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Optimization of Solar-Wind-Battery Hybrid Energy System Using Artificial Bee Colony Algorithm

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Abstract

Access to reliable and sustainable power generation in remote areas is a critical challenge faced by many regions worldwide. In such areas, hybrid energy systems integrating solar, wind, and battery components have emerged as a promising solution to overcome the lack of electricity infrastructure. This research primarily focuses on modeling the power supply for houses in remote areas of Iraq. It discusses a hybrid system to meet the electrical demand of a small area. The simulations and optimal sizing of the system are performed in MATLAB 2023a using a swarm-based artificial bee colony (ABC) algorithm. The findings have been compared with results from HOMER, a program commonly used to optimize combinations of electric and renewable energy sources, to confirm the effectiveness of the proposed approach. The main goals of this optimization project are to optimize the system component sizes and obtain the minimum cost of energy (LCOE). The results from the ABC algorithm show that the system exhibits good performance and convergence. This study also evaluates the proposed system's performance in the event of a failure from any source. The results confirm that the proposed method and optimal configuration can handle an efficient and reliable system.

Keywords: Artificial Bee Colony, Levelized Cost of Energy, Photovoltaic Array, Wind Energy.

1. Introduction

According to recent scientific studies, more than 75% of the world's energy is derived from burning fossil fuels. High carbon emissions have a significant harmful influence on our environment and health. That's why the growing consumption of fossil fuels promotes an ongoing search for alternative resources. For these reasons, the world shifted toward lower-carbon resources. There are several renewable energy sources, such as solar PV, wind, and clean resources. These kinds of resources are never-ending, and their accessibility is at no cost, as is the generation of electrical power, which is extremely low-cost [1].

In recent years, the integration of renewable energy resources has been encouraged by many governments worldwide, as they have revised their policies and regulations to promote renewable energy systems. This can be accomplished by increasing capacity and efficiency, and by implementing renewable system preservation strategies. The most challenging factor is the irregular patterns of renewable energy resources; however, developing modern hybrid systems can provide reliable, constant energy output [2]. The design of a hybrid renewable energy system (HRES) is affected by several factors, for example, energy availability, the technical and physical state of the area, the efficiency of renewable resources, and the physical condition of the location. Optimal sizing is a crucial factor to consider [3].

A hybrid energy system can be utilized in standalone or grid-connected modes. The main difference between standalone and grid-connected modes is that standalone requires a large storage system, whereas a small one may suffice in grid-connected mode. Hybrid energy systems, especially those with solar PV and wind turbines, interest many researchers in developing methodologies for designing, sizing, and optimizing various system types. Most of the time, the energy production profile of PV-wind hybrid systems does not match load demand. Therefore, reliability investigations are required, especially in standalone mode, to achieve a highly efficient system at a lower cost.

Before implementing HRES units, it is important to calculate capacity using design methodologies to find the optimal solution with the lowest overall cost and to conduct feasibility analyses. Unit sizing is the process of selecting the size of a hybrid energy system component to reduce overall cost while maintaining the system's reliability in its optimal state. Selecting larger equipment results in a more expensive system, whereas opting for smaller equipment increases the likelihood of power-generation failures [4].

The main parts of the HRES are renewable power sources (sometimes non-renewable), a storage system, a load or the grid, and a power conditioning unit. Optimization of the system refers to the process and methodology for developing a functional design for the hybrid system. From another perspective, it is defined as finding innovative ways to achieve the highest performance and cost-effectiveness under the same constraints by increasing desirable factors and reducing undesirable ones [5]-[7].

According to a recent report by the World Meteorological Organization (WMO), the world should triple its investment to reach net-zero emissions by 2050 [8],[9]. Iraq's conditional emissions reduction target reaches 15% by 2030 [10]. Iraq receives intense solar radiation every year, up to 2000 kWh per square meter, which requires cooperation between governmental and non-governmental organizations to exploit these free resources fully [11].

Delton et al. [12] report an expectation that the gradual rise in gasoline costs and the imposition of a carbon tax will result in a significant decrease in the net present cost (NPC) of off-grid systems. A carbon tax is the most effective way to lower emissions because it allows each company to emit a certain amount. This policy has not yet been implemented in Iraq. Targeting emissions requires a smart annual plan that uses not only regulations but also all the forms of renewable energy available in our region [13]-[15].

This study aims to examine the effectiveness of renewable energy sources in Iraq, raise public awareness, and advocate for greater efforts and funding from local governments toward these projects [16], [17].

2. Related Work

Multiple studies have examined the use of the ABC algorithm to optimize hybrid renewable energy systems, namely those integrating solar PV, wind, biomass, and battery components. Singh et al. [18] introduced an optimal sizing methodology that uses the ABC algorithm to determine the optimal capacities of photovoltaic (PV) panels, wind turbines, biomass, and batteries. This approach considers both the energy requirements and the potential of renewable energy sources in isolated locations in India. The results were also compared with the HOMER software tool and the particle swarm optimization (PSO) algorithm, revealing the ABC algorithm's ability to identify near-ideal solutions that maximize renewable energy consumption while minimizing system expenditures.

In addition, Frimpong et al. [19] conducted a comparative analysis of the ABC algorithm against other commonly used optimization algorithms for renewable energy systems. Their study assessed the efficacy of the ABC algorithm in terms of its convergence rate, solution accuracy, and resilience. He also identifies the optimal configuration of multiple energy sources (solar PV, wind, biomass, and battery) in South Africa using the social spider prey (SSP) algorithm. The findings demonstrated that modern SSP algorithms exhibited strong performance and efficacy in identifying solutions close to ideal for hybrid renewable energy systems.

This work is related to other nature-inspired optimization algorithms, like genetic algorithm (GA) [20], ant colony optimization (ACO) [21], biogeography-based optimization (BBO) [22], artificial immune system (AIS), distributed gray wolf optimizer (DGWO), and cuckoo search (CS).

In this research, our contribution is based on the application of the ABC algorithm to optimize a (solar PV-wind-battery) hybrid energy system, considering the specific problems and requirements of the target location. We strive to overcome the intermittency of renewable energy sources, fluctuating load demand, and system constraints to identify an optimal design that maximizes renewable energy utilization, reduces system costs, and ensures a reliable power supply.

By conducting simulations utilizing real local data, we will evaluate the performance of the ABC algorithm. This evaluation will include criteria such as energy production, cost-effectiveness, system reliability, and compliance with hybrid system limits. The outcomes of this research will contribute to the developing body of knowledge on the application of the ABC algorithm in optimizing (solar PV, wind, and battery) hybrid energy systems. Furthermore, it can be used to research the hybridization of various optimization algorithms. Hybrid algorithms combine the strengths of multiple algorithms to overcome their individual constraints and improve overall optimization performance.

3. Method of the Research

3.1. Introduction to the ABC Algorithm

Optimization using the ABC method is recommended for HRES systems after all accuracy and delay issues have been addressed with other techniques [23]. The ABC method, a recently discovered swarm-based algorithm, imitates the intelligent foraging behavior of honeybee swarms. This model has three important factors [24]: food sources, employed foragers, and unemployed foragers. It also highlights two fundamental actions of honeybee colonies: recruitment of a food source and abandonment of a source.

