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Techno-economic assessment of a hybrid connected PV solar system



Hasan Falih*, Ahmed J. Hamed and Abdul Hadi N. Khalifa

Abstract

The current work was performed a techno-economic analysis of a 5-kWp capacity hybrid-connected solar system installed on the roof of a house at Diyala province, Iraq (33.77° N, 45.14° E, elevation 44 m). The rooftop PV solar system consists of 18 polycrystalline PV modules of 355 W each, an energy storage system consisting of 8 batteries of 150 Ah, 12 V, and an intelligent inverter of 5-kWp capacity. The PV string output energy and the load sharing between the PV output, the grid, and the discharging energy from the energy storage system are studied. While the economic assessment of the PV system is performed by calculating the net present value (NPV) depending on the discount cash flow method, from the results, the payback time is found. The PV system's annual results showed that the PV system's energy yield is 8.9 GWh/year, and the array efficiency, performance ratio, and load efficiency were 0.126, 0.66, and 0.92, respectively. The reference, array, and final yields were 6.1, 3.88, and 3.99 h/day, respectively. The minimum energy feed to the grid was in summer, and the maximum was in winter. On the other hand, the results showed that the maximum purchasing energy was in summer, and the less was in winter. The economic assessment showed that the minimum tariff for Iraq should not be less than 0.1 \$/kWh with a PB time equal to PV lifetime; a tariff of 0.12 \$/kWh is profitably for Iraq, as the PB time is 10 years.

Keywords: Hybrid-connected PV solar system, Economic analysis, Feed-in-tariff, Energy storage system

1 Introduction

In the mid-eighties of the last century, an equivalent of 10 billion metric tons of coal was burned each year. In 2025, the expected burn of coal will be 55 billion metric tons. This massive consumption of fossil fuels will deplete these non-sustainable resources and subject the Earth to more profound climate change and global warming threats. Thus, fossil fuels should be used efficiently; other clean energy sources must be developed simultaneously to achieve economic development without drastic changes to the Earth's climate. Solar energy can be an acceptable alternative to fossil fuels; the global PV industry has been growing at an average compound annual rate greater than 35% for the last decade. At the end of 2021, the world's cumulative PV capacity will be 714 GW [1].

Generally, Decker and Jahn [2] study the installation of 2000 rooftop grid-connected PV systems ranging from 1 to 5 kW to produce 5 MW at the federal state of Lower Saxony, Germany. The annual yield was between 430 and 875 kWh/kWp.a, with an average yield of 680 kWh/kWp.a. The system's annual performance ratio was 47.5 to 81%, with an average ratio of 66.5%. The low-performance ratio was due to the shadow effects and operational failure. Pietruszko and Gradzki [3] have evaluated the performance of a solar PV solar grid-connected system of 1-kW capacity in Warsaw, Poland. The system was installed in December 2000. The annual system of the measured energy was about 830 kWh, the performance ratio obtained between 60 and 80%, and the efficiency of the PV system was between 4 and 5%. Agrawal and Tiwari [4] study a building-integrated photovoltaic thermal (BIPVT) installed on the roof of the building to generate the energy and the thermal energy needed to heat the building. The results showed that the system performs better for the constant airflow velocity. The

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system is annually able to produce net electrical and thermal energy of 16209 and 1531 kWh, respectively, with an overall thermal efficiency of 53.7%. In 2008, Ayompe et al. [5] studied a 1.72-kW PV system installed on the flat roof in Dublin, and all the power generated has been fed at low voltage to the building. The total annual energy generated was 885.1 kWh/kWp; the reference yield, array yield, and annual average daily final yield were 2.85, 2.62, and 2.41 kWh/kWp/day, respectively. In Karnataka, India, Padmavathi and Daniel [6] use a 3-MW grid-connected solar PV plant installed to evaluate the performance. The average annual energy productivity was 1372 kWh; a performance ratio of less than 60% was reported from August to November 2011. Grid and inverter failure losses were estimated for 2 years of system operation. The final average annual yield and the reference yield were 3.73 and 5.36 kWh/kWp/day, respectively. Shiva Kumar and Sudhakar [7] study the performance of a 10-MW grid-connected solar PV power plant in India. Various system losses due to the high temperature, internal network, inverter wiring, and ohmic were calculated. The performance results were then compared with the simulated values obtained from the PVsyst and PV-GIS software. The final yield of the plant was found to range from 1.96 to 1.07 h/day, and an annual performance ratio is 86.12%. The annual amount of energy generated from the plant was about 15.7982 GWh. Sundaram and Babu [8] investigated the performance of a 5-MW grid-connected solar PV plant in India, with 24.11 MWh/day energy production. The analysis showed that the average daily array productivity, reference yield, and final productivity were 5.128, 5.46, and 4.81 h/day, respectively. It was found that the daily capture loss and system loss were 0.384 and 0.65 h/day,

respectively, and the efficiency of the inverter, unit, and system was 88.20, 6.08, 5.08%, respectively. In Malaysia, Farhoodnea et al. [9] studied the performance of a 3-kW grid-connected PV system between October 2013 and March 2014. The collected data showed that the average efficiency of the PV module is 10.11%, with the efficiency rate of the inverter being 95.15%. The system's performance ratio and capacity factor were 77.28% and 15.70%, respectively. Elhadj Sidi et al. [10] have built and analyzed the first solar PV plant in Mauritania, and the system capacity was 15 MWp. The system consists of seventeen arrays connected to the inverters, and the yield power is supplied to a 33-kV grid through nine transformers. The results showed that the performance of PV plants depends on both insolation and environmental conditions. Elkholy et al. [11] investigated the performance of an 8-kWp grid-connected PV system consisting of a 28×295 Wp polycrystalline module and an 8-kW three-phase grid inverter. The system was installed in August 2014 and generated 5.7 MWh until February 2015. The power produced by the system is directly injected into the grid without a storage device. Attari, Elyaakoubi and Asselman [12] studied the performance of a 5-kWp PV solar system in Morocco; the system consists of 20 modules of 250-Wp capacity and a 5-kW inverter. The total power delivered to the grid was 6411.3 kWh during 2015. The final yield ranged from 1.96 to 6.42 kWh/kWp; the annual averages of the unit, system efficiency, and the inverter were 12.39, 11.99, and 96.7%, respectively. Sahooane et al. [13] collected and analyzed the data of a 28-kWp PV system installed in the Sahara region in southern Algeria in 2017. The data analysis showed that the final output was 5.3 h/day. The annual production injected into the grid was



