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Collective self-consumption of solar photovoltaic and batteries for a micro-grid energy system

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ABSTRACT

The paper carried out a techno-economic analysis in order to obtain the optimum battery storage capacity in conjunction with a photovoltaic array that can match the desired household load at highest possible self-consumption. In addition, it determined the economic feasibility of a proposed micro-system. Annual energy consumption, irradiance, and ambient temperature were measured at 1-min resolution for the year 2021. Simulations of a stationary economic model are performed for the years 2021 through 2030.The results showed that the photovoltaic array at 2.7 kWp capacity can generate an annual energy of approx. 4295.4 kWh and the optimal battery capacity which can satisfy 91.1% of self-consumption and energy cost of $0.256/kWh is 14.4 kWh. Furthermore, two third-order polynomial relationships between self-consumption and net present cost with energy cost were solved.

1. Introduction

Solar energy is generally considered crucial for addressing climate change by reducing greenhouse gas emissions from the energy sector [1]. After a downturn in 2018, the worldwide solar energy sector benefitted from a strong rebound in 2019, with total (PV) installations around the World reaching approx. 627 GW [2]. This capacity provides approximately 3% of global electrical consumption and corresponds to 5% of global CO_2 emissions connected to electricity [3]. The supply of assistance and the general decline in costs are major factors in the expansion of the PV market. However, subsidies designed to compensate for the capital-intensive nature of PV investments are evolving. Injection remunerations paid by distribution center network operators, which will be termed the injection price in the following context. Now or soon, it will be lower than the retail rate, which promotes PV self-consumption. The use of battery storage (BA), which might increase the rate of self-consumption of locally generated energy while simultaneously resolving real-time imbalances created by forecast errors, is one of the strategies to allow the continued expansion of PV installations [4]. In the past, exorbitant prices and restricted use-case configurations were significant barriers to battery installations. Batteries are currently considered one of the most promising alternatives to enable the shift to renewable energy sources since the rapid drop in battery prices during the last decade, driven by improvements in the electric vehicle sector [5].

In recent years, considerable research has been conducted on the techno-economic evaluations of PV/battery-based systems, particularly in German where favorable renewable law was established. Allwyn et al. [6] optimised a PV/BA system for the Sultan Qaboos University Street lighting system in Oman. The authors compared the life cycle cost analysis and cost per capita for two configurations of PV and battery systems, the first with a large capacity of PV/BA and the second with a small one, which helps to determine the techno-economic viability of implementing the system in Oman. For that research study, MATLAB tool was used to evaluate optimum system sizing, and inputs were based on experimental data. The results indicated that the cost per kilowatt hour of energy produced with the large panel/BA system was $/0.08 compared to $/0.9 per kilowatt-hour for the small system capacity.

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Table 1
A review of PV/BA energy micro-systems.

Load type	Location	Year	Model type	Battery type used with PV system	Ref.
Experimental	Germany	2014	Optimization	PV/Lead–acid	[24]
Experimental	Germany	2016	Simulation	PV/Lithium-ion	[25]
Experimental	Germany	2016	Simulation	PV/Lithium-ion	[26]
Experimental	Germany	2016	Simulation	n/a	[27]
Experimental	Sweden	2016	Optimization	PV/Lithium-ion	[28]
Experimental	Australia	2016	Optimization	PV/Lithium-ion & lead–acid	[29]
Fabricated	Europe	2016	Simulation	n/a	[30]
Fabricated	Portugal	2017	Simulation	PV/Lead–acid	[31]
Experimental	Germany	2017	Optimization	PV/Lithium-ion	[32]
Fabricated	Germany	2017	Simulation	PV/Lithium-ion	[33]
Experimental	Sweden	2017	Optimization	PV/Hydrogen & lithium-ion	[34]
Experimental	UK	2017	Simulation	PV/Lithium-ion	[35]
Experimental	UK	2017	Optimization	PV/Lithium-ion	[36]
Fabricated	Portugal	2017	Simulation	PV/Lithium-ion	[37]
Experimental	Belgum	2017	Simulation	PV/Lithium-ion	[38]
Experimental	Australia	2017	Simulation	n/a	[39]
Fabricated	China	2017	Optimization	PV/Lithium-ion & lead–acid	[40]
Experimental	China	2018	Optimization	PV/Lithium-ion	[41]
Fabricated	United States	2018	Simulation	PV/Lithium-ion	[42]
Experimental	Australia	2019	Simulation	PV/Lithium-ion	[43]
Fabricated	China	2019	Simulation	Reused EV battery	[44]
Fabricated	Finland	2019	Simulation	PV/Lithium-ion	[45]
Fabricated	Italy	2020	Simulation	n/a	[46]
Experimental	Thailand	2020	Simulation	PV/Lithium-ion	[47]

Furthermore, the results indicate that the conversion of an 8.6-km-long grid-connected street lighting system with 285,400-W lamps to a PV/BA system with an 80 W lamp is predicted to cut yearly CO_2 emissions by 133,600 tonnes.

Gul et al. [7] developed a novel mathematical model for the PV/BT system to optimise power production and balance load demand. The System Advisor Model evaluates energy generation, energy consumption, and economic performance, including capital cost, total investment, net present cost (NPC), and project levelized cost of electricity (COE), using mathematical optimization software. The use of decentralised load centers to exchange electricity with neighbouring towns is an innovative solution. The created model is connected to the grid with the purpose of enhancing the flexibility, dependability, and environmental protection of the system to decrease CO_2 emissions. The analysis revealed that the yearly energy expenses with the proposed solution reduced these costs by 45%, in addition the environmental research on the model shows that CO_2 emissions have decreased by 1150 tonnes per year.

Li et al. [8] explore the techno-economic aspects of hybrid renewable energy design decisions that satisfy the multi-vector energy demand, that is, electricity, hydrogen, and heat, in four different locations in China. A two-stage strategy for optimization is proposed: First, the HOMER programme is used to determine every viable scenario that meets requirements at the lowest cost; Then, a Multi-Criteria Decision-Making approach is used to assess all viable situations in order to establish the ideal option for economic and environmental aspects monitoring. The optimal combination of the following technologies is determined as follows PV/BA and PV/WT (wind turbine). The results obtained indicate that the PV/WT hybrid system has advantages over PV alone and WT alone in terms of power production in regions with abundant solar and wind energy. Ashtiani et al. [9] demonstrate how backup PV/BA systems could turn off power bills, even in countries with inexpensive and subsidised electricity. The NPC and COE of the on-grid PV/BA system are 15.6% and 16.8% higher, respectively, than in the non-renewable scenario. The indicators NPC and COE were evaluated and compared with two other optimization algorithms, in order to verify the proposed methodology and determine the efficiency and precision of the results. Several cities were analysed to compare the results, and the comparability of the statistics demonstrated that the system is effective regardless of the local climate. In addition, sensitivity analysis based on climate data from different cities, different load needs, and PV costs helped to find the best size system for the economy. Ma et al. [10] examined PV/BA and PV/WT and found that a hybrid power plant with BA can decrease NPC by around 9 and 11% compared to PV and WT alone. Merei et al. [11] provide optimization results for a supermarket in Aachen, Germany, in terms of self-sustainability. Using precise experimental load data and solar radiation data, optimization is achieved. Furthermore, techno-economic and sensitivity assessments have been conducted to assess the impact of various PV system capacities, PV system prices, and interest rates. In addition, to increase self-sustainability, several battery sizes and prices have been explored and analysed for the 2015 and 2025 scenarios. The results indicate that the implementation of a PV system may reduce power prices through self-consumption of PV energy. Furthermore, the combination of battery energy storage with PV systems may reduce power prices even further, provided that battery costs can be reduced to €200/kWh in the future.

Shabani et al. [12] examine the technological effects of the two battery configurations on the size of a PV/BA system. The first configuration is based on a standard, straight-forward battery model and control approach that reflects the battery condition exclusive of dynamic behavior. The second configuration is based on a complicated battery model that estimates battery parameters in different operating

Table 2
The technological and economic specifications of the components of the studied system.