Food Sources: The selection process involves a forager bee considering various parameters of the food source, such as proximity to the beehives, energy intensity, nectar flavor, and the ease or difficulty of energy gathering [25].

Employed foragers: bees that are currently exploring a specific food source. They know this source and communicate it with other bees in the hive. This information provides the location, direction, and value of the food source [26].

Unemployed foragers: bees in search of a profitable food source. They can either be scouts who randomly discover the area or observers who aim to identify a food source based on the information given by the hired bees.

The ABC algorithm's distinguishing feature is its use of fewer control parameters than other optimization algorithms, such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). It is considered one of the superior evolutionary algorithms because it provides excellent convergence accuracy and results close to the optimal solution [27]. The results will be based on the levelized cost of energy (LCOE) value; the optimal design will have the lowest LCOE. The main goals for this study have been outlined below:

To develop mathematical models for each unit of the designed hybrid system (PV-wind-battery storage) to supply power to off-grid locations or areas in Iraq experiencing long-term electricity shortages.

To use the ABC algorithm to determine the optimal sizing for each component that has the lowest LCOE by minimizing the Net Present Cost (NPC) of the hybrid energy system.

In this paper, the main contribution is the design of a reliable and cost-effective hybrid (PV-wind-battery storage) system to meet maximum load demand. The mathematical models and operation strategies for different units have been discussed in detail.

3.2. Mathematical Modeling of the Hybrid System

This section presents an in-depth analysis of the proposed hybrid system's formulation. The system is designed to connect various pieces of equipment to the proposed microgrid to supply electricity to remote areas or to support an electrical shortage in this location, as shown in Fig. 1.

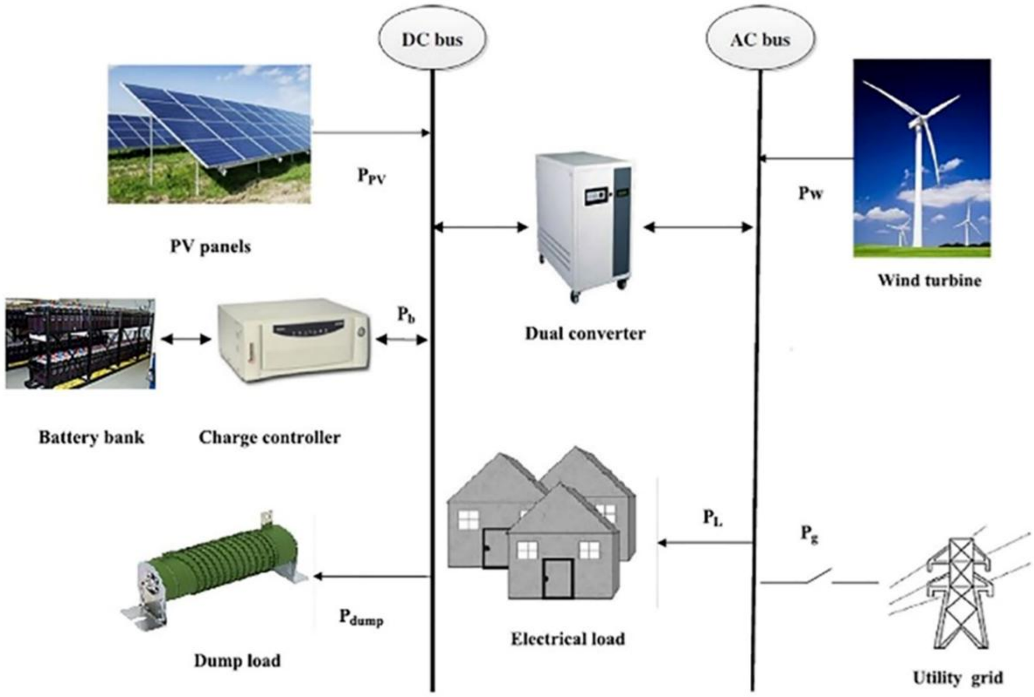

Figure 1. A hybrid renewable energy system consists of different units.

The system comprises AC and DC buses. In this scenario, wind turbines will be linked directly to the AC bus, while PV panels and battery banks will be connected to the AC bus through a converter. To ensure a continuous, uninterrupted supply of electrical power and to properly manage the rates at which the batteries are charged and discharged, the system uses a charge controller. This system is not only used in certain isolated locations, such as villages or small homes in developing countries that suffer from power outages. Still, it may also be integrated into the grid in any area experiencing a deficiency in electricity production [28]. The mathematical model of each component will be addressed as shown below:

3.2.1. Solar photovoltaic panel (PV)

PV cells are the main structural components of solar PV panels, which convert sunlight directly into DC via the photovoltaic effect. A single PV cell can generate approximately 1-2 W of electricity [29].

The solar PV panel's output power, which relies upon solar PV irradiation, is calculated as follows:

$$P_{sol} = P_r^s \; f_{loss} \; \frac{G_{h(t)}}{G_s} \quad (1)$$

Where: P_r^s is the rating power, f_{loss} is the loss factor, $G_{h(t)}$ is the PV hourly radiation incident at the surface, G_s is the standard incident radiation, equal to 1000 W/m2.

Factors such as shadows, ambient temperature, and dirt may significantly affect the power output and efficiency of the solar PV panel. Therefore, these factors, together with the length of daylight, must be examined.

3.2.2. Wind power generation

Wind speed is an important variable in weather and climate; wind power plants require enormous open areas to operate because of the structure of their turbine blades [30]. Isolated areas with low human density, such as offshore islands, are ideal for building wind energy systems, provided wind speeds are favorable. This is typically calculated by taking hourly measurements of wind velocity over a specified period.

$$P_{wt(t)=}\begin{cases} 0 & V(t) \le V_{cin} \ or \ V(t) \ge V_{cout} \\ P_r^w & V_{rat} \le V(t) \le V_{cout} \\ P_r^w \frac{v(t)-v_{cin}}{v_{rat}-v_{cin}} & V_{cin} \le V(t) \le V_{rat} \end{cases} \quad (2)$$

Where: $P_{wt(t)}$ is the power generated by the wind turbine at a given time, P_r^w is the rated power of one unit of the wind turbine, V_{rat} is the rated wind velocity; V_{cin} is the cut-in velocity, V_{cout} is the furlong velocity.

The wind velocity at a selected hub height varies with geographical location and differs from that at the reference hub height. It's calculated as follows:

$$V(t)=V_{r(t)} \left(\frac{H_{wT}}{H_r}\right)^{\gamma} \quad (3)$$

Where: V(t) is the wind velocity at height H_{wT}, $V_{r(t)}$ is the wind velocity at the reference height H_r and γ is the friction coefficient.

The optimum value for a low-roughness surface and a favorable exposed location lies between (0.14) and (0.25), with the ideal value being (0.14).