Fig. 1 Installation of the PV system

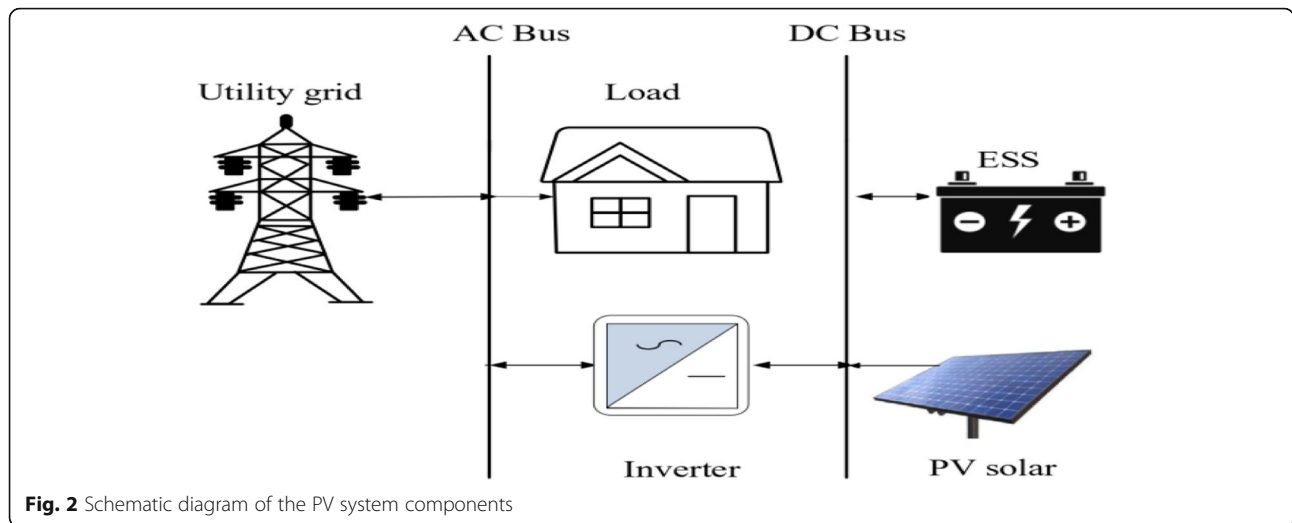


Fig. 2 Schematic diagram of the PV system components

45.12 MWh, with a grid voltage loss of 2.4 MWh. Yahya et al. [14] have studied the performance of a 48-kW grid-connected PV system in Nouakchott, Mauritania. It was found that the PV plant provides 65.668 MWh to the grid; the annual averages of the efficiency of the PV module, system, and inverter combination were 11.22, 9.49, and 84.6%, respectively. The average annual performance ratio and capacity factor were 77.66 and 19%, respectively. The final yield ranges from 3.91 to 5.09 kWh/kWp/day, with a performance ratio varying from 69.69 to 89.35%. Fetyan and Hady [15] studied the performance of an on-grid rooftop PV system of a capacity of 90 kW in Egypt. It was simulated using the MATLAB software to incorporate more accurate information about the system configuration. The simulated output power of the system was compared with different solar energy densities; a deviation was found due to the blackout. In

July, the maximum power generation was 14.5 MWh, while the average power that was generated in December and January was 5 MWh.

Various studies of the PV solar systems available in the literature can be divided into two main categories: a grid-tied PV solar system and a hybrid renewable system consisting of wind and diesel generators. It can be seen from the literature that the previous main works were only theoretical work, and they are a shortage studied on the performance of the on/off grid-connected solar PV system with an ESS system, which is called a hybrid-connected solar system. However, hybrid solar energy systems are considered uneconomical because of the need for an energy storage system. However, the power supply situation in Iraq needs a long-term study on the performance of the hybrid-connected PV systems to cover the load throughout the day. Techno-economic analysis of a 5-kWp capacity hybrid-connected solar system is performed in this work. The rooftop PV solar system consists of 18 polycrystalline PV modules of 355 W each, an energy storage system consisting of 8 batteries of 150 Ah, 12 V, and an intelligent inverter of 5-kWp capacity. The system is installed in Diyala, Iraq (33.77° N, 45.14° E, elevation 44 m). The PV string output energy and the load sharing between the PV output, the grid, and the discharging energy from the energy storage

Table 1 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	

*Standard test conditions: irradiance 1000 W/m², cell temperature 25 °C, and AM 1.5

**Normal operating cell temperature: irradiance 800 W/m², ambient temperature 20 °C, and AM 1.5 wind speed 1 m/s

Table 2 The 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

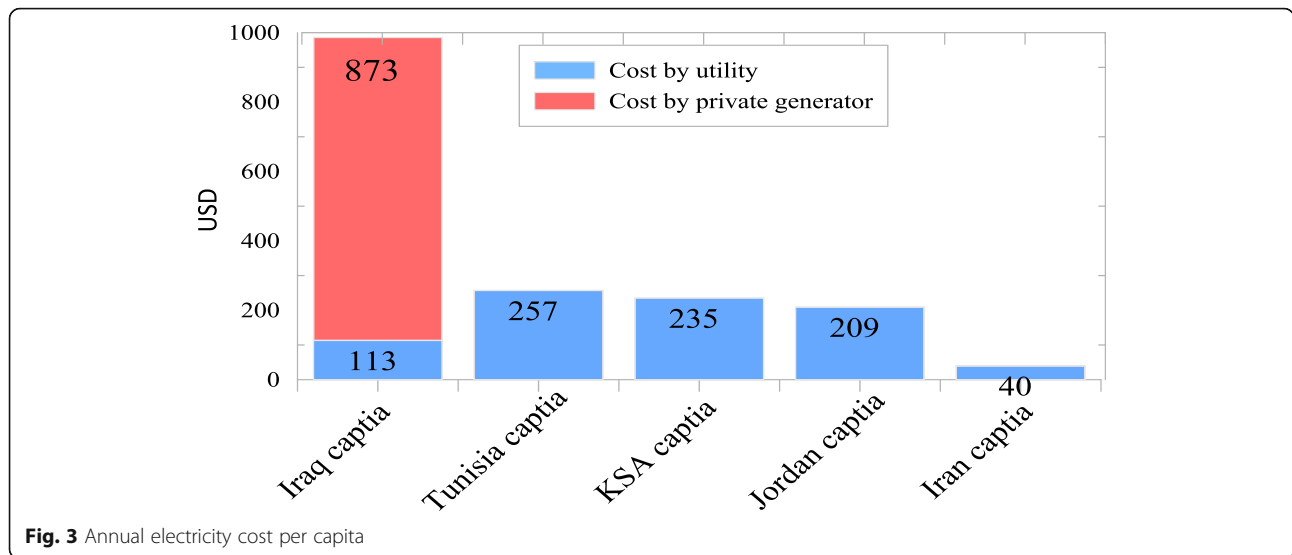


Fig. 3 Annual electricity cost per capita

system are studied. While the economic assessment of the PV system is performed by calculating the net present value (NPV) depending on the discount cash flow method, from the results, the payback time is found.

2 Methods and materials

2.1 Description of the hybrid solar PV system

The current roof PV solar system’s installed capacity is 5 kWp installed on the roof of a house at Diyala, Iraq (33.77° N, 45.14° E, elevation 44 m) as shown in Fig. 1. The PV string consists of two arrays, each of 9 polycrystalline solar modules of 355 Wp (Fig. 2). The net installation area of the system was 30.6 m²; the specification of the PV module and PV array is shown in Tables 1 and 2. The tilt angle of the strings is 35° toward the south.

The EES consists of 8 tubular deep cycle solar battery lead-acid batteries of 12 V and 150 Ah. The ESS array consists of two strings for compatibility of the electrical connection between the batteries and the inverter (Fig. 3). Each string consists of 4 batteries in series to achieve 48 V. The two strings are connected in parallel to give 300 Ah. Table 3 shows the specification of the batteries used in ESS. A solar infinity pure sine wave

Table 3 Specifications of the lead-acid battery

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

hybrid inverter of the rated power of 5 kW is used. The inverter can stimulatingly manage power to/from solar, battery, load, and generator which also provides multiple inverter parallel operation functions with on-grid and off the grid; Table 4 shows the inverter specifications. The system data was analyzed for an entire year, starting from the first of September 2020 to the end of August 2021.

2.2 Technical analysis

According to the Indian Standard IEC 61724 [16], the following parameters should be measured to perform the PV solar system’s hourly, daily, monthly, and annual analysis; for the outdoor conditions, the hourly global solar radiation on a tilted surface by 35° and the ambient temperature; for the inverter, the output voltage, current, and output power; for the load, the voltage, current, and the measured data for the utility grid: the voltage, the current to the utility grid, the power supplied to the utility grid, the current from the utility grid, and the power from the utility grid; and for the ESS, the

Table 4 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

operating voltage, the current to the ESS, the power to the ESS, the current from the ESS, and the power from the ESS. After getting the above measurement variables, the techno analysis is performed including the net energy supplied and delivered by the ESS and the utility grid the efficiencies with which the energy supplied from all sources is transmitted to the load. The PV system yields, namely, the final and reference yields. The performance ratio indicates the effect of overall losses on the rated array output and, finally, the overall PV efficiency. Table 5 shows the mathematical expression for the system technical analysis.

