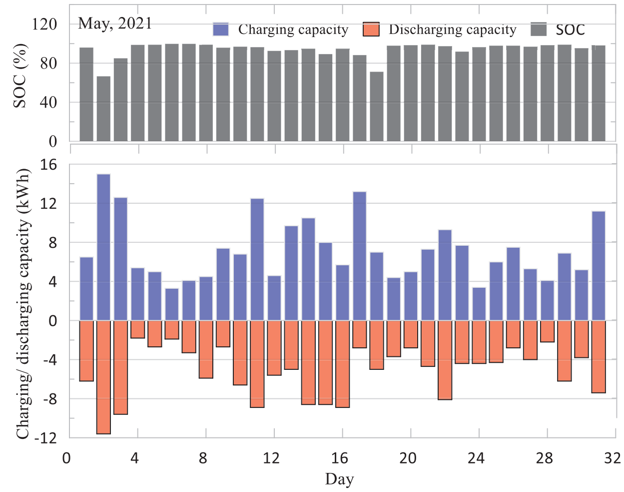


Figure 10: The charging and discharging of the storage system

Figs. 11–14 summarise the average daily analysis of the abovementioned variables for May 2021. Fig. 11 shows that the total DC energy produced was 830 kWh. Given the system losses, the AC energy produced reduces to 823 kWh. The AC energy produced is distributed to feed the grid, charging the energy storage system, and the rest is used to share the load. Fig. 12 shows the percentage of energy sharing the load and the percentage of the DC production component. It can be seen from the figure that three sources cover the consumed energy by the load of 1085 kWh; namely, the net produced energy, discharging energy from ESS, and purchased energy, representing about 33%, 16.6%, and 50%. While the system DC-produced energy is divided into 1% system losses, 34% supply the grid, 27% charge the ESS, and the rest of 37.6% is used to share the load. Fig. 13 shows that the average daily reference yield is about 6 h/day, the array yield is about 4 h/day, and the average daily final yield is about 3 h/day. Fig. 14 shows that the lowest average daily efficiency is for the PV array, while the R_P is about 65.4% and the average load efficiency is about 92%. Table 8 shows the performance indicators of the PV system in May.

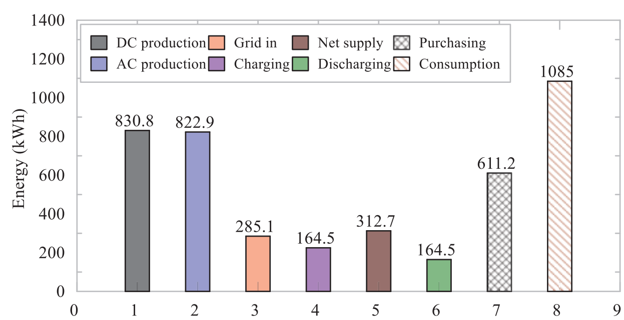


Figure 11: Distribution of the average daily energy produced by the PV system and consumed by the load

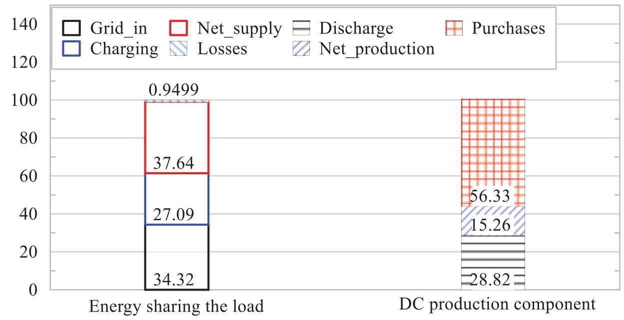


Figure 12: Percentage of energy sharing the load and the percentage of the DC production component

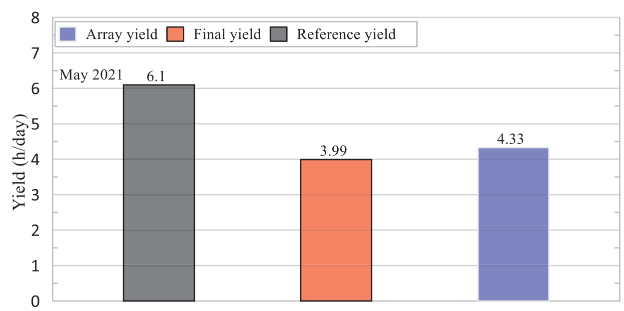


Figure 13: Average daily reference, array, and final yields

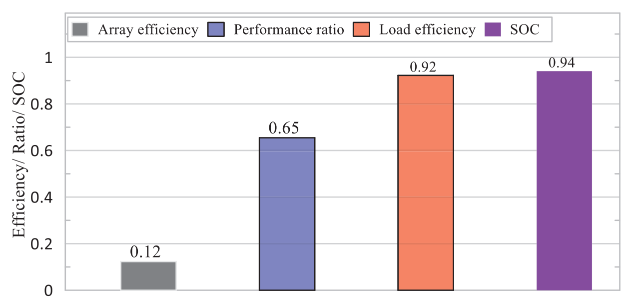


Figure 14: Performance ratio, the array, load efficiencies, and SOC

Table 8: Performance indicators for PV system in May

Parameters	Value	Parameters	Value
DC production energy (kWh)	830.8	Reference yield (h/d)	6.097
AC production energy (kWh)	822.9	Array yield (h/d)	4.327
Grid feed-in energy (kWh)	285.1	Final yield (h/d)	3.99
Charging energy (kWh)	164.5	Array efficiency (%)	12.3
Discharging energy (kWh)	164.5	Performance ratio (%)	65.4
Energy consumption (kWh)	1085	Load efficiency (%)	92.2
Purchasing energy (kWh)	611.2	Stat of charge (SOC) (%)	94.1

The monthly average daily final yield (Y_f) and the performance ratio (P_R) for May for the current work were compared with three selection sites, namely Iraq (4.68 kWp), Brazil (2.2 kWp), and Algeria (9.5 kWp), as shown in Table 9. The table shows that the present value of Y_f is close to the theoretical value calculated for Iraq, higher than reported in Algeria and less than reported in Algeria. In contrast, the current R_P is less than those reported in Iraq, Brazil, and Algeria.

Table 9: Comparative of system performance

Location	Cell type	Ht* (kWh/m^2)	System size (kWp)	Y_f (h/day)	R_p	
Baghdad, Iraq	Polycrystalline silicon	197	4.68	4.27	0.838	[17]
Fortaleza, Brazil	Polycrystalline silicon	150	2.2	3.9	0.92	[5]
Bouzareah, Algeria	Polycrystalline silicon	193	9.5	4.5	0.71	[18]
Diyala, Iraq	Polycrystalline silicon	197	5	4	0.654	Current study

Notes: *Global solar radiation on a horizontal surface for May.

5 Conclusion

The following conclusions are drawn from the results of the 5-kW rated PV solar system installed in Diyala, Iraq (33.77° N, 45.14° E elevation 44 m). The monthly energy production for May was about 822.9 kWh, while the monthly energy consumption was 1085 kWh. The percentage distribution of the DC energy produced was about 1% system energy losses, 27.9% used to charge the ESS, 34.3% used to feed to the grid, and the rest of 37.64% was used to share the load. The load's energy percentage was 16.67% from ESS, 33.33% from the PV system, and 50% purchased. The average daily reference, array, and final yields were 6.07, 4.327, and 3.991, respectively. The average array and load efficiencies were 12.3% and 92.24%, respectively, where the performance ratio was 65.4%.

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