3.2.3. Battery storage

The modeling of this system accounts for the state-of-charge (SOC) and depth-of-discharge (DOD) limitations. Generally, renewable energy sources exhibit slower response times, which may be mitigated by incorporating faster-response energy storage devices [31]. The use of a battery bank in the hybridized system is primarily to store excess power, which can be discharged during periods of low energy or when energy is unavailable. The calculation of energy in this context can be performed using precise estimates of SOC and DOD. The SOC of the batteries, which varies over time, can be determined as follows:

$$\frac{SOC(t)}{SOC(t\text{-}1)} = \int_{T-1}^{T} \frac{P_{b(t)}\, \tau_{batt}}{V_{bus}} \, dt \quad (4)$$

Where: $P_{b(t)}$ battery's input-output power, τ_{batt} the battery's round-trip efficiency, V_{bus} the bus voltage. The battery's power might be either positive or negative.

When the battery is charging, its power is considered positive. Conversely, during the discharge phase, the battery's power is considered negative. Each manufacturer sets specific allowable SOC limitations. The limitations are as follows:

$$SOC(t)^{min} \le SOC(t) \le SOC(t)^{max} \quad (5)$$

$$SOC(t)^{min} = (1 - DOD) \times SOC(t)^{max} \quad (6)$$

Furthermore, it is essential to understand and determine the round-trip efficiency, as shown below:

$$\tau_{batt} = \sqrt{\tau_{batt}^{c}\ \tau_{batt}^{d}} \quad (7)$$

Where: τ_{batt}^{c} is the battery charging efficiency, τ_{batt}^{d} is the battery discharging efficiency [32].

This study claims that the battery's round-trip efficiency is predicted to be 90%, with a charging efficiency of 85% and a discharging efficiency of 100%. Additionally, a 30% safety margin has been identified as suitable for ensuring safety and extending the battery's lifetime. The maximum capacity of the batteries can be calculated as follows:

$$C_n\,(Ah) = \frac{N_{batt}}{N_{batt}^{s}}\ C_b\,(Ah) \quad (8)$$

Where: N_{batt} is the overall amount of the batteries, N_{batt}^{s} is the overall number of batteries coupled in series, $C_b(Ah)$ is the capacity of a single battery. The total number of batteries linked in series may be found using the following:

$$N_{batt}^{s} = \frac{V_{bus}}{V_{batt}} \quad (9)$$

Where: V_{batt} It is a single battery voltage.

The final step in the battery's mathematical modeling is to calculate its maximum charge and discharge power, which depend on the maximum charge current.

$$P_b^{max} = \frac{N_{batt}\ V_{batt}\ I_{max}}{1000} \quad (10)$$

Where: I_{max} is the maximum battery current in Ampere.

3.2.4. Power converter

The necessity for dual power converters, particularly (AC-DC) and (DC-AC), principally comes from the use of both AC and DC units in the electrical system. In this scenario, the solar PV panels and batteries supply direct current (DC) output power; however, the load requires alternating current (AC) [33]. The electrical power of the inverter is calculated as follows:

$$P_{inv}(t) = \frac{P_L^{m}(t)}{\tau_{inv}} \quad (11)$$

Where: $P_L^{m}(t)$ the peak load demand, τ_{inv} is the efficiency of the inverter.

3.3. Proposed Work

In this section, the primary focus was on designing reliable and economically affordable hybrid energy systems. The main output variables are the evaluation and size of the (PV-wind-battery storage). The main objective function, operation strategy, and summary of the ABC algorithm will be discussed.

3.3.1. Operation strategy

For this proposed system to be efficient and reliable, a suitable design with good power management is required. The operational strategies in simplified steps are shown below:

If the combined energy production from photovoltaic (PV) panels and wind turbines is adequate and wind generation falls short of load demand, renewable sources alone may meet demand. Any extra power generated beyond the load requirement can be preserved in battery storage, as shown below:

$$P_b\,(t) = P_{pv}\,(t) - [P_L\,(t) - P_w(t)]\,/\,\tau_{inv} \quad (12)$$

Where: $P_{L(t)}$ is the load demand, τ_{inv} is the inverter efficiency.

If wind turbines generate sufficient electrical power to fulfill the load requirement, extra power from (PV & wind) will be preserved in the battery. The power of the battery in this case is shown in (13):

$$P_b(t) = [P_w(t) - P_L(t)]\,\tau_{rec} + P_{pv}(t) \qquad (13)$$

Where: τ_{rec} is the efficiency of the rectifier.

For both cases in (12) and (13), if $P_{b(t)}$is more than the upper capacity limit of battery storage (P_b^{max}). In some circumstances, extra power can be dumped or sold to the grid. Dump energy is determined as shown below:

$$P_{dump}(t) = P_b(t) - P_b^{max}(t) \qquad (14)$$

If the power of PV and wind is insufficient, then balancing power from the batteries can be provided in the following:

$$P_b(t) = [P_L(t) - P_w(t)]\,/\,\tau_{inv} - P_{pv}(t) \qquad (15)$$

The operation strategy flow chart of the proposed hybrid energy system is shown in Fig. 2. Calculate $P_{pv}(t), P_w(t)$ and check $P_L(t)$.