3 Economic analysis

The annual energy consumption per capita in Iraq in 2019 was 4.74 MWh/year; the state can provide only 3.77 MWh/year. As shown in Fig. 6, the shortage in energy supply is the private generator covered 0.97 MWh/year. The annual cost of the energy shortage is about \$873, while the state average tariff is 0.03 \$/kWh [21]. The annual cost of the energy demand per capita is \$986, then 0.2 \$/kWh is the total tariff of the energy supplied by the private generator and the state. So, the solar system’s economy is calculated based on the lowest tariff in Iraq, which is equal to 0.01 \$/kWh up to the actual tariff for Iraq.

To perform the economic analysis of the PV solar system, four main metrics should be assigned and calculated, namely, investment, capital cost, electricity generating infrastructure, and operating costs and the levelized cost of electricity (LCOE). The four assessment metrics mentioned are calculated using the equations in Table 6. Table 7 shows the requirement for performing the economic analysis of the current PV solar system.

4 Results and discussions

Figure 4 shows the average monthly wind speed, ambient temperature, and the incidence of solar radiation on a 35° tilted surface facing south for Diyala, Iraq (33.77° N, 45.14° E, elevation 44 m). The typical average seasonal load profile is shown in Fig. 5. Figure 6 shows the average monthly solar intensity, the energy production by the PV system, and the string efficiency. It can be seen from the figure that the solar system produced less energy as compared with the solar intensity. The main reason for that is the low PV string efficiency. The higher energy production by PV system from May to October is due to the increases of the solar intensity and the length of the summer days compared to the other season days.

PV systems at different locations and configurations can be compared by calculating their normalized systems performance indices such as losses, efficiencies,

Table 5 Mathematical expression for the system technical analysis [17–20]

Expression	Mathematical expression	Unit	Eq. no.
Final energy output corresponding time (τ)	$E_{i,\tau} = \tau \cdot \sum_{\tau} P_i$	kWh/ τ_{τ}	(1)
The mean daily global solar radiation	$H_{i,d} = \frac{24 \cdot \tau \cdot \sum_{\tau} G_j}{1000 \cdot \sum_{\tau} T_{AM}}$	kWh/m ² day	(2)
The net energy supplied to the ESS	$E_{TSN,\tau} = E_{TS,\tau} - E_{FS,\tau}$	kWh/ τ_{τ}	(3)
The net energy delivered from the ESS	$E_{FSN,\tau} = E_{FS,\tau} - E_{TS,\tau}$	kWh/ τ_{τ}	(4)
The energy delivered to the utility grid	$E_{in,\tau} = E_{A,\tau} + E_{FUN,\tau} + E_{FSN,\tau}$	kWh/ τ_{τ}	(5)
The energy supplied from the utility grid	$E_{use,\tau} = E_{L,\tau} + E_{TUN,\tau} + E_{TSN,\tau}$	kWh/ τ_{τ}	(6)
The fraction of the energy from all sources	$F_{A,\tau} = \frac{E_{A,\tau}}{E_{in,\tau}}$	–	(7)
The efficiency with which the energy from all sources is transmitted to the load	$\eta_{Load} = \frac{E_{use,\tau}}{E_{in,\tau}}$	–	(8)
Array yield	$Y_A = \frac{E_{A,d}}{P_{rated}}$	h/day	(9)
Reference yield	$Y_r = \frac{\tau \cdot \sum_{\tau} G_j}{G_{i,ref}}$	h/day	(10)
Final yield	$Y_f = Y_A \cdot \eta_{Load}$	h/day	(11)
Array capture loss	$L_c = Y_r - Y_f$	h/day	(12)
Performance ratio	$R_p = \frac{Y_f}{Y_r}$	–	(13)
Mean array efficiency	$\eta_{A,mean} = \frac{E_{A,\tau}}{A_{o,\tau} \cdot \sum_{\tau} G_j}$	–	(14)
Overall PV system efficiency	$\eta_{tot,\tau} = \eta_{A,mean} \cdot \eta_{load}$	–	(15)

Table 6 Mathematical expression for the PV solar system economic assessment [22–24]

Expression	Eq.	Unit	Eq. no.
The average daily energy supplied from the battery bank	$E_{F-B} = \sum_{t=0}^{8759} \frac{P_{F-B}(t)}{365 \times 1000}$	kWh/day	(16)
Battery life	$Life_{bat} = \frac{C_{bat} \cdot N_{cycles}}{\frac{E_{PSN-365}}{\eta_{bat-D} \cdot \eta_{AC/DC}}}$ $N_{cycles, act} = 0.8 \cdot N_{cycles}$	years	(17)
The component replacement number	$Nrep_j = \text{Integer} \frac{Life_{system}}{Life_j}$	–	(18)
The net present cost of replacing the components	$NPCrep_j = \sum_{k=1}^{Nrep_j} (Cost_j \cdot \frac{(1+g)^{k \cdot Life_j}}{(1+l)^{k \cdot Life_j}}) - Cost_j \cdot \frac{(Life_{sys} - Nrep_j \cdot Life_j) \cdot (1+g)^{k \cdot Life_{sys}}}{(1+l)^{k \cdot Life_{sys}}}$	\$/year	(19)
The overall net present cost of the components of the system	$NPC_{comp. \&O\&M} = \sum_{k=1} (Cost_j + NPCrep_j) + \sum_{k=1}^{Life_{sys}} (Cost_{O\&M} \frac{(1+g_{O\&M})^k}{(1+l)^k})$	\$/year	(20)
The NPC of the electricity that is used to charge the battery	$NPC_{E_{F-B}} = \sum_{k=1}^{Life_{sys}} (Pr_{elec} \cdot \frac{E_{F-B} \cdot 365}{\eta_{Overall}} \cdot \frac{(1+g_{pr_elec})^k}{(1+l)^k})$ $\eta_{Overall} = \eta_{AC/DC} \cdot \eta_{bat_ch} \cdot \eta_D \cdot \eta_{DC/AC}$	\$/year	(21)
Then the system total cost with storage,	$NPC_{WO} = NPC_{comp.+O\&M} + NPC_{E_{F-B}} + \sum_k^{Life_{sys}} \{ \{ (Pr_{elec} \cdot E_{F-B} \cdot 365) + (Cost_{f-y}) \} \cdot \frac{(1+g_{pr_elec})^k}{(1+l)^k} \}$	\$/year	(22)
Profitability index (PI)	$PI = \frac{\sum_{j=1}^N \frac{Revenue_t}{(1+d)^t}}{\text{Investment Cost}}$	%	(23)
Benefit-to-cost (B/C) ratio	$B/C = \frac{\sum_{j=1}^N \frac{Revenue_t}{(1+d)^t}}{\sum_{j=1}^N \frac{Cost_t}{(1+d)^t}}$	%	(24)
Modified internal rate of return (MIRR)	$MIRR = \left(\frac{\sum_{j=1}^N PCF_t \cdot (1+r)^{N-1}}{\sum_{j=1}^N \frac{PCF_t}{(1+d)^t}} \right)^{1/N} - 1$ $PCF_t = \begin{cases} Revenue_t - cost_t & \text{if } Revenue_t > cost_t \\ 0 & \text{if } Revenue_t \leq cost_t \end{cases}$ $NCF_t = \begin{cases} 0 & \text{if } Revenue_t \geq cost_t \\ Revenue_t - cost_t & \text{if } Revenue_t < cost_t \end{cases}$	%	(25)
Simple payback	$PBP = \frac{PV \text{ price} - \text{Federal ITC}}{\text{Annual PV Revenue} - O\&M}$	years	(26)
Levelized cost of energy	$LCOE = \frac{\sum_{j=1}^N \frac{Cost_t}{(1+d)^t}}{\sum_{j=1}^N \frac{\text{Electrical Energy}_t}{(1+d)^t}}$	\$/kWh	(27)

and yields. The yield’s units are kWh/day/kW or h/day and represent the energy quantities normalized to PV-rated string power. Three categories of average monthly daily yield are shown in Fig. 7. The first is the average array yield, representing the daily energy output by array per kilowatt of installed capacity. The second is the reference yield which is the total daily irradiation divided by the standard irradiance test conditions of the module. The final yield is net AC energy output divided by the rated DC power of the PV array. The figure shows the higher yields are for the summer, and the lowest is for

spring and autumn. This is due to the difference in the daily number of sunny hours for each season. However, the reference yield is the maximum, followed by array yield, and the minimum is the final yield.