Component	Rated Power	Model	Cost	Ref.
PV module	0.45 kWp	Sunceco	$110	[48]
Battery	200 Ah/2.4 kWh	Visionbat	$200	[49]
Converter	8 kW	Absopulse	$1500	[50]

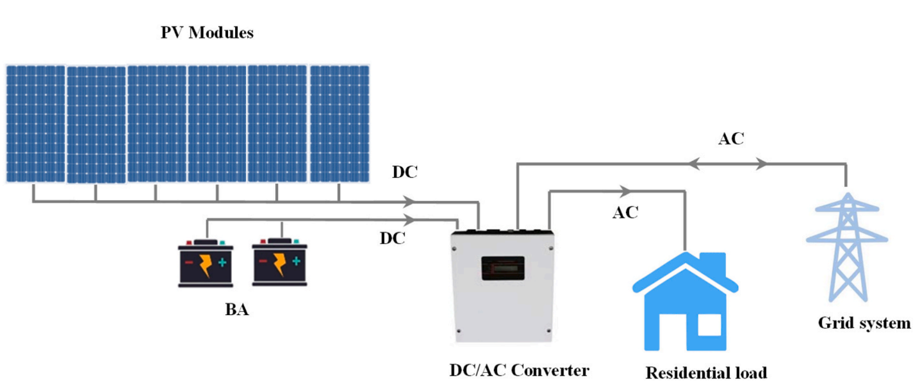

Fig. 1. Schematic of the studied PV/BA grid energy system.

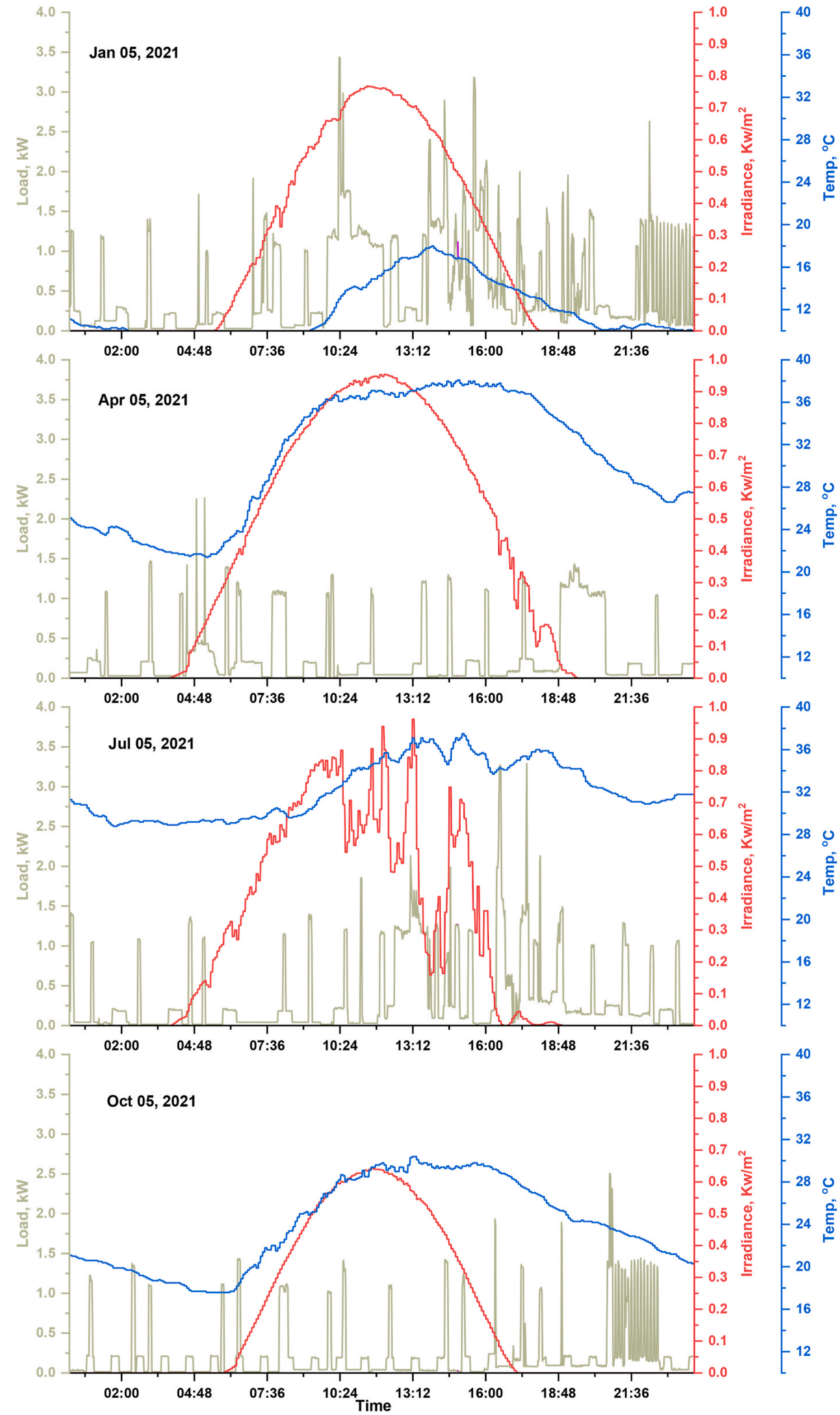

Fig. 2. Ambient temperature, solar irradiation and load from experimental measurements for four selected days throughout the year.

situations. The results indicated that to obtain the same level of self-sufficiency, optimization of a proposed system based on the first configuration requires options with a higher life-cycle cost and larger battery capacity than the second configuration. Furthermore, given the same design specifications, the system optimization based on the second configuration provides the end-user with more electricity, resulting in a larger self-sufficiency ratio than when the system is simulated according to the first configuration. This study indicates that a comprehensive battery model with appropriate efficiency is more advantageous from a technological point of view and results in a more precise battery size. The work by Jamroen [13] attempts to find the best techno-economic size of a floating solar PV/BA energy system to power an aquaculture aeration and monitoring system while maintaining the PV modules and BA weights under consideration. The reliability was computed to assess

Table 3
The daily energy, irradiance, and ambient temperature for four selected days.

Day	Energy (kWh)	Irradiance (kWh/m^2)	Average Temp. (^{o}C)
Jan 05	12.84	3.62	11.8
Apr 05	6.64	8.71	30.7
Jul 05	8.51	6.08	32.2
Oct 05	5.53	4.34	23.9

the power supply capacity of the energy system to ensure its properly functioning. Additionally, the levelized COE was examined to establish the cost-effectiveness of energy system designs. According to the conclusions, the PV/BA system is the most technically and economically viable design for both daytime and nighttime ventilation situations. Hassan et al. [14] evaluated the economic viability of a PV/BA system to power the household in a high renewable energy fraction. In terms of energy cost, the research showed that the proposed system was economically viable.

Abbas et al. [15] studied the viability of a PV/BA system to provide electrical energy for irrigation. The size of the proposed system was determined over the course of many summer days. From an environmental and economic point of view, the study found that a PV/BA system that works on its own is a good way to power an irrigation system. Hassan et al. [16] constructed a PV/BA system to power small-scale pump-based diffuser aerators in rural areas. The results suggested that the system safety factor was adequate to power the aerators. According to Uddin et al. [17], a techno-economic model has implemented HOMER and MATLAB/Simulink for the electrical parameters of the modelled PV/BA energy system. Throughout, techno-economic and ecological assessments are provided to determine the viability and utility of the micro-grid system. The simulations show an outstanding correlation, such that the optimal COE for the power plant is estimated to be $18.3. The researchers estimate that 2500 home scooters could reduce annual CO_2 emissions by 466,56 tonnes. Hassan [18] identified the appropriate size of a PV/BA system to meet the electrical requirements of household applications. At day time, the PV array was used to feed the electrical load and charge the batteries, and at night the battery was used to provide energy for load. The ideal system size was reached with the lowest COE.