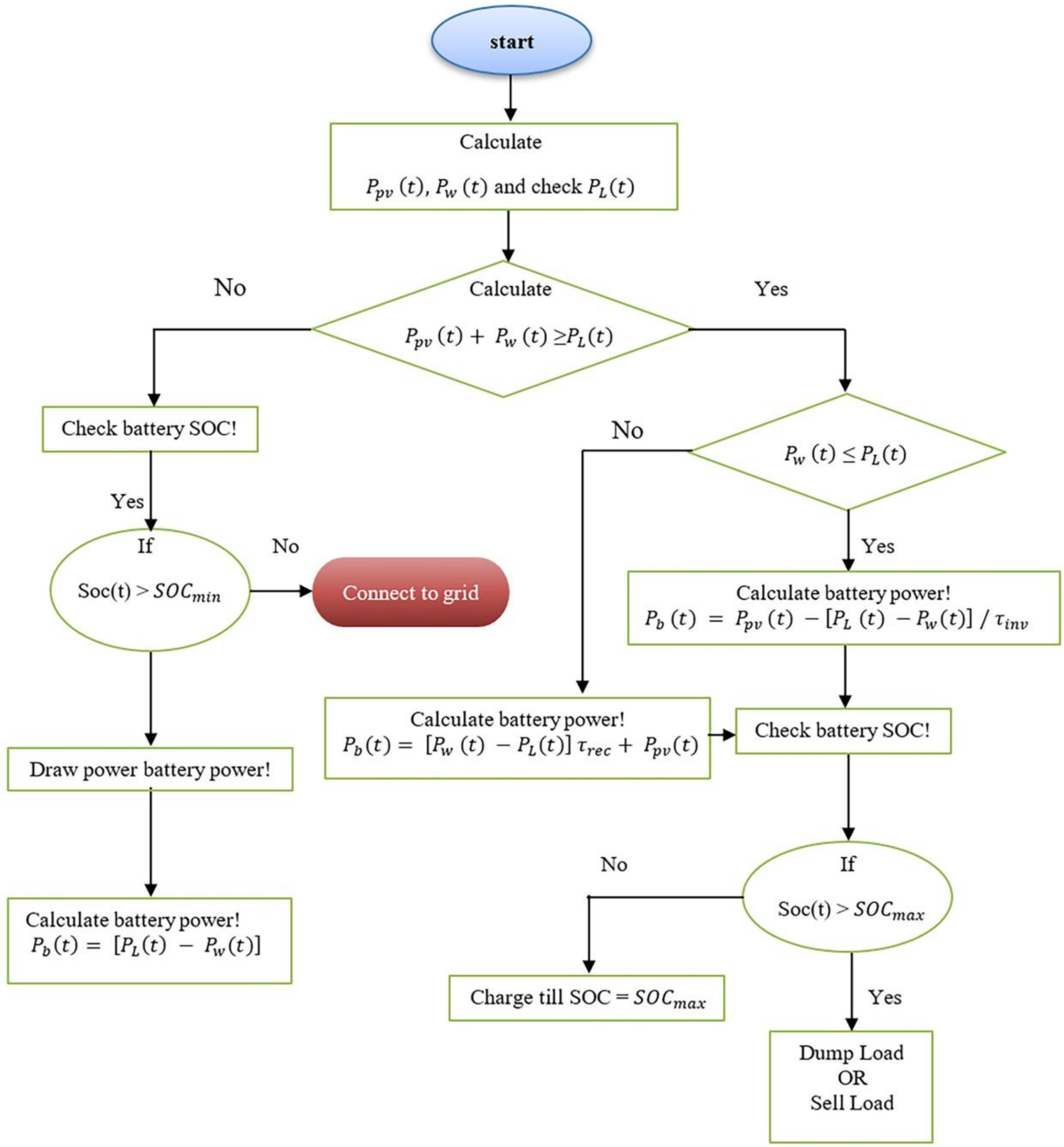

Figure 2. A schematic diagram presenting the operation strategy of the hybrid electrical system.

3.3.2. Objective Function and Limitations

The primary objective of this proposed system is to minimize the net present cost (NPC) while maximizing energy production.

Three items need to be selected for a proper setup:

- The number of PV panels
- The number of wind turbines
- The number of batteries

The annualized system cost (ASC) method is used due to its economic implications. This method was selected as the most suitable, taking into account all important aspects and constraints. The result with the smallest ASC is used to calculate the total cost of the system, which includes the following factors:

- Total capital cost, which includes installation and civil work.
- Operation and maintenance costs
- Replacement

The most important function, which needs to be lowered. It's subject to limitations:

$$Minimized\ ASC = F\left(N_{pv}C_{pv} + N_{wt}C_{wind} + N_{batt}C_{batt} + P_{inv}C_{inv}\right) \quad (16)$$

Where: C_{pv} is the cost of a PV panel per KW, C_{wind} is the cost of wind per KW, C_{batt} is the cost of the battery (per unit), C_{inv} is the cost of the inverter per KW, P_{inv} is the inverter's rating power.

The ASC of the equipment being used consists of various elements, such as capital and installation costs (C_{acap}), replacement costs (C_{arep}), operating costs (Cf), annual maintenance costs (C_m), and salvage costs (C_{sal}). Additionally, the overall ASC of each piece of equipment can be calculated as shown below:

$$C_{PV} = C_{pv}^{acap} + C_{pv}^{arep} + C_{pv}^{m} - C_{pv}^{sal} \quad (17)$$

$$C_{wind} = C_{wind}^{acap} + C_{wind}^{arep} + C_{wind}^{m} - C_{wind}^{sal} \quad (18)$$

$$C_{batt} = C_{batt}^{acap} + C_{batt}^{arep} + C_{batt}^{m} - C_{batt}^{sal} \quad (19)$$

$$C_{inv} = C_{inv}^{acap} + C_{inv}^{arep} + C_{inv}^{m} - C_{inv}^{sal} \quad (20)$$

The calculated capacity recovery factor (CRF) is used to determine the annual cost for each unit. CRF is a factor utilized for calculating the present value of money, as shown below [34].

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (21)$$

The variables i and N represent the annual interest rate and the lifespan for each unit, respectively.

The cost-effective layout of our hybrid system will guarantee that the limitations of each renewable energy component are met, as shown below:

$$1 \le N_{pv} \le N_{pv}^{m} \quad (22)$$

$$1 \le N_{wt} \le N_{wt}^{m} \quad (23)$$

$$1 \le N_{batt} \le N_{batt}^{m} \quad (24)$$

$$SOC_{min} \le SOC \le SOC_{max} \quad (25)$$

Where: N_{pv}^{m} is the highest number of PV panels, N_{wt}^{m} is the highest number of wind turbines, N_{batt}^{m} is the largest quantity of batteries.

$$LCOE = \frac{ASC(\$/annual)}{Total\ useful\ energy\ (Kwh/year)} \quad (26)$$

The optimal configuration depends on the levelized cost of energy (LCOE). The LCOE can be described as the mean expense per kWh of the usable energy produced by the entire system, as shown below [35].

3.3.3. ABC algorithm implementation steps

Input: PV radiation data, wind speed data, and equipment prices as shown in Fig.3.

Output: (N_{pv} , N_{wt} , N_{batt})

1. Input the values of SOC_{max} , SOC_{min} , D, Food Number, Limit, Max-cycle.
2. Input N_{pv}^{m} , N_{w}^{m} , N_{batt}^{m}
3. Calculates $P_{sol}(t)$, P_{wt}(t) using Eq. (1) and Eq. (2).
4. Produce a random initial population as follows:

$$X_{uv} = X_v^{min} + rand\,[0,1]\left(X_v^{max} - X_v^{min}\right) \quad (27)$$

5. Input the trial counters equal to zero.
6. Determine the primary random. values of the generated solution (N_{pv} , N_{wt} , N_{batt}).
   - Determine P_{pv}(t), $P_w(t)$ using equations.
   - Determine unit costs for the primary solution using (17, 18, 19, and 20).
7. Estimate the objective function F using (16) for the primary sources of food.
8. The following formula can be used to determine the fitness value of the bees that are employed within the colony:

$$fitness_i = \begin{cases} \frac{1}{1+f_i} & 0 \le f_i \\ \frac{1}{1+abs(fi)} & f_i \le 0 \end{cases} \quad (28)$$

Where f_i is the solution's calculated cost value X_{uv}

9. Cycle =1.
10. For the employed bees, produce an updated food task.

$$X_{uv}^{new} = X_{uv} + rand[-1,1](X_{uv} - X_{wv}) \quad (29)$$

(D is a randomized value) & (w must not be equivalent to v).

11. Follow step 6 to calculate the objective function F using (16).
12. Operate a greedy selection process.
13. Calculate a probability factor P_i .
14. Produce new solutions (X_{uv}^{new}) by applying (29) for the onlookers' bees using solutions selected according to the probability factor P_i .
15. Calculate the objective function F (16) for the updated solution by going through step 6.
16. Operate a greedy selection process.
17. Examine if you have a missing answer for the scouts, (27) enabling the scouts to create another food source.
18. Save the most suitable answer received.
19. (Cycle = Cycle + 1)
20. Till, (Cycle = Max-cycle)

4. Results

This chapter systematically demonstrates the design and simulation process for a compact (PV-wind-battery storage) hybrid energy system. Table 1 shows the electricity load demand of a small home in Baghdad, Iraq. The scheme is designed for households with a peak load of 360 kW. The investigation of the data location shows an adequate supply of solar and wind resources for almost the entire year. It was discovered that the average annual wind velocity at that location is 5.3 m/s, and the average daily solar radiation is 6.16 kWh. Tables 1 and 2 contain data concerning both the economic and technical aspects of our project's equipment. The experimental data provided by the Iraqi Ministry of Electricity (MOE) - Center for Renewable Energy [36]. The project lifetime is up to 20 years, and the interest rate is taken as (5%).