The ESS is used to cover the energy shortage supplied by the PV system during nighttime, rainy, or stormy days. For the current PV solar system, it was observed that the ESS was mainly charged during nighttime using the purchased energy from the grid. It can be seen from Fig. 8 that the minimum energy used to charge the ESS is for summer due to the low consumption of energy

Table 7 The requirement for performing the economic analysis of the current PV solar system

Item	Value	Units
Capital investment	5360	\$
Yearly EAC	8960	kWh
Electric tariff	0.1	\$/kWh
Inverter cost	900	\$
Inverter lifecycle	10	years
PV panels cost	2520	\$
PV panels lifecycle	20	years
PV panels degradation	1	%/year
Batteries cost	1440	\$
Batteries lifecycle	5	years
Operating cost (including the replacement of batteries and inverter)	335.82	\$/year
The annual inflation for the operation and maintenance	0.057	%
The annual interest rate	4	%

(discharge energy) at the short summer nights. The charging energy is always higher than the discharging energy due to the ESS efficiency and losses.

The extra energy generated by the PV system was supplied to the grid; the amount of energy supplied is different from season to season, as shown in Fig. 9. The figure shows that grid feed-in energy is insignificant in summer due to the high energy consumption, as shown in Fig. 5a. The grid feed-in energy increases in the winter and then in the autumn and spring seasons due to the lack of heating and cooling devices. The purchasing energy is used to cover the shortage of energy supplied by the grid, as it is expected that the maximum purchasing energy was in summer due to the use of cooling devices, and the less was in winter.

Two types of losses can be seen in Fig. 10. Namely, the array capture loss is due to the weather conditions, PV electrical resistance, and electrical mismatching. The second is the system loss due to the conversion of energy from DC to AC, wiring, and inverter. It can be seen from the figure that the array capture loss is the maximum as compared with that for the system; the array capture loss is maximum in spring, autumn, and winter, and the minimum is in summer.

Figure 11 shows the variation of the average monthly daily performance ratio (R_p) and the system efficiency. The R_p denotes the effect of the overall system losses on the output of the PV array due to the inefficiencies of the system components, incomplete solar radiation utilization, and PV modules temperature. In contrast,