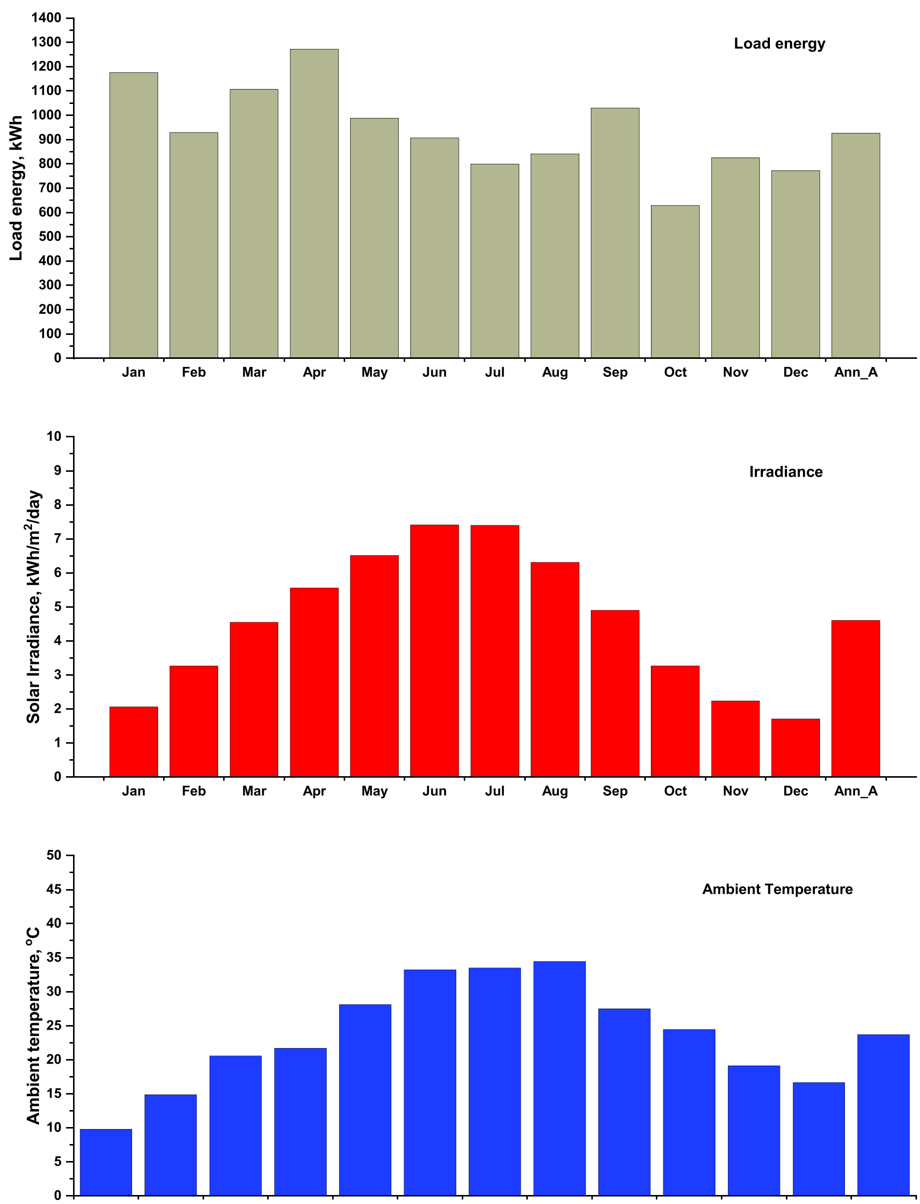

Fig. 3. The monthly and annual load, irradiance, and ambient temperature form experimental measurements.

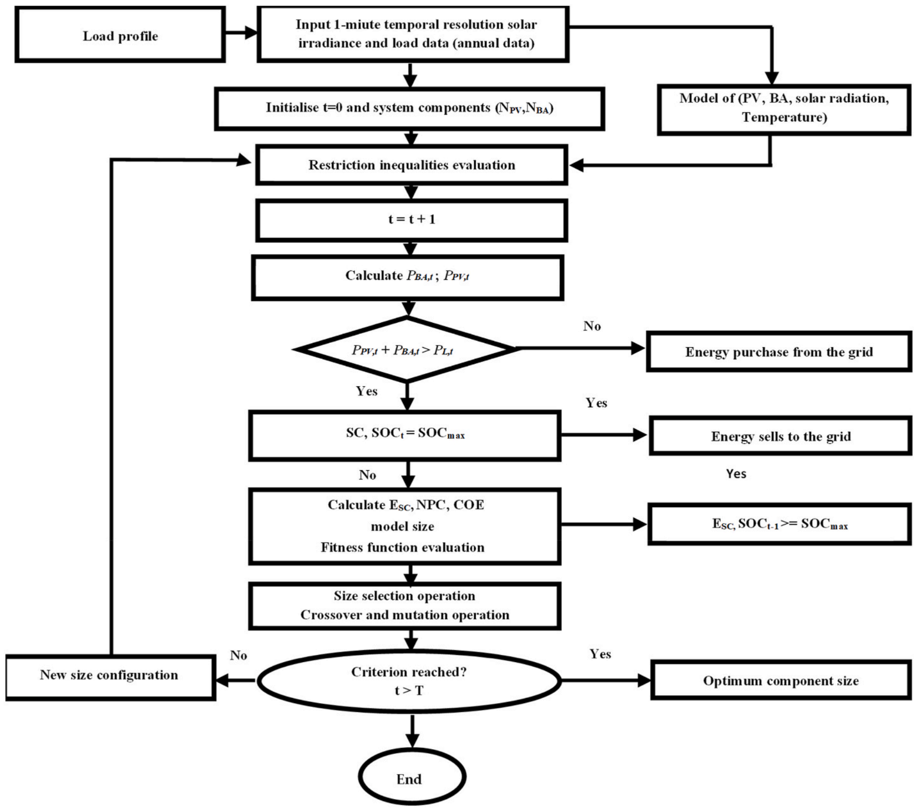

Fig. 4. The studied system simulation flowchart.

Jaszczur et al. [19] analyse PV/BA system in terms of both economical and the environmental impact. The economic feasibility assessment showed that the proposed system could generate electricity at $0.13 per kilowatt-hour, which was much less than the price of regular electricity. Ceran et al. [20] construct a computational approach for the techno-economic evaluation of a PV system with and without energy storage systems. A mathematical model used to compute the economic impact of the PV system integration. Using computational methodologies, five examples were investigated, including the use of no storage system, two configurations including lithium-ion batteries, and two cases involving flow batteries. Compared to other PV systems with batteries, the PV system with lithium cobalt oxide battery levelized cost $0.034/kWh. The study indicates that an integrated system with lithium-ion batteries was considered to be the most practical and cost-effective option. In general, the comprehensive study of PV system with energy storage options demonstrates the distant application of this technology.

According to Table 1, current techno-economic models can be classified as optimization or simulation models, depending on whether the capacity of PV and battery units are optimization variables or simulated as exogenous factors. While most available research concentrates on residential PV/BA systems, several also study commercial and industrial applications [21–23].

There are several more benefits to using solar energy for powering households and residential communities and support the national grid systems. Using renewable energy sources to generate electricity contributes to environmental care, which could be used by a company to enhance its image. The presented research study analyses the impact of techno-economic visibility in contrast to the self-consumption household with an annual energy consumption of 3760 kWh. Furthermore, a technical and economic study was carried out for PV installation with and without battery storage for a period of time from 2021 up to 2030, taking into account various parameters affecting the installation. This work is primarily concerned with addressing problems related to the appropriate size of the battery that can be integrated with the PV system and the best combination of the size of the PV system and battery capacity ensuring at the same time the highest self-consumption. The study addresses the following issues:

1. The optimum battery as a storage unit can match the higher self-consumption in conjunction with a PV array based on one-year span energy consumption.
2. The Middle East region is rich with abundant solar energy, a study was carried out using households supplied by renewable energy for Iraq. It can be concluded that realistic results may be used in real-world systems to save millions of dollars.
3. Obtaining the relationship between the self-consumption level and the COE.

In this study, the scheduling difficulty of uninterrupted power supply paddle shift devices is handled from a multi-agent viewpoint, and two strategies are used. Alternatively, a new partially distributed architecture is provided to address the same issue by distributing decision-making across agents and utilizing a heuristic algorithm and a virtual dynamic tariff as a coordination mechanism. The solar energy system is evaluated for PV panels and energy storage batteries of various capacities in order to achieve high self-consumption with optimal capacity. The suggested unique technology indicates that the quick reaction of batteries functioning as a storage unit may greatly increase energy self-consumption. This work is essential for system designers and fills a scientific need in this area. Prior to the implementation of renewable energy systems on a worldwide scale, it is essential to improve energy self-consumption to maintain the grid stability of the system and boost local energy usage.