4.1. Results and Discussion

The data is simulated using MATLAB 2023a. The simulation scale interval has been considered for (1 hour), and the data has been executed for (1 year). Table 3 illustrates the control variables of the ABC algorithm. Prior to executing the ABC algorithm, the estimated numbers for the maximum quantity of photovoltaic panels (N_{pv}), wind turbines (N_{wind}), and battery storage (N_{batt}), are determined with arbitrary assumptions of 500, 350, and 750, respectively. The size of the inverter is calculated by calculating the peak load demand (360 KW) using (11), which results in a value of (379KW) in our particular scenario. In this optimized hybrid energy system, load-following strategies are utilized instead of cycle charging.

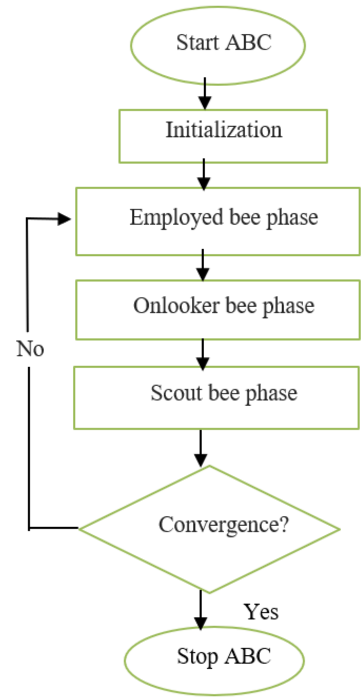

Figure 3. Simple flow chart for the ABC Algorithm.

Table 1. Estimated load demand for each house.

Type of Load for one home	Quantity	Power (KW)
Kitchen fan	1	0.13
Ceiling fan	4	0.5
Cooler	5	2.25
TV	2	0.2
Computer	1	0.2
Heater	6	3.23
Table fan	1	0.01
Vacuum cleaner	1	0.23
Lighting LED	10	0.05
Washing machine	1	0.4
No. of Houses	50	360

Table 2. Technical and economic data for each unit.

Unit	Parameter	Value	Unit
Solar PV	Rated power (P_r^s)	1	KW
	Derating factor (f_{loss})	87	%
	Capital cost (per kW)	650	$
	Replacement cost (per KW)	650	$
	maintenance cost (per KW)	5	$/year
	Lifetime	20	year
Wind Turbine	Rated power (P_r^w)	1	KW
	Rated wind speed (V_{rat})	10	m/s
	Hub height	40	m
	Cut in velocity (V_{cin})	3	m/s
	Cut out velocity (V_{cot})	20	m/s
	Capital cost (per KW)	900	$
	Replacement cost (per KW)	900	$
	maintenance cost (per KW)	3	$/year
	Overall efficiency	27	%
	Lifetime	20	year
Battery	Nominal capacity	350	Ah
	Nominal voltage	5	V
	Max charging current	19	A
	Round-trip efficiency	90	%
	Minimum state of charge	30	%
	Maximum state of charge	100	%
	Capital cost (per unit)	55	$
	maintenance cost (per unit)	1	$/year
	Lifetime	10	year
Converter	Rated power	379	KW
	Rectifier efficiency (τ_{rec})	90	%
	Inverter efficiency (τ_{inv})	95	%
	Replacement cost	300	$/year
	Lifetime	20	year

The most effective approach is determined by the ASC and LCEO, which indicate the algorithm's ability to target [37]. The convergence curve for the ABC algorithm's outputs is shown in Fig. 4. The results clearly demonstrate that the ABC algorithm yields the lowest ASC and the minimum LCEO. The results of the ABC algorithm indicate (425 kW) of PV, (300 kW) of wind turbines, and (737) batteries, with an ASC of (143,990 $/year), resulting in an LCOE of (0.0729 $/kWh). In contrast, HOMER results indicate LECO of (0.0816$/kWh).

Table 3. The ABC algorithm controls variables.

Parameter	Value
Dimension of the problem (D)	3
Employes bees = onlooker bees	12
Colony size (NP)	45
Food number	22
Maximum cycle	300
Limit	300

Interestingly, the results of ASC and other parameters generated by the ABC algorithm are available after roughly 45 iterations and an average time of less than 3 minutes. Table 4 summarizes the key unit sizes for our proposed system.

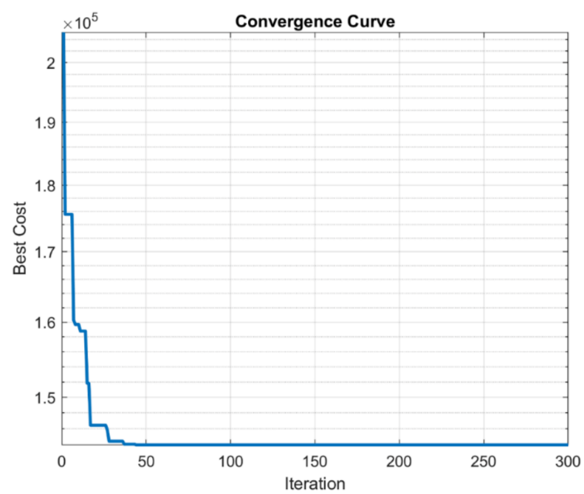

Figure 4. ASC Value ($/year) after 7 iterations using the ABC algorithm

Table 4. The ABC algorithm and HOMER generate the optimal sizing values.

Unit	HOMER	ABC
PV Unit	436	425
Wind Unit	305	300
Battery Unit	698	737
Inverter KW	379	379
ASC ($/year)	145,853	143,990
LCEO ($/KWh)	0.0816	0,0729

Table 5 illustrates the annual cost investigation of the proposed hybrid system. CRF is used to calculate the price of each unit. The lifetimes of the PV modules, wind turbines, and inverters are assumed to equal the project lifespan of 20 years; therefore, no replacement is needed. The main piece of equipment that requires replacement is the battery bank. The technical life of the battery bank is 10 years. For that reason, the number of battery bank changes during the project's life is two.

Table 5. Analysis of the ASC generated by the ABC algorithm for the hybrid system.

Unit	C_{acap} \$/year	C_{arep} \$/year	\$/year	Total \$/year
PV	43,250	0	2125	45,375
Wind	59,689	0	900	60,589
Battey	1646,6	3685	737	6068.6
Inverter	30,059	0	1895	31,954
Total	134644,6	3685	5657	143,990

The hybrid system shows a proper amount of energy output from solar (PV), wind, and batteries. The monthly energy patterns over one year are shown in Fig. 5. It is evident that January, February, March, and August offer good wind and solar resources, resulting in higher output power and battery charging rates.