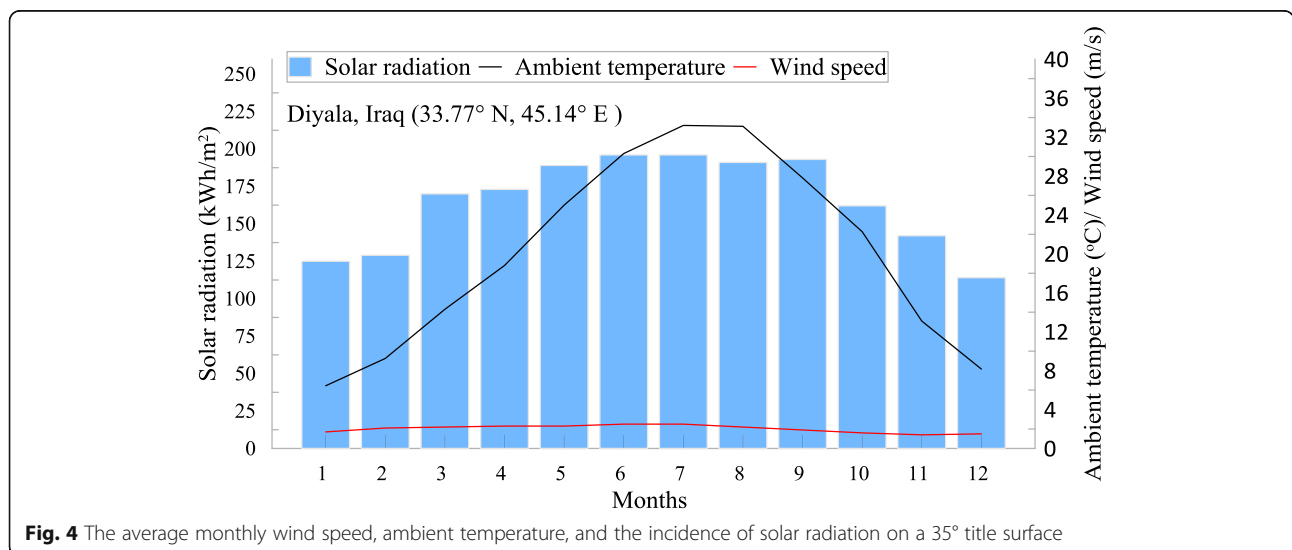
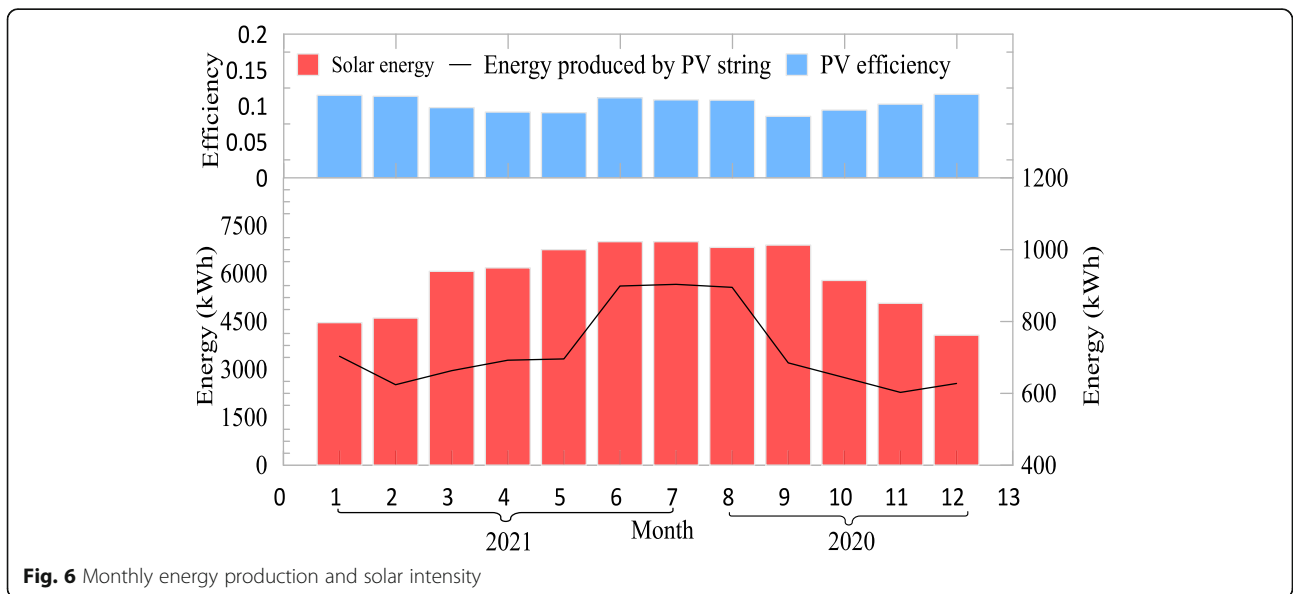
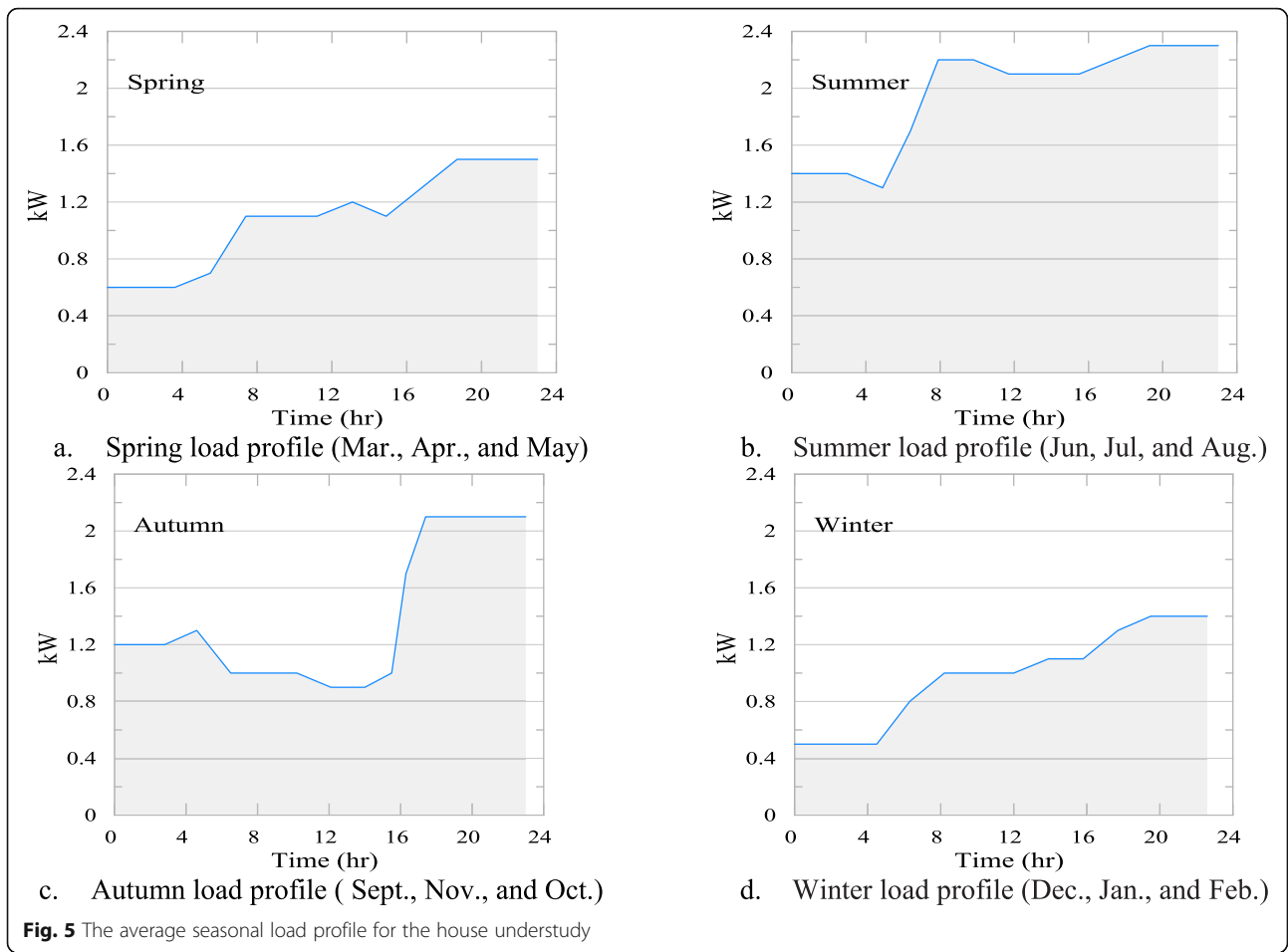
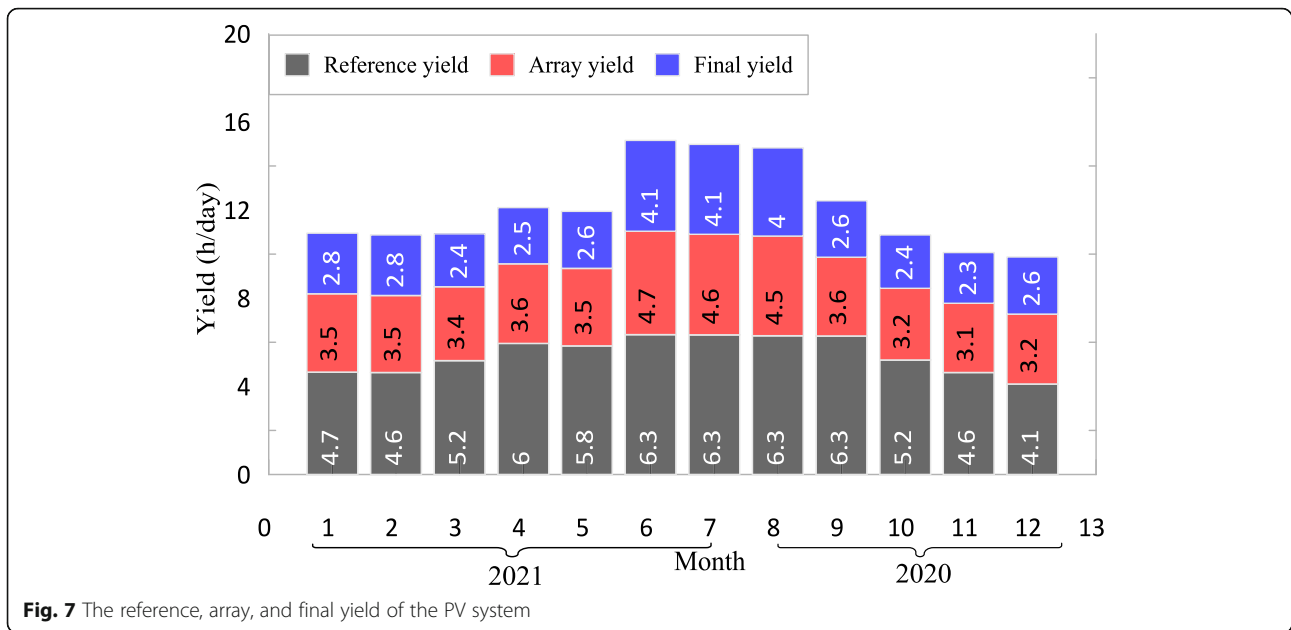


Fig. 4 The average monthly wind speed, ambient temperature, and the incidence of solar radiation on a 35° title surface