2. System modelling and experimental set-up

The analysed system under investigation is a PV/BA on-grid system

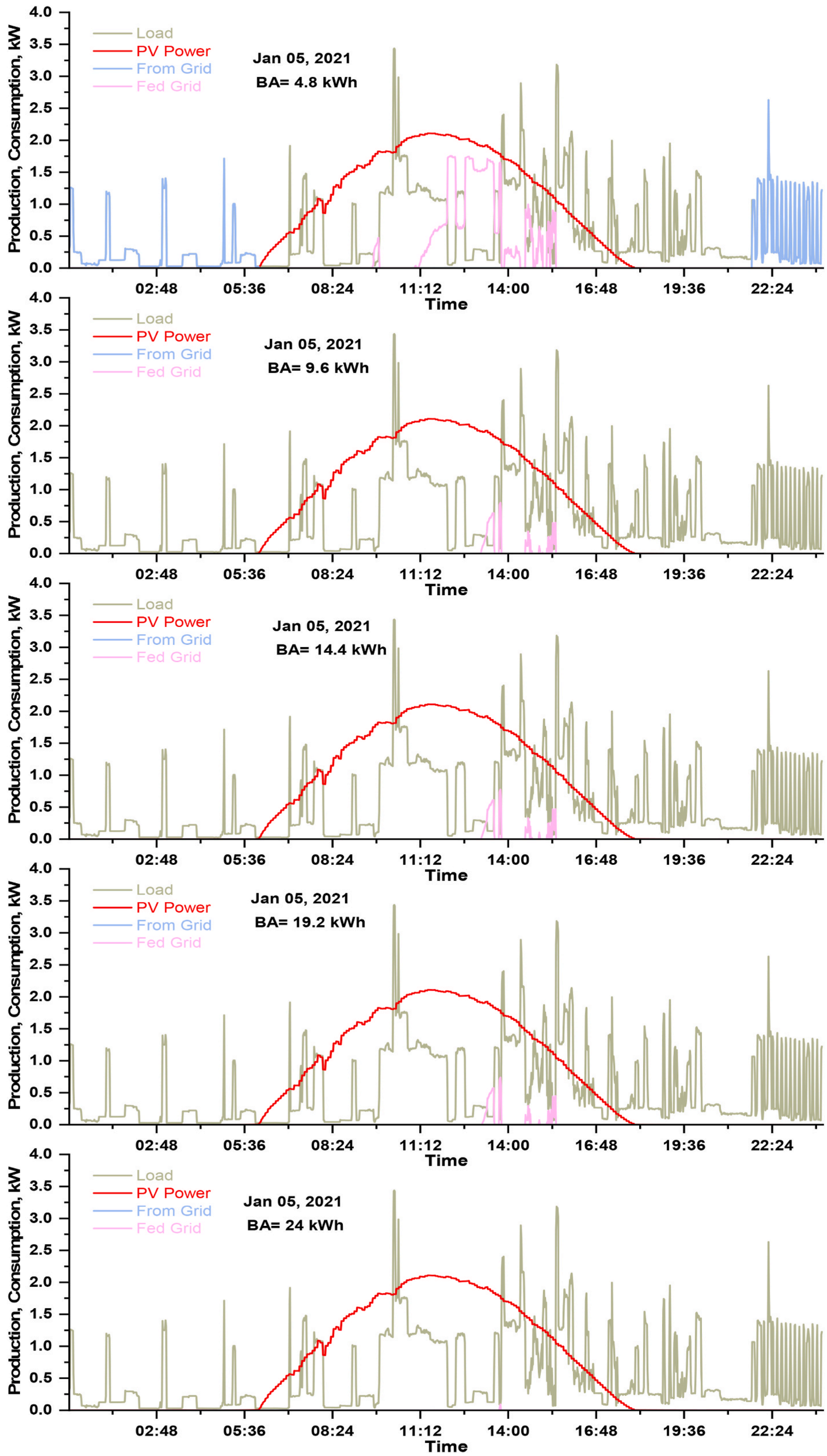

Fig. 5. Daily power flow at different battery capacity for the day of Jan 05, 2022.

in which the batteries are charged by the PV array during the day in order to supply the required load at night and on cloudy days. The most important criterion for a reliable system is that the energy stored in the batteries can support the required load with the maximum level of self-consumption. Consequently, system modelling entails optimising the number of batteries to extract adequate storage power to fulfil demand with the optimal number of batteries to store the required energy. Several terminologies are used in the literature to evaluate the dependability of PV/BA energy systems. In this study, numerical simulations are used to determine the battery capacity and assess the

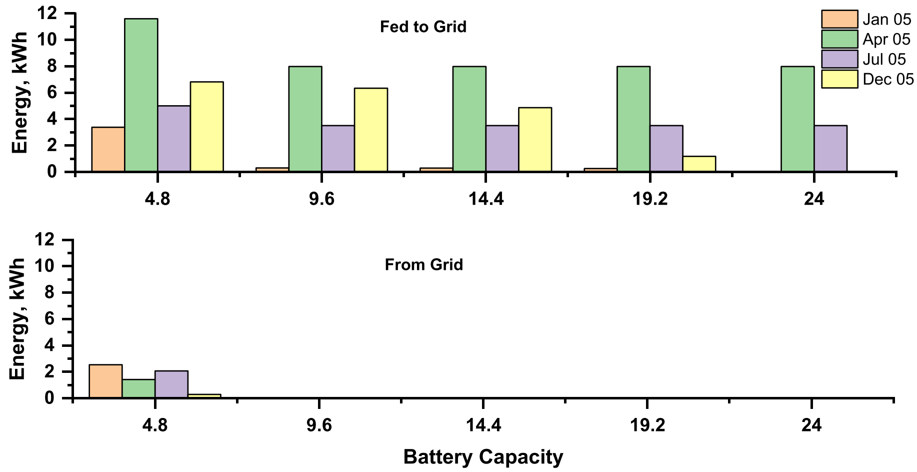

Fig. 6. Daily energy from the grid/fed to the grid at different battery capacities for four selected days.

dependability of the studied system to supply the load with renewable energy at the highest efficiency and at the lowest cost. Fig. 1 shows the schematic of the investigated PV/BA grid energy system.

The technological and economic specifications of the system components are presented in Table 2.

The PV array was positioned at the optimum annual adjustment (tilt angle = 30, azimuth angle $\alpha = 0°$) south direction for the annual highest incident solar radiation at the investigated site (latitude 33.7733° N, longitude 45.1495° E), where the simulation process was conducted at 1-min resolution. The project life span is nine years until 2030, and the economic assessment is made based on the Iraqi regulation (buy from the grid at $0.33/kWh and sell to the grid at $0.11/kWh), which means that the annual interest rate is 6%.

The experimental measurements of load, irradiance, and ambient temperature that are required for calculations were carried out over a period of one year in 2021 with an acquisition time equal to 1 min. The most important aspect of such a design system is the yearly electrical energy, and the energy provided by the PV panel is dependent on daily variations in solar irradiation and ambient temperature. Fig. 2 shows the daily experimental measurements for electrical load, solar irradiance, and ambient temperature for four selected days (at different seasons). Table 3 shows the daily average of energy consumed, solar irradiance, and ambient temperature for the four selected days. The energy consumption is varied from day to day. It showed the highest for January 05 by about 12.8 kWh and the lowest for October 05, while solar irradiance and ambient temperature were recoded as the lowest during winter time for January 05 and October 05, and the highest during spring and summer. Fig. 3 shows the monthly and annual averages for experiment load, irradiance, and ambient temperature. Energy consumption varies from month to month, which showed the highest in April approximately 1271.71 kWh and the lowest in October approximately 628.55 kWh, and the annual average showed 925.47 kWh. Solar irradiance and ambient temperature recoded the lowest during the winter months and the highest during the summer months, where the annual average was recoded as 4.6 kWh/m^2/day and 23.7 °C, respectively (see Fig. 3).

2.1. Energy flow distribution model

In the studied system the energy consumption (kWh) can be expressed as:

$$E_T = E_{PV} + E_{BA} + E_G \tag{1}$$

where E_T represents the total energy usage, E_{PV} is the energy generated by the PV array, $E_{BA,}$ is the energy stored in the battery, and E_G is the energy drawn from the grid.

The energy of the PV array can be calculated as follows [51]:

$$E_{PV} = C_{PV} \cdot \left(H_T / H_{T,STC}\right) \cdot \left(\alpha_P \left(T_{C,t} - T_{C,STC}\right) + 1\right) \cdot \eta_{PV} \tag{3}$$

where C_{PV} represents the capacity of the PV arrayη_{PV} represents the PV array derating factor (%), H_T and $H_{T,STC}$ represents incident solar radiation and solar radiation under standard condition, α_P represents the module cell temperature coefficient of power [52,53], T_C and $T_{C,STC}$ represents the module cell temperature and cell temperature under standard condition (STC) respectively.