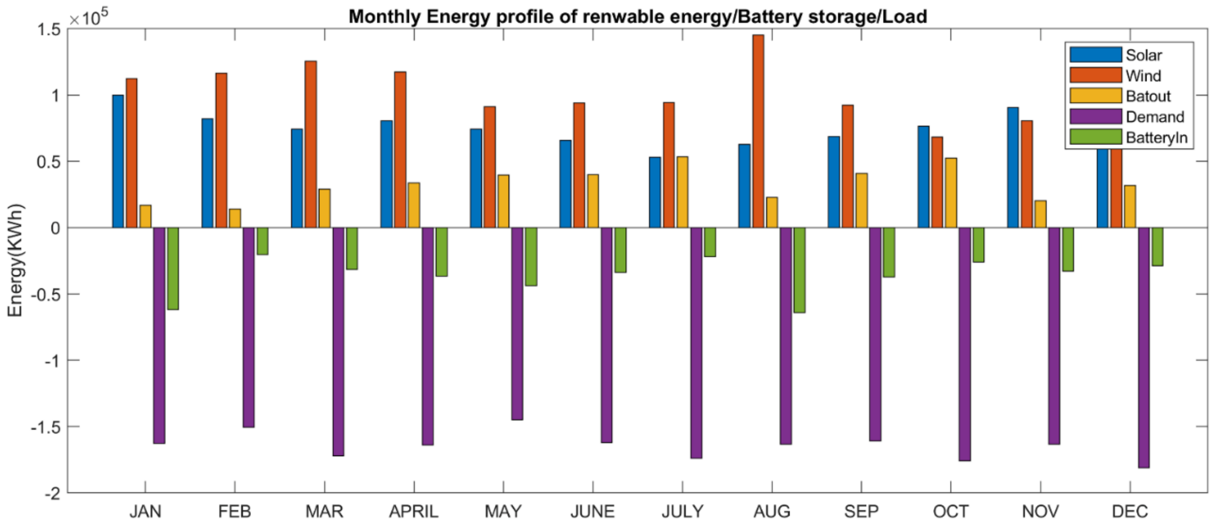

Figure 5. Monthly energy profile of the renewable hybrid system.

In accordance with (10), the maximum charging and discharging power for one hour is (70) kW. Under certain conditions, when the energy produced for battery charging exceeds the charging rates, it may be either sold to the grid or dumped. Similarly, if the discharge energy exceeds the batteries' discharge rates, we can connect to the grid. Fig. 6 shows the annual charging and discharging rates of the batteries. The SOC levels of the batteries have been carefully set at a minimum of (30%) and a maximum of (100%). Fig. 7 shows that the batteries consistently maintain their SOC levels within the predefined range. In the first week of February, at hour 825, SOC reaches (100%), and it reaches a minimum limit of (30%) at some times in the whole year. Most of the year, the SOC of the batteries remains within an acceptable range, except for a few periods: between September and October, when renewable resources are insufficient, and the last week of June and the last week of November, when load demand is high.

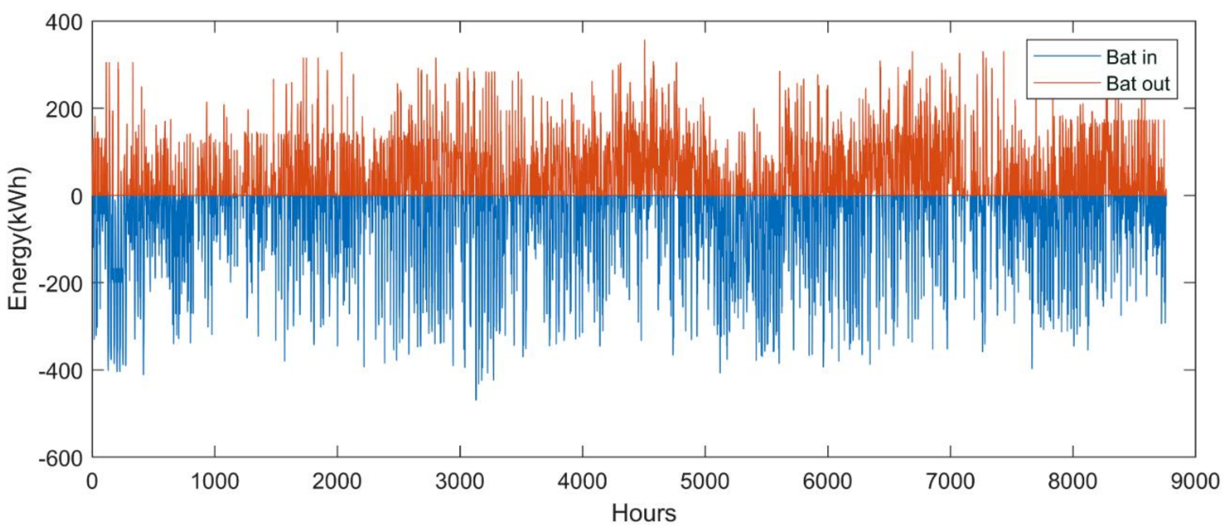

Figure 6. Annual charge and discharge rates of the batteries.

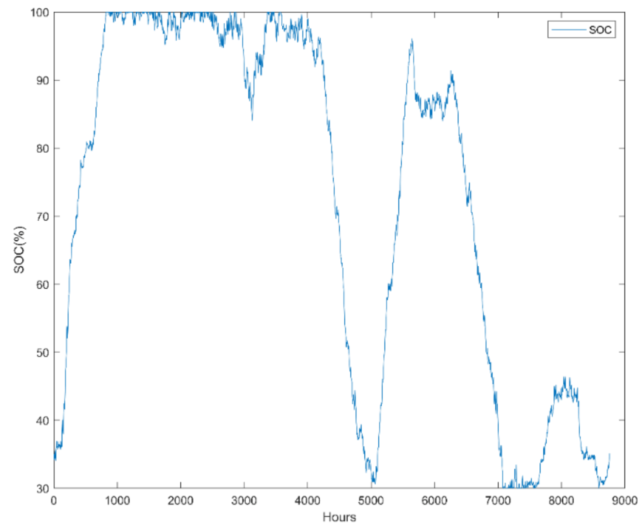

Figure 7. Annual SOC rate of the batteries.

Figs. 8 and 9 show annual solar and wind energy profiles with good availability throughout the year. The graphs reveal that anytime there is an increase in electrical energy output, the system's reliability can potentially be improved by utilizing more charging power for the batteries, as shown in Fig. 10.

The annual sum of wind and solar energy production in Fig. 11 shows good results, as generation is significantly higher than load demand most of the time, yielding the highest robustness and reliability.

4.2. Hybrid System Reliability Investigation

In this academic research, we evaluate the unexpected breakdown of a production unit contained within our hybrid energy system to measure its reliability and efficiency. More precisely, we evaluated the failure of both wind and solar sources during the third week of September. This failure leads to an imbalance between energy supply and demand in the hybrid energy system. Fig. 12 shows the full energy profile for the third week of September, with the optimal parameters unchanged.