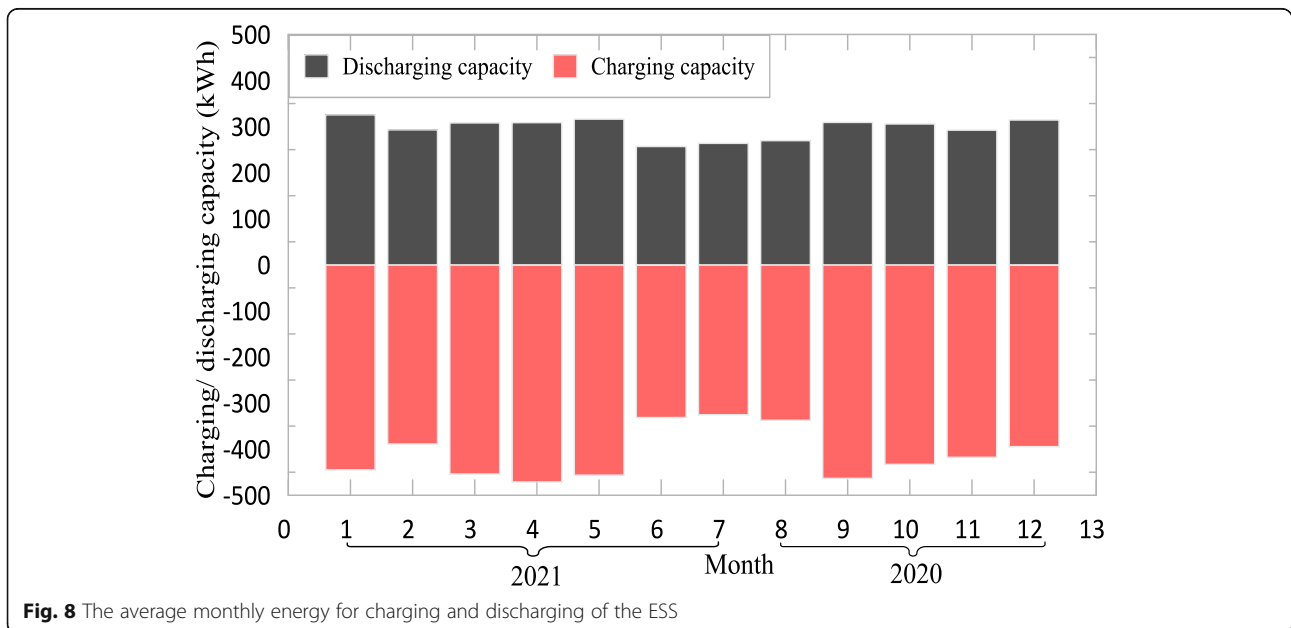


system efficiency is defined as the AC energy generated by the PV system to the irradiation on the PV array. According to the figure, R_p is 0.4 in autumn and 0.65 in summer. At the same time, the minimum system efficiency is 0.72 in autumn and a maximum of 0.89 in summer.

Figures 12 and 13 show the yearly performance of the system; it can be seen from Fig. 12 that the array efficiency is 0.1, the R_p is 0.536, and the system efficiency is

0.78, while Fig. 13 shows that the average yearly monthly reference, array, and final yields are 5.46, 3.7, and 2.6 h/day, respectively.

Figure 14 shows the variation of the return on investment (ROI), the net present value (NPV), and the pay-back of the PV solar system vs. the tariff. It can be seen from the figure that when the tariff is less than 0.1 \$/kWh, the total costs of the PV system are more significant than returns. Thus, the system is unprofitable. The



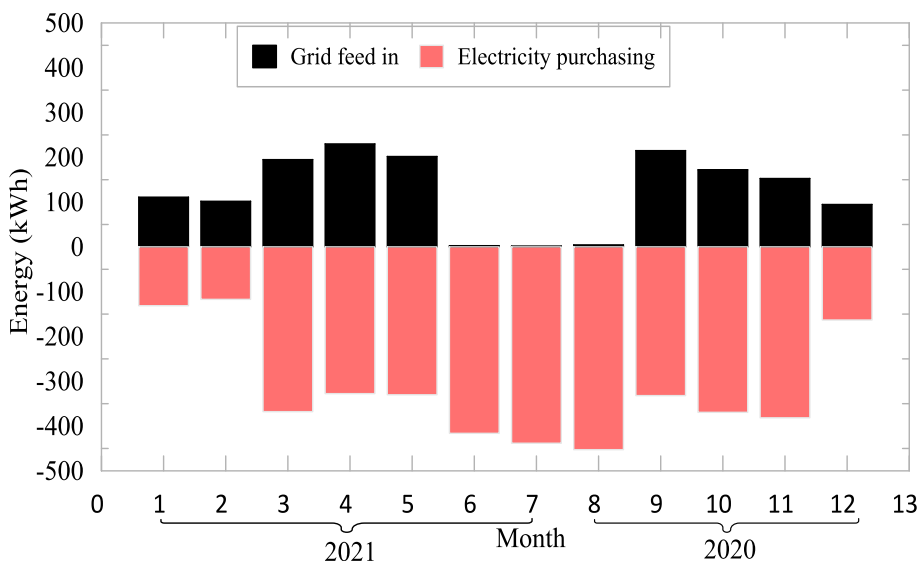


Fig. 9 The average monthly daily grid feed-in and the purchasing energy

positive NPV means that the produced cash flow at the investment end life gives more revenue than the initial investment cost; this is not true when the NPV and ROI are negative. The payback time is about 15.5 years at the minimum profitable tariff of 0.1 \$/kWh; the payback time reduces to about 5 years when the tariff is 0.2 \$/kWh. Figure 14 shows the cash flow and system components cost at a tariff of 0.2 \$/kWh.

Figure 15 shows the cash flow and system components cost at a tariff of 0.2 \$/kWh. It can be seen from the

figure that the annual cash flow does not increase as much as the investment cost during the first to the fifth year of PV system life. The cost of replacing the ESS and the inverter is shown in the fifth, tenth, and fifteenth years of the system life. The cost of O&M shows an increase during the system life due to the annual inflation of the O&M cost.

Figure 16 shows the effect of the tariff on the payback time and NPV. It can be seen from the figure that as the tariff increases, the payback time reduces, and the NPV

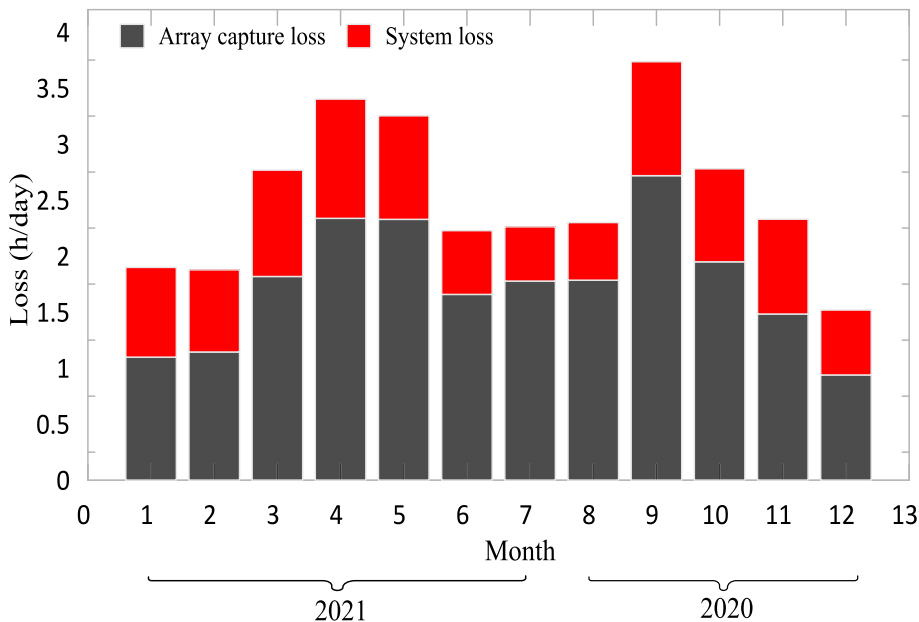
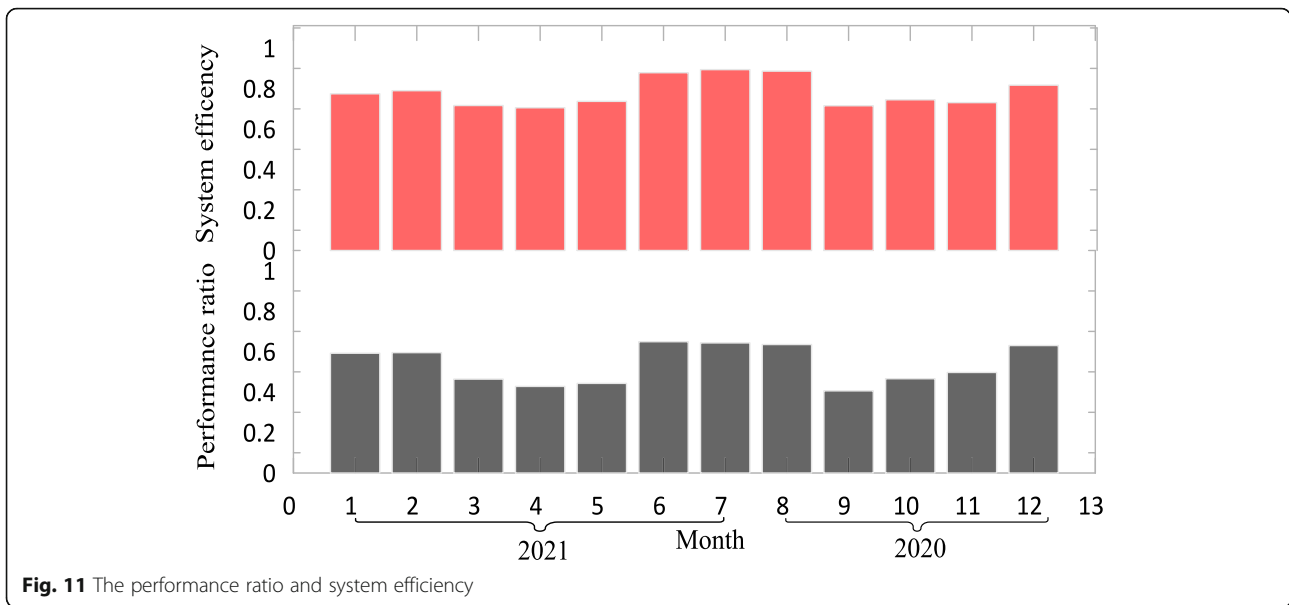