The limitation applies to the battery-stored energy that can be expressed as:

$$E_{BA,\min} \leq E_{BA} \leq E_{BA,\max} \tag{4}$$

where $E_{BA,min}$, and $E_{BA,max}$ are the minimum and maximum battery energy levels, respectively.

Considering that on sunny days the storage batteries are fully charged, the energy stored is used to supply the load at night, however, on partially cloudy days the storage batteries supply the load only with available energy, and the excess required energy can be provided by the grid as follows [54]:

$$E_{BA,\max} = Ah \cdot V \tag{5}$$

The maximum permitted battery energy level can be expressed as:

$$E_{BA}(t-1) = \left(E_{BA,\max} \cdot N_{BA} - E_L\right) / N_{BA} \tag{6}$$

where N_{BA} is the number of batteries and t is the maximum depth of discharge of the batteries, and E_L is the desired energy of electrical load.

The minimum permitted battery energy level can be expressed as [55]:

$$E_{BA,\min} = E_{BA} \cdot N_{BA} \cdot (t-1) \tag{7}$$

The simultaneous load-balancing formula, which describes the energy transport between all system components, is as follows:

$$E_T = \begin{cases} E_{PV} & \text{for} \quad E_{PV} \geq E_T \\ E_{BA} & \text{for} \quad E_{BA} \geq E_T; E_{PV} = 0 \\ E_G & \text{for} \quad E_{PV} + E_{BA} = 0 \\ E_G + E_{PV} + E_{BA} & \text{for} \quad E_{PV} + E_{BA} < E_T \\ E_G + E_{PV} & \text{for} \quad E_{BA} = 0 \quad \text{and} \quad E_{PV} < E_T \\ E_G + E_{BA} & \text{for} \quad E_{PV} = 0 \quad \text{and} \quad E_{BA} < E_T \\ E_{PV} + E_{BA} & \text{for} \quad E_{PV} + E_{BA} \geq E_T \end{cases} \tag{8}$$

2.2. Technical and economic indicators

The following section describes the technical metrics for the self-consumption rate, as well as the economic indicator that will be used

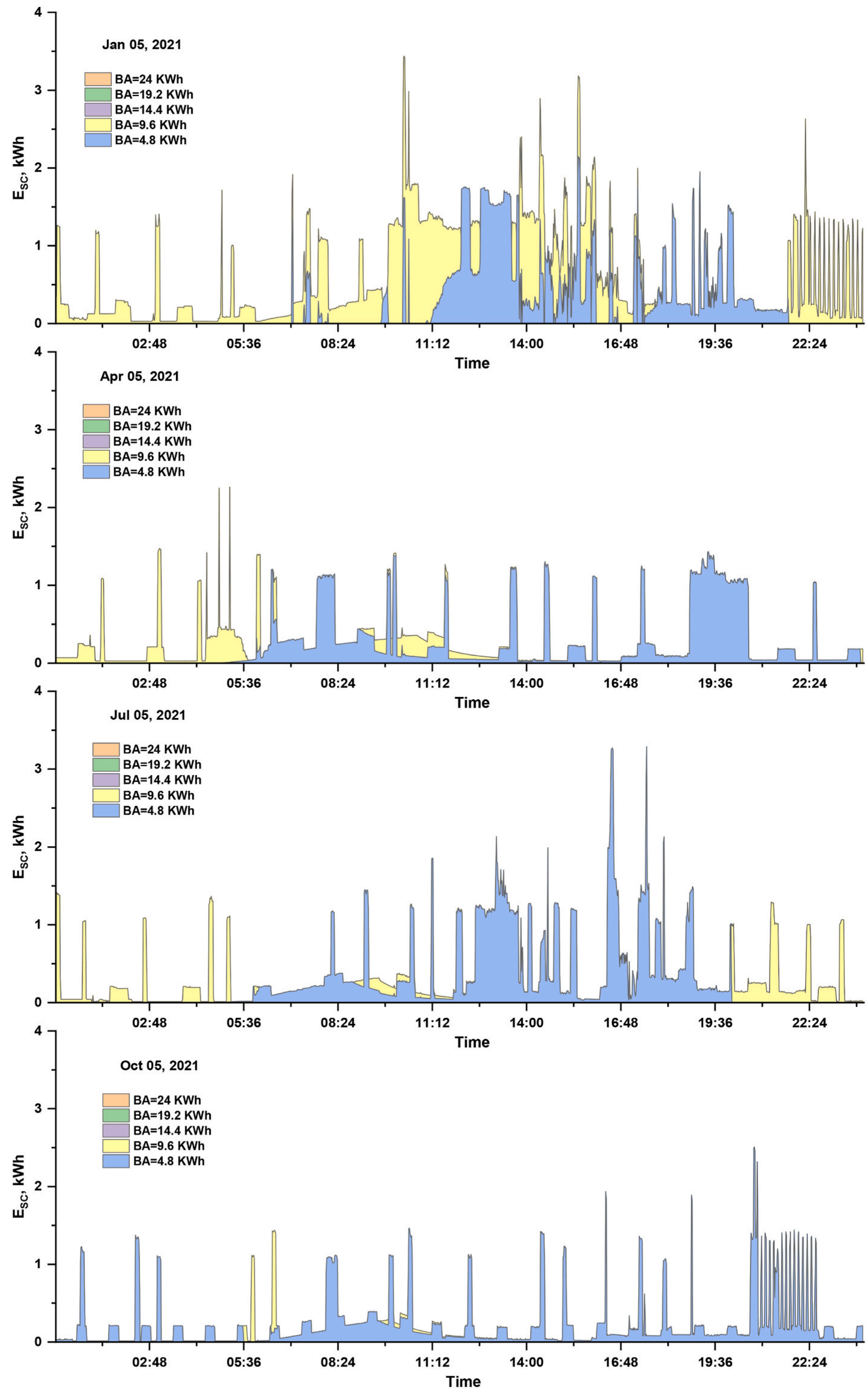

Fig. 7. Daily energy self-consumption for the selected days with several battery capacities.

in the subsequent study.

2.2.1. Rate of self-consumption (E_{SC})

The self-consumption indicator defined in Ref. [56] based on load profiles and generated energy and the value can be defined in kWh as follows:

$$E_{SC,(kWh)} = \sum_{i=1}^{i=n} E_R - \sum_{i=1}^{i=n} E_{Fed\ \ to\ \ grid} \tag{9}$$

The E_{SC} in percentage is given as:

$$E_{SC,(\%)} = \left(\sum_{i=1}^{i=n} E_R - \sum_{i=1}^{i=n} E_{Fed\ \ to\ \ grid} \right) \Big/ \sum_{i=1}^{i=n} E_R \cdot 100\% \tag{10}$$

where E_R is the energy generated or stored as a consequence of generation ($PV + BA_{charge}$ - $BA_{discharge}$) and E_{Fed} to the grid is the energy fed to the grid (kWh), n denotes the number of simulation steps.

2.2.2. Cost of electricity

The COE is computed using the "discounting" approach, which

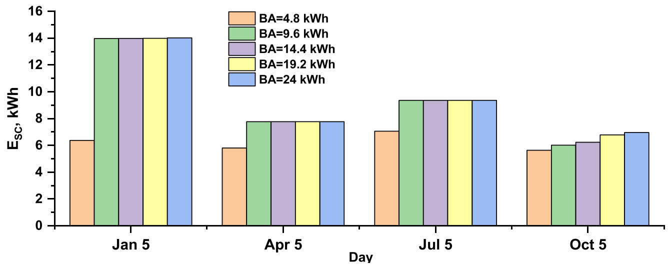

Fig. 8. Daily total energy self-consumption for the selected days with various battery capacities.