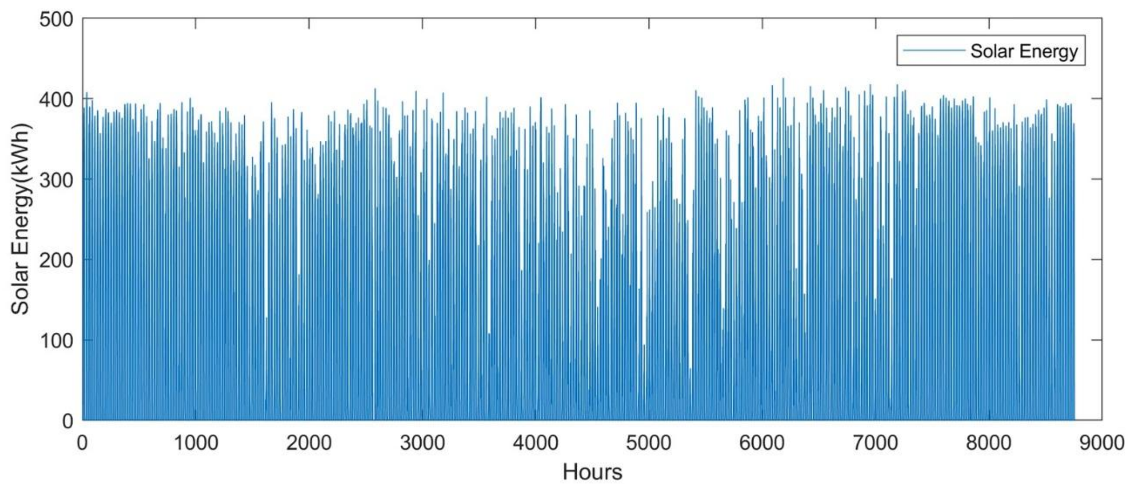

Figure 8. Annual solar PV production.

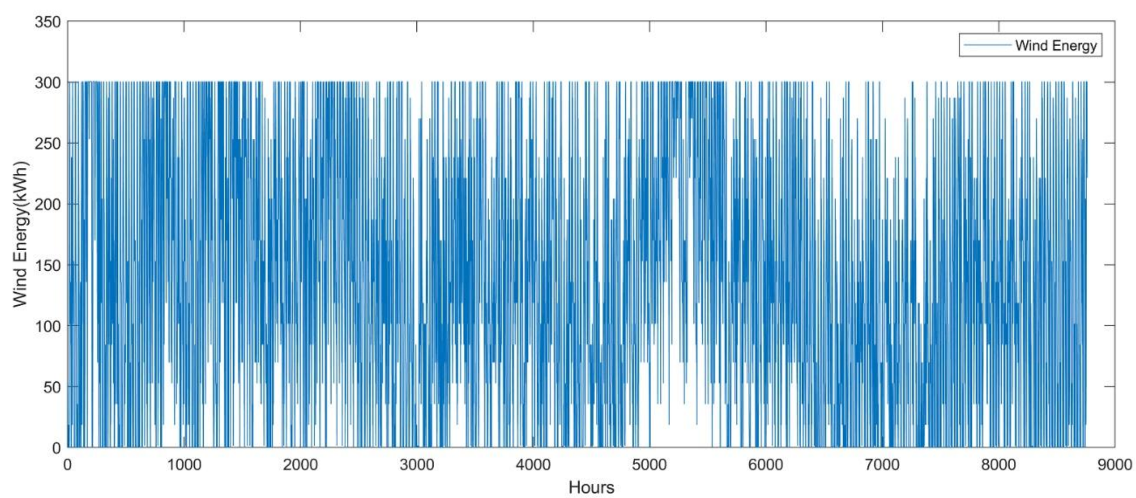

Figure 9. Annual wind turbine production.

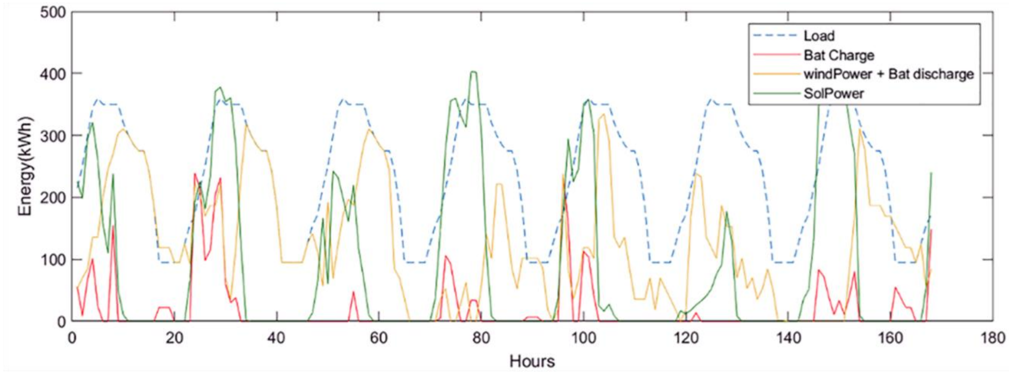

Figure 10. Battery charging profile for the first week of February.

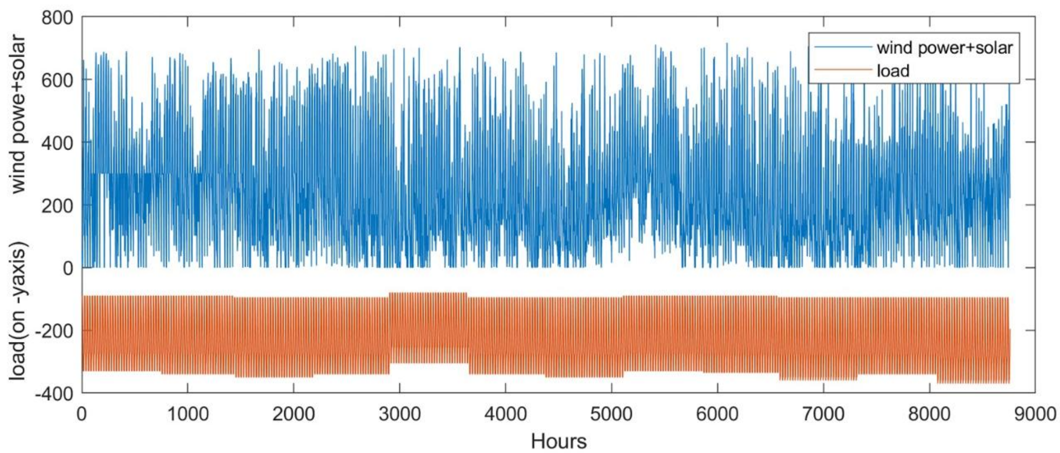

Figure 11. Annual sum of solar and wind production.