Fig. 10 Array capture and system losses

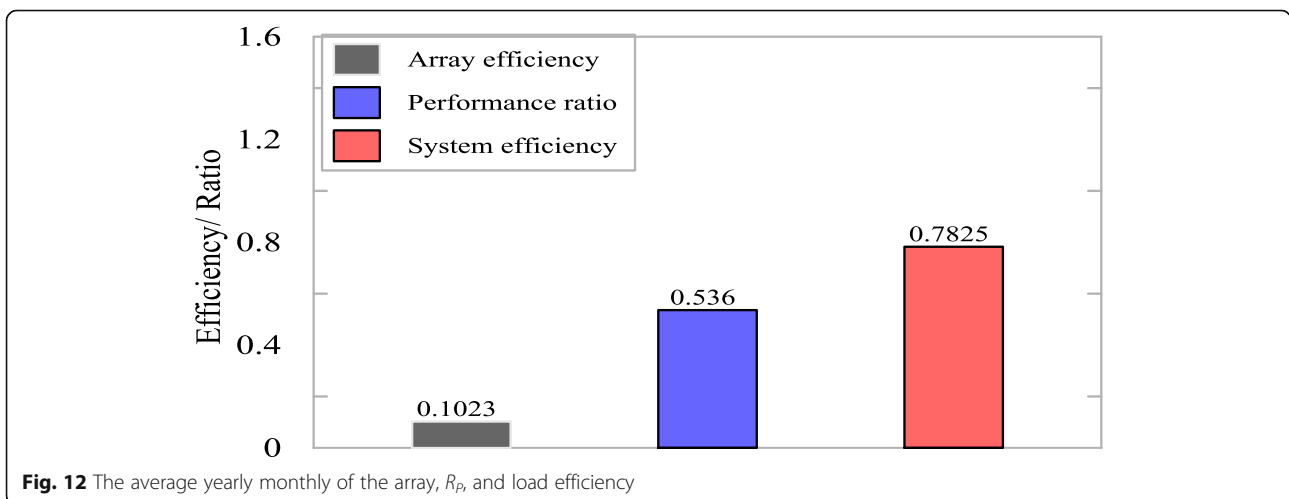


increases. The minimum tariff for Iraq should be not less than 0.1 \$/kWh to make the residential PV solar profitable. The figure shows that a tariff of 0.12 \$/kWh is profitably for Iraq, as the payback time decreases from 15.5 to 10 years, and an increase in the tariff greater than 0.12 \$/kWh leads to a gradual decrease in payback time that is not commensurate with the increase in tariff.

5 Conclusions

The following conclusions are derived from the annual results of the techno-economic analysis of the system:

- The annual energy yield of the current PV system is 8.9 GWh/year.
- The annual array efficiency, performance ratio, and load efficiency were 0.126, 0.66, and 0.92, respectively.
- The reference, array, and final yields were 6.1, 3.88, and 3.99 h/day, respectively.
- The minimum energy feed to the grid was in summer, and the maximum was in winter.
- The maximum purchasing energy was in summer, and the less was in winter.
- The economic assessment showed that the minimum tariff for Iraq should not be less than 0.1 \$/kWh where the PB approximately time equals PV lifetime.
- The energy tariff in Iraq should be 0.2 \$/kWh, which makes the PB time is 10 years