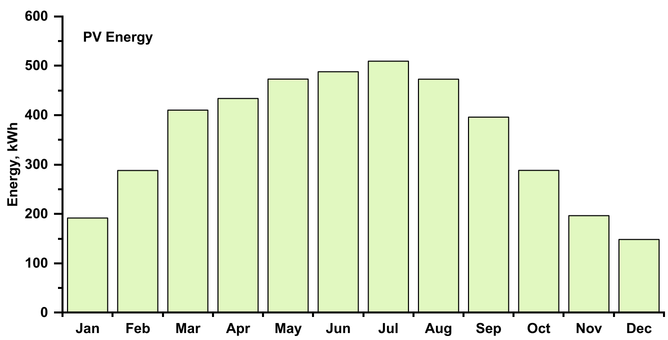

Fig. 9. Monthly energy generated by PV array with capacity 2.7 kWp.

equals the ratio of projected total lifetime cost to lifetime generating output. Importantly, numerous versions of COE metrics have been established in recent years, particularly for hybrid systems, and the conclusions may not be directly comparable due to the varying assumptions and COE formulae they include. Although the COE value is a good way to compare the results of different studies, readers should be careful when using these values [57].

$$COE = A_{\text{cost}} \Big/ \left(E_{AC,DC} + E_{grid\ sales}\right) \tag{11}$$

where A_{cost} is the total annualized cost of the system, $E_{AC,DC}$ is the annual AC, DC primary load served, and $E_{grid\ sales}$ is the annual energy sales to the national grid.

The total NPC can be determined using the following formula [58–60]:

$$NPC = \frac{S_c}{R\ \ (i, P_S)} \tag{12}$$

where S_c is the system annual cost ($/year), R is recovery factor capital, i is the annual interest rate (%) and P_s is the project lifespan (year).

The studied system simulation flowchart is shown in Fig. 4. In this part, the theory of the optimization technique is briefly explained. Fig. 4 displays the MATLAB/SIMULINK-based optimization method diagram. Each step of the optimization technique, from the definition of design parameters through the selection of a strategy, is crucial for generating precise and optimal results. As optimization commences, the performance obligation for planned self-consumption must be met at each stage of the process; otherwise, the preceding steps must be executed. If the produced requirements do not accurately specify the system, model parameters must always be replaced immediately. The optimization

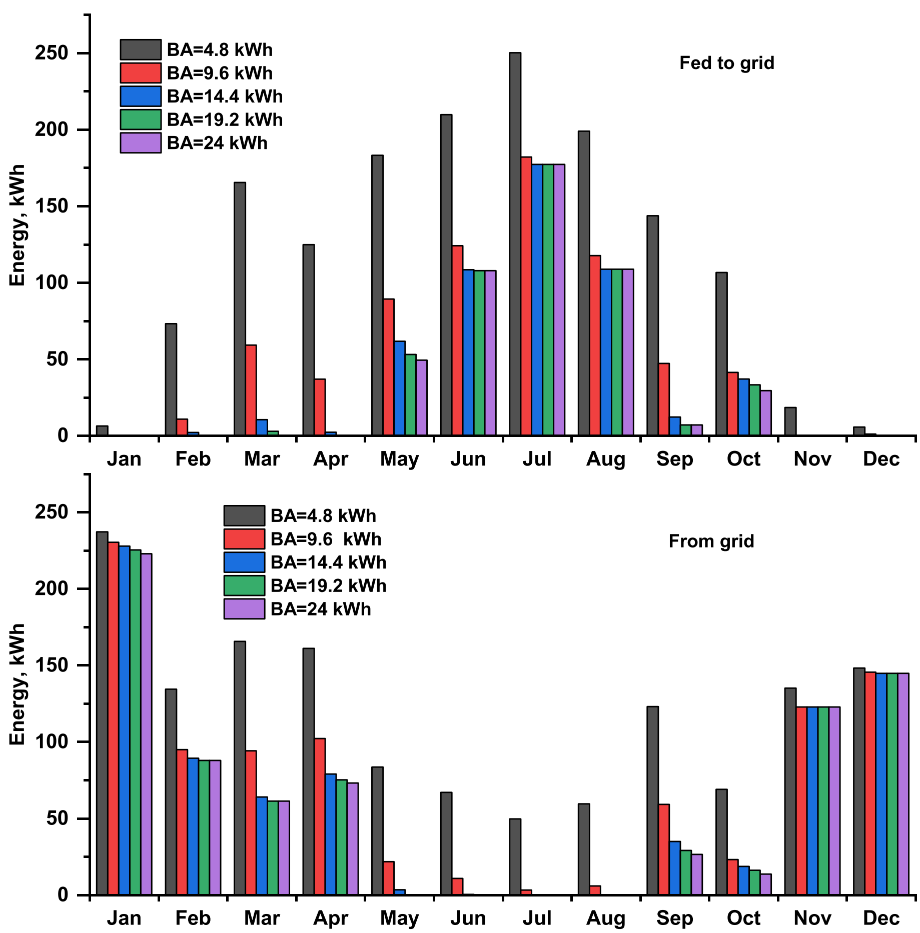

Fig. 10. Monthly energy amount fed to the grid and taken from the grid for several battery capacities.

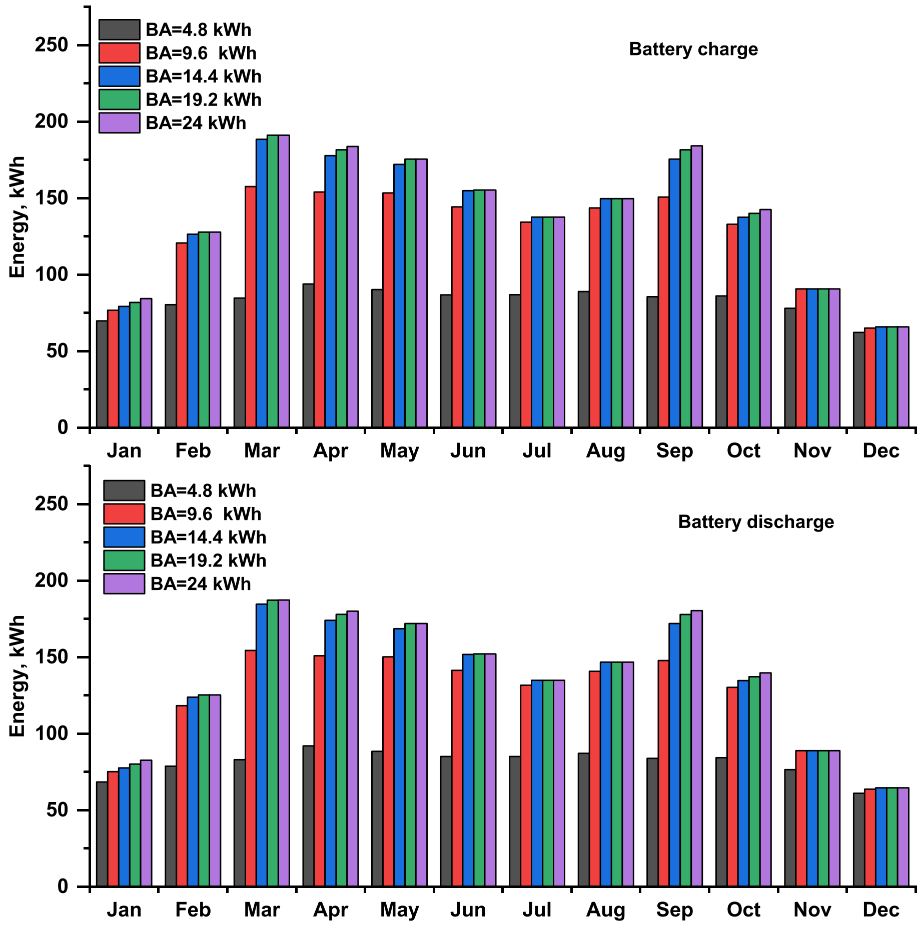

Fig. 11. Monthly energy charge and discharge battery for several battery capacities.

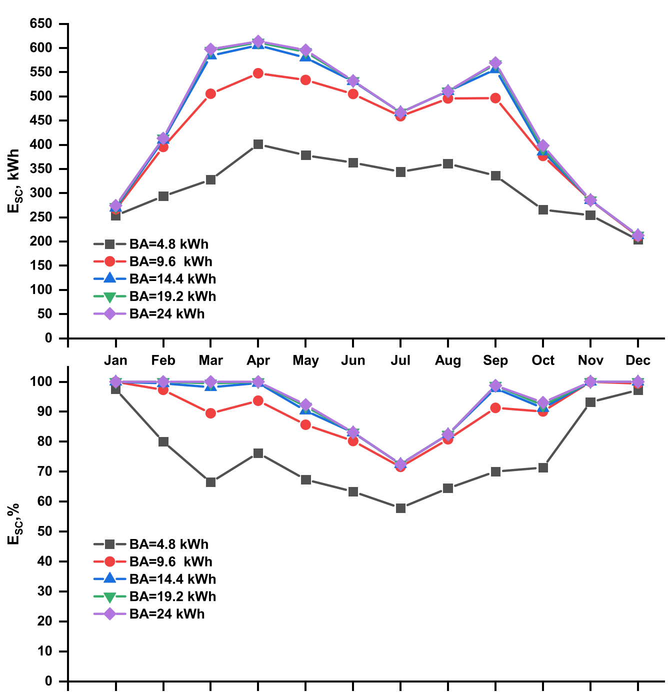

Fig. 12. Monthly energy self-consumption and percentage for several battery capacities.

process will move on after the second phase is successfully completed. If variable parameters do not meet the system's criteria, the fourth phase may be sent to the first and second phases. The subsequent step is to choose an appropriate optimization approach for the specified maximum self-consumption.

3. Results and discussion

This study analyses various PV/BA energy system configurations in order to find the best solution for residential applications using a 2.7 kW PV array and various battery sizes. The number of batteries is adjusted using a MATLAB programme for each battery to reach the optimal capacity to provide the highest self-consumption and lowest energy cost.

Fig. 5 shows the daily power flow at different battery capacities for the day of January 05, 2021. The PV array generated approximately 15.172 kWh and the energy consumption was 12.84 kWh. The energy from the grid decreases by the battery capacity that compensates for the desired load. At the same time, the energy fed to the grid is decreased by increasing the battery capacity, which means more energy for battery charging.

Fig. 6 shows the daily energy from the grid/fed to the grid for the four selected days. For all selected days, the energy taken from the grid is zero at a battery capacity of 9.6 kWh or higher. This means that the renewable energy generated by the PV array and the BA storage unit can feed the desired load at the optimal point. For all days, increasing battery capacity reduces energy fed to the grid because the energy generated by the PV array goes to charge the batteries, which are designed to only charge from the PV array (not from the grid).

Fig. 7 shows the flow of energy self-consumption for the selected four days with several battery capacities (from 4.8 up to 24 kW, based on the

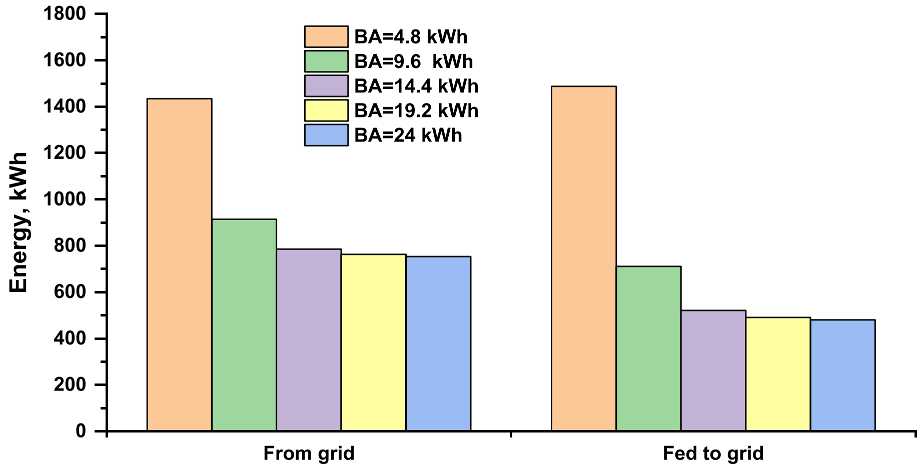

Fig. 13. Annual energy taken from the grid and fed back to the grid with several battery capacities.

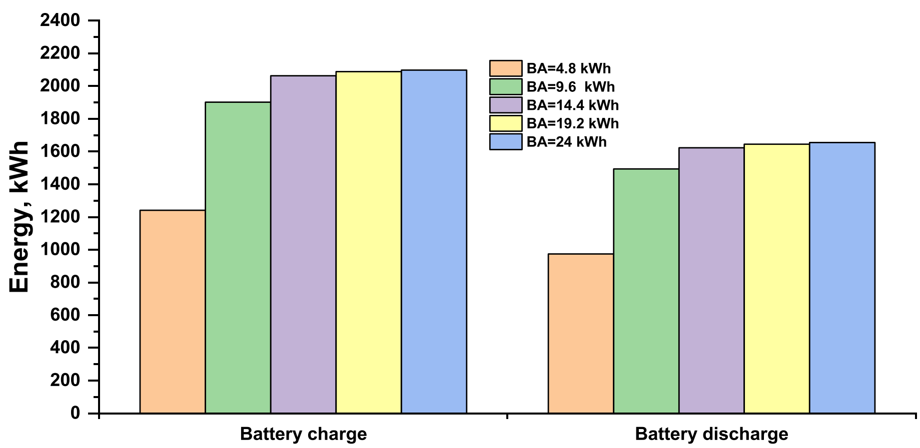

Fig. 14. The annual energy that charges and discharges batteries at several capacities.

battery specification presented in Table 1). Energy self-consumption increases by increasing the battery capacity for all selected days. On all days, increasing battery capacity reduces the energy fed to the grid because the energy generated by the PV array is designed in load following strategy and the batteries designed only to charge from the PV array (not from the grid).

Fig. 8 shows the daily total energy self-consumption for the selected four days with various battery capacities (4.8 kW–24 kW, based on the battery specification presented in Table 1). The value of energy self-consumption increases as the battery capacity increases for all selected days. For all days, increasing battery capacity reduces energy fed to the grid because the energy generated by the PV array goes to charge the batteries, which are designed to only charge from the PV array (not from the grid).

Fig. 9 shows the monthly energy generated by a PV array with a selected capacity of 2.7 kW based on the modules presented in Table 1. The energy generated by the array is highly dependent on incident solar irradiance (see Fig. 3). The results showed that the highest energy can be generated by the specified array by about 510 kWh during July and the lowest by about 148 kWh during December, and the total annual energy can be generated by about 975 kWh.

Fig. 10 shows the monthly energy supplied to the grid and taken from the grid. First, the highest energy is fed to the grid during the summer months and the lowest during the winter months, and this is in contrast to the energy that is taken from the grid, which increases during the winter months and decreases during the summer months, but in both cases it depends on the amount of electricity that was produced from the solar energy array (refer to Fig. 9). Second, the amount of energy fed to the grid decreases with increasing batteries storage capacity due to the energy delivered to charge the batteries, and this value increases with increasing batteries capacity, in contrast to the energy taken from the grid, which decreases with increasing batteries capacity.

Fig. 11 shows the energy charge and discharge of the batteries in various battery capacities. The amount of energy that batteries store increases with increasing battery storage capacity and decreases with decreasing battery capacity.

Fig. 12 shows the monthly energy self-consumption and percentage with several battery capacities. The amount of energy self-consumption increases as the battery storage capacity and decreases as the battery capacity decrease, which explains why this value differs from month to month. The results of the analysis depend on the desired load, energy generated by the PV array, and the battery storage capacity. It is unreasonable to evaluate battery storage capacity that guarantees the highest energy self-consumption based on daily and monthly results only. Such a decision requires at least one year of lead time.