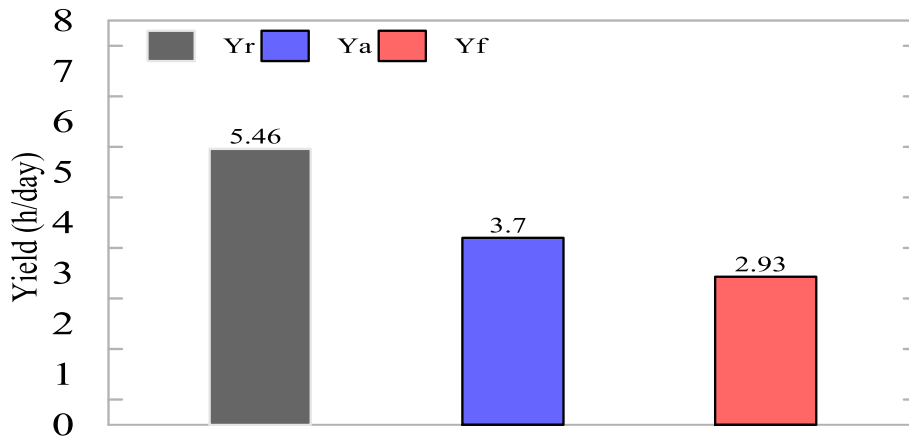


Fig. 13 The average yearly monthly system yields

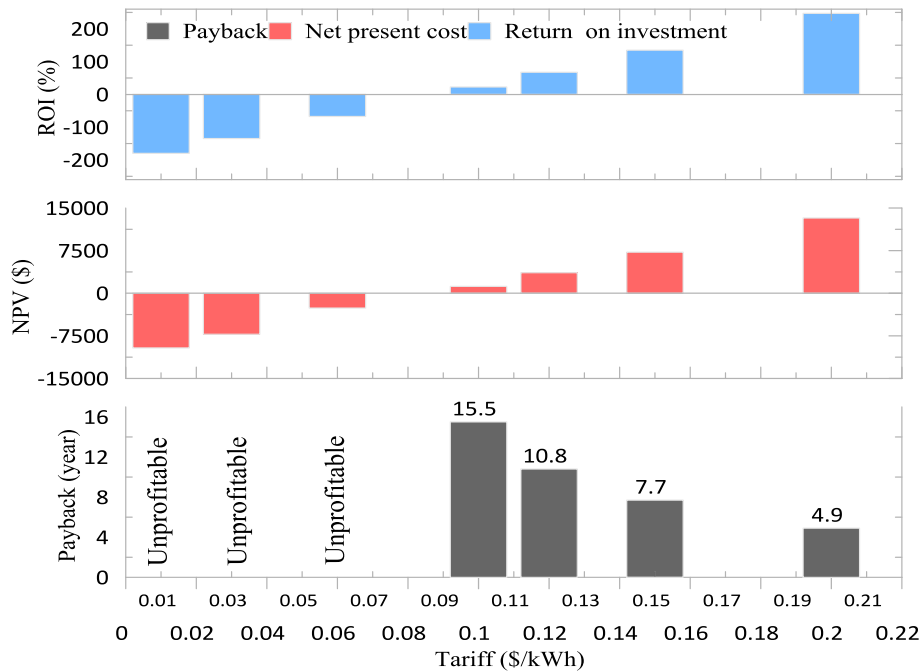


Fig. 14 The return on investment, NPV, and payback time for different tariff

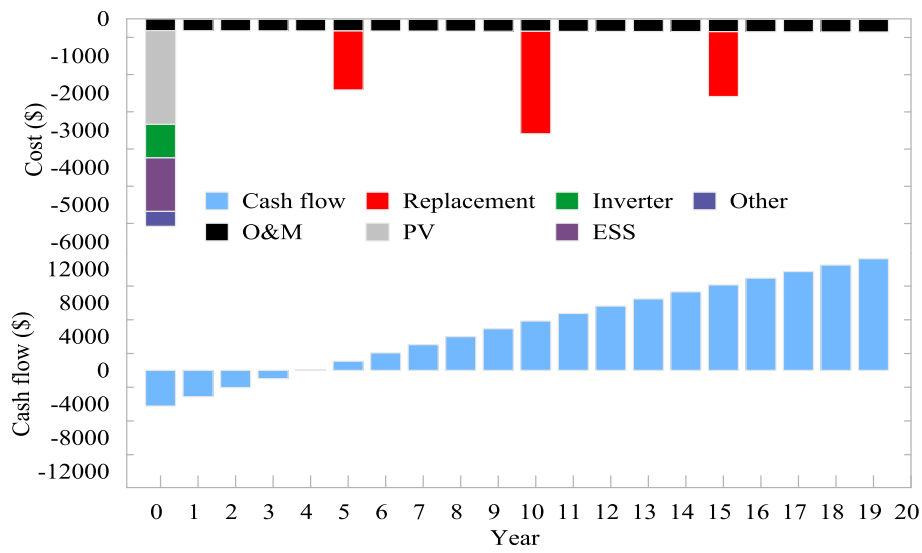


Fig. 15 The cash flow and system component cost at a tariff of 0.2 \$/kWh

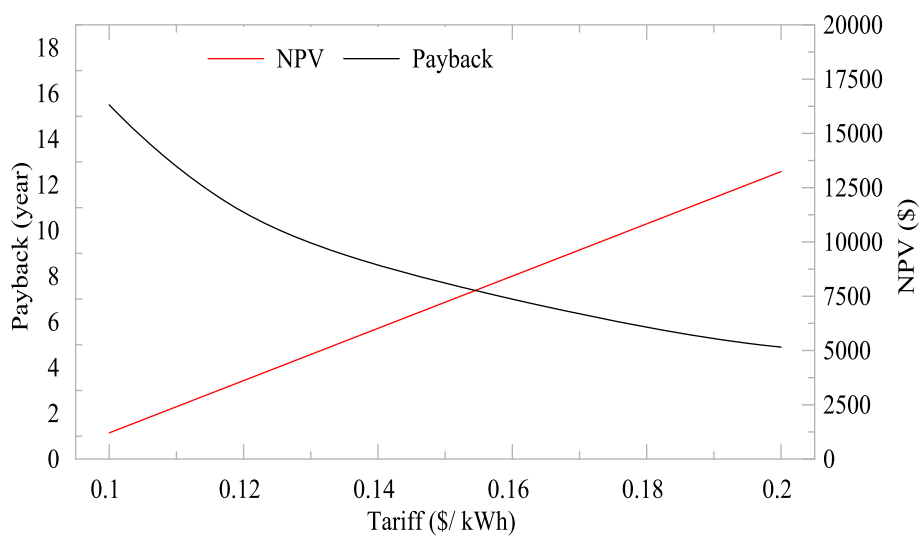


Fig. 16 The effect of the tariff on the payback time and NPV

- The payback periods were between 5 and 15.5 years when the tariff is between 0.1 and 0.2 \$/kWh.

5.1 Symbols

A_d : area of PV string	m^2
B/C: benefit-to-cost ratio	%
$Cost_{fixed_year}$: the annual fixed cost due to the electrical power from the grid	\$
$Cost_c$: cost of components	\$
$Cost_{O\&M}$: cost of operation and maintenance	\$
$E_{A,d}$: daily net energy from the array	kWh
$E_{A,\tau}$: net energy from array corresponding time (τ)	kWh
$E_{FS,\tau}$: energy from the ESS system corresponding time (τ)	kWh
$E_{FSN,\tau}$: net energy from storage	kWh
$E_{FUN,\tau}$: net energy from the utility grid	kWh
$E_{in,\tau}$: total system input energy	kWh
$E_{l,\tau}$: final energy output corresponding time (τ)	kWh
E_L : net energy to load	kWh
$E_{TSN,\tau}$: the net energy supplied to the ESS	kWh/ τ_T
$E_{use,\tau}$: the energy supplied from the utility grid	kWh/ τ_T
$F_{A,\tau}$: the fraction of the energy from all sources	-
G_i : total irradiance in the plane of the array	W/ m^2
g_j : the annual inflation for the cost of the component	
$G_{l,ref}$: reference solar radiation	W/ m^2
$g_{O\&M}$: the annual inflation for the operation and maintenance	
g_{pr_elec} : the annual inflation for the price of electricity	
H_i,d : the mean daily global solar radiation	kWh/ m^2 day
i : the annual interest rate	%
$I_{bat}(\Delta t)$: input/output current by the battery	A
L_c : array capture loss	h/day
LCOE: levelized cost of energy	\$/kWh
$Life_{system}$: the duration of the study period	years
MIRR: modified internal rate of return	
N_{cycles} : the number of equivalent complete cycles until battery failure, usually	cycle
$NPC_{comp. \& O\&M}$: the overall net present cost of the components of the system	\$/year
$NPC_{comp. + O\&M}$: net present cost of operation and maintains	\$
$NPC_{E_{F,d}}$: the NPC of the electricity that is used to charge the battery	\$/year
NPC_{rep} : the net present cost of replacing the components	\$/year
NPC_{WO} : the system total cost with storage	\$/year
N_{rep} : net replacement cost of components	\$
PBP: simple payback	years
$P_{F_B}(t)$: output power	kW
PI: profitability index (PI)	%

Symbols (Continued)

P_{rated} : rated power	kW
$Pr_elec_off_peak$: cost of electricity and off-peak time	\$/kWh
R_p : performance ratio	
Y_d : array yield	h/day
Y_f : final yield	h/day
Y_r : reference yield	h/day

5.2 Greek symbols

δ : the self-discharge coefficient	
$\eta_{A,mean}$: mean array efficiency	-
$\eta_{AC/DC}, \eta_{bat_chr}, \eta_{D}$, and $\eta_{DC/AC}$: the efficiencies of converting AC to DC, battery, discharge, and AC to DC	
$\eta_{A,mean}$: mean array efficiency	
η_{bat_Ch} : battery charging efficiency	
η_{load} : load efficiency	
$\eta_{tot,\tau}$: overall PV system efficiency	-

Authors' contributions

The authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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