The experimental measurement of annual energy consumption was 3755.8 kWh, and the simulation results showed that the PV array at 2.7 capacity can generate an annual energy of 4295.4 kWh. Fig. 13 shows the annual energy taken from the grid and fed the grid at different battery capacities. The results showed that the highest energy taken was 1435 kWh at the 4.8 kWh battery, and the lowest energy fed to the grid was 1487 kWh at the 4.8 kWh battery. Both the energy taken and the energy fed to the grid are degreased by increasing the battery storage capacity. Due to increasing battery capacities, more energy for charging

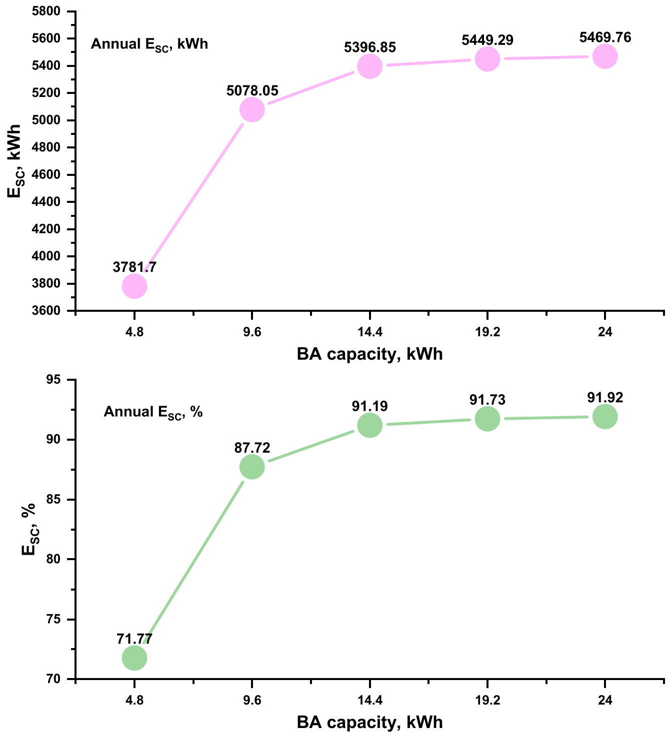

Fig. 15. The annual energy self-consumption for several battery capacities.

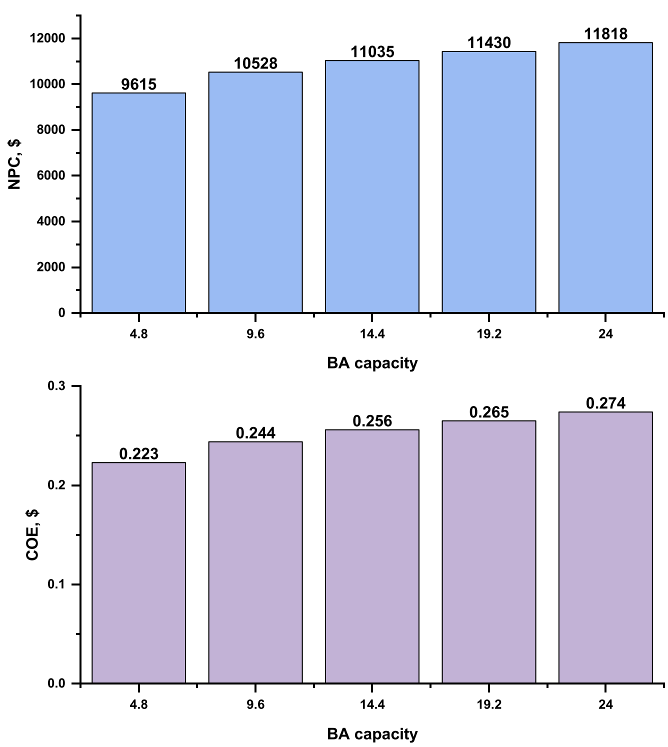

Fig. 16. Annual NPC and COE with several battery capacities.

is required – only the surplus energy generated by the PV array (energy that exceeds the desired load requirements) is going to charge the batteries.

Fig. 14 shows the annual energy charge and discharge of batteries. In general, the energy for charge is higher than the energy for discharge due to the selected batteries round-trip efficiency of 85%. The batteries energy to charge or discharge is increased by increasing the battery storage capacity.

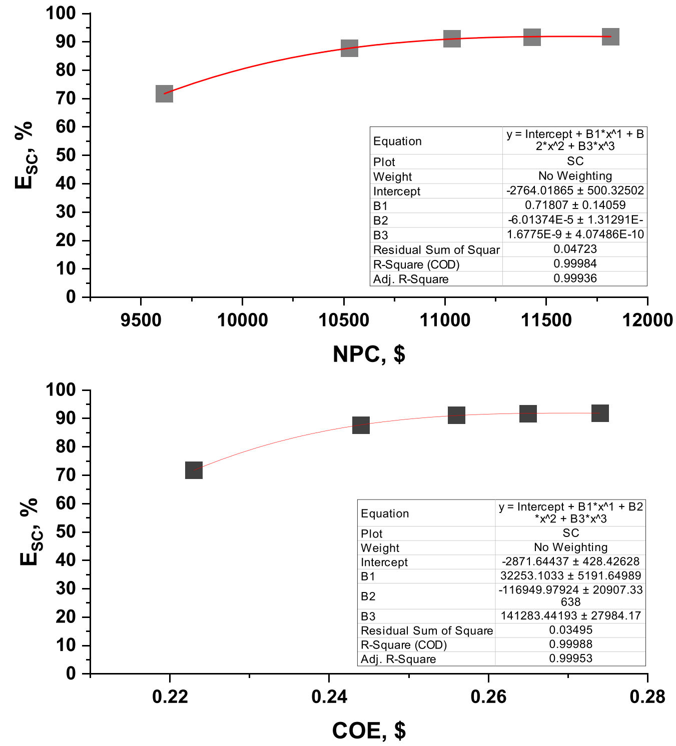

Fig. 17. Relation between self-consumption % with NPC and COE for several battery capacities.

Fig. 15 shows the annual energy self-consumption and percentage with several battery capacities. The simulation results demonstrated that the increasing percentage is raised very low after a capacity of 14.4 kWh (6 batteries), which is the energy self-consumption of 5396.85 kWh. It can be said that the optimal battery capacity is 14.4 kWh, which can match the highest self-consumption for the investigated design.

Fig. 16 shows the annual NPC and the energy cost for several battery capacities. The simulation showed that both the NPC and the cost of energy increased as the battery storage capacity increased. The lowest NPC was $9615 at battery capacity 4.8 kWh and the highest was $11818 at battery capacity 24 kWh. The same was true for the energy cost, which showed that the lowest was $0.223 at battery capacity 4.8 kWh and the highest was $0.274 at battery capacity 24 kWh.

Fig. 17 illustrates the percentage of relationship between the percentage of energy self-consumption and the total net present plus the energy cost. The resulting relationship is a polynomial of the third order. The simulation revealed that when energy self-consumption increased, both the NPC and the cost of energy increased.

4. Conclusions

Although the integration of PV arrays with batteries leads to higher NPC than PV alone for various residential customer groups today, the payback time frames fluctuate between 2021 and 2030 owing to regulatory changes, increased costs and price of the power market prices. Optimal PV array and battery size increase with time, and by 2050, PV investment is mostly limited by the size of the roof. The economic viability of PV/BA system investments varies between different residential customers, with the most favorable investment being most accessible to residential customer groups with higher annual irradiance and electricity consumption. Furthermore, investment decisions are strongly influenced by payback periods, future costs, electricity prices, and tariff adjustments.

This research study was used to develop a model of the microgrid energy system for the Central Iraqi municipality to determine potential trends. Furthermore, the authors will begin investigating and incorporate solar energy sources and new energy storage technology to expand not only the scope of the use of renewable energy in the electrification field, but to include industrial, agricultural and commercial load centers for long-term energy distribution in the municipality of Iraq.

The outcome of the study can be summarized as follows:

- The average annual daily solar irradiance (4.6 kWh/m^2/day) can generate energy of about 4295.4 kWh with 2.7 kWp of the PV array placed in the annual orientation.
- For annual energy consumption (3755.8 kWh), the optimal battery capacity that can be injected with 2.7 kWp of PV array is 14.4 kWh, which can satisfy 91.1% self-consumption.
- The NPC for the optimum system configurations mentioned above was $11053 with a project life span from 2021 to 2030.
- The COE for the optimum system configurations mentioned above was $0.256/kWh.
- Two third-order polynomial relationships were solved between self-consumption and NPC with the energy cost (see Fig. 17).

This research tries to propose solutions to global concerns of mitigating the escalation of environmental problems and meeting energy needs. The presented method provides a realistic technological, fiscal, and environmental answer to the aforementioned issues. The energy system model of a solar PV system that integrates batteries and a local grid is an excellent method for meeting energy requirements. The numerical approach used to determine optimal system configurations is applicable to any system capacity, allowing the designer to determine optimal system component capacities.

Credit author statement

Qusay Hassan: Conceptualization, Methodology, Software. Majid K Abbas: Data curation, Writing- Original draft preparation. Vahid Sohrabi Tabar: Visualization, Investigation. Sajjad Tohidi: Supervision. Marek Jaszczur: Supervision. Imad Saeed Abdulrahman: Software, Validation. Hayder M. Salman: Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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