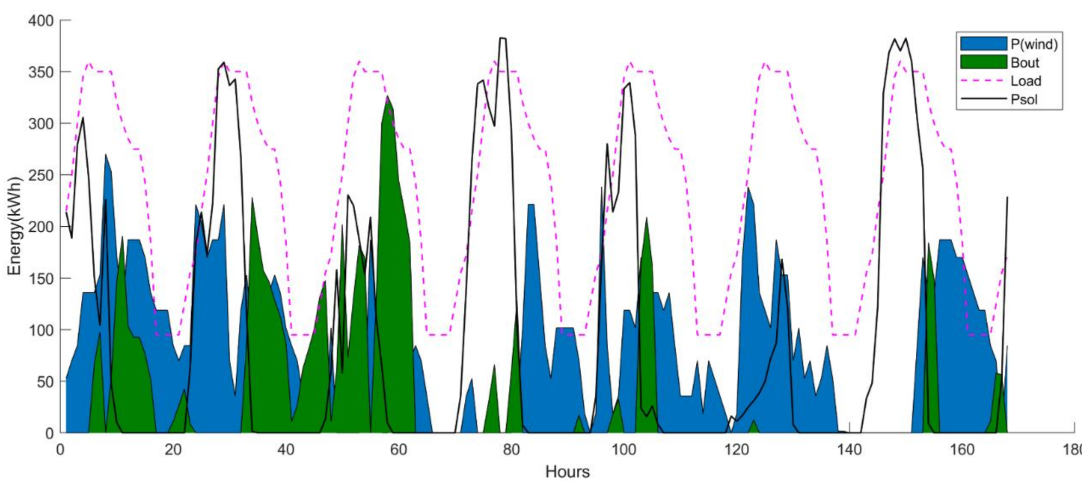

Figure 12. Energy balance for the third week of September.

We notice from Fig. 12 on the hours (66-70) and hour (140) that the SOCs of the battery banks are lower than the threshold value (30%); in that case, we can connect to the grid. The total ASC of the hybrid energy system increases from $143,990/year to $144,140/year, resulting in a slightly higher LCOE.

5. Conclusions

This study provides a comprehensive evaluation of a hybrid system that is composed of solar photovoltaic (PV) panels, wind turbines, and batteries. The work involves energy system optimization, economic analysis, and mathematical modeling for each piece of equipment and the whole system using MATLAB 2023a. The selection of components for our optimal solution was performed using the ABC algorithm. The findings were contrasted using the software tool HOMER. The operational strategy for the algorithm and the hybrid energy system is discussed in detail.

Additionally, the failure of a single unit is tested to demonstrate the system's reliability across different scenarios. In conclusion, certain key steps must be prioritized to achieve a highly efficient and reliable hybrid system. These steps comprise the careful selection of appropriate renewable energy sources, the implementation of effective energy storage, the utilization of energy conditioning techniques, the proper sizing of units, and the configuration of the hybrid system.

Future research can integrate machine learning techniques into the optimization of renewable energy sources. Machine learning can predict renewable energy generation patterns and energy demand, which enhances system performance.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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Author Contribution Statement

Marwan J. Hussein conceived the research idea, designed the study, and developed the research methodology.

Afrah T. Abdullah supervised and interpreted the findings in the context of existing literature.

Ahmed M. Almawla collected and investigated the data and wrote the article.

All authors reviewed and approved the final version of the content.

List of Symbols

C_{PV}	Cost of PV panel
C_{wind}	Cost of wind
C_{inv}	Cost of the inverter
C_{batt}	Cost of battery
C_{acap}	Capital and installation cost
C_{arep}	Replacement cost
Cf	Operation cost
C_m	Annual maintenance cost
C_{sal}	Salvage costs
$C_b(Ah)$	Single battery capacity
D	Dimension of the problem
F	Objective function
f_i	The fitness number of the bee colony
f_{loss}	The losing factor of the solar PV panels
$G_{h(t)}$	Solar PV hourly- radiation incident
G_s	The standard incident of radiation of the PV panel
H_{WT}	Hub height of the wind turbine
H_r	Reference height for a wind turbine
I_{max}	Max battery current
i	Annual interest rate
N	lifetime of each unit
N_{batt}	Number of batteries
N_{batt}^s	Number of series-connected batteries
N_{pv}	Number of solar PV panels
N_{pv}^m	Highest number of solar PV panels
N_{wt}	Number of wind turbines
N_{wt}^m	The highest value of wind turbines
P_{sol} , P_{pv}	Output power from the solar PV
P_r^s	Rating power from the solar PV panel
P_{wt}	Wind output power
P_r^w	Rated power of a single wind turbine
$P_{b(t)}$	Battery's input/output power
P_b^{max}	Upper capacity limit of battery storage
P_L^m	Peak load demand
P_{int}	Inverter output power
P_{dump}	Dump energy
V(t)	Speed of the wind at a desirable height
V_{cin}	Cut-in speed for a wind turbine
V_{cout}	Furlong speed for a wind turbine
V_{bus}	Bus voltage
V_{batt}	Single battery voltage
V_{rat}	Rated wind speed

Greek Letters

γ	Friction coefficient of a wind turbine
τ_{batt}	Round-trip efficiency of the battery
τ_{batt}^c	The battery charging efficiency
τ_{batt}^d	The battery's discharging efficiency
τ_{inv}	Inverter efficiency
τ_{rec}	Rectifier efficiency

Abbreviation

ABC	Artificial bee colony algorithm
AE	Alternative energy
ASC	Annualized system cost
CRF	Capacity recovery factor
DOD	Depth of discharge
GA	Genetic Algorithm
HRES	Hybrid renewable energy system
LCEO	Levelized cost of energy
NPC	Net percent cost
PV	Photovoltaic array
PSO	Particle swarm algorithm
SOC	State of charge

References

[1] F. A. Khan, N. Pal, and S. H. Saeed, "Review of solar photovoltaic and wind hybrid energy systems for sizing strategies, optimization techniques, and cost analysis methodologies," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 937–947, 2018. doi: https://doi.org/10.1016/j.rser.2018.04.107.

[2] S. Upadhyay and M. P. Sharma, "A review on configurations, control, and sizing methodologies of hybrid energy systems," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 47–63, 2014. doi: https://doi.org/10.1016/j.rser.2014.05.057.

[3] A. A. Khan, F. M. Minai, and R. K. Pachauri, "Optimal sizing, control, and management strategies for hybrid renewable energy systems: A comprehensive review," *Energies*, vol. 15, no. 17, p. 6249, 2022. doi: https://doi.org/10.3390/en15176249.

[4] S. Moghaddam, M. Biglari, M. Moradlou, and P. Siano, "Designing of stand-alone hybrid PV/wind/battery system using improved crow search algorithm considering reliability index," *International Journal of Energy and Environmental Engineering*, vol. 10, pp. 429–449, 2019. doi: https://doi.org/10.1007/s40095-019-00319-y.

[5] S. Singh, S. C. Kaushik, and R. K. Chauhan, "Optimal sizing of grid integrated hybrid PV-biomass energy system using artificial bee colony

algorithm," *IET Renewable Power Generation*, vol. 10, no. 5, pp. 642–650, 2016. doi: https://doi.org/10.1049/iet-rpg.2015.0298.

[6] S. Mahapatra and S. Dasappa, "Rural electrification: Optimising the choice between decentralized renewable energy sources and grid extension," *Energy Sustain. Dev.*, vol. 16, no. 2, pp. 146–154, 2012. doi: https://doi.org/10.1016/j.esd.2012.01.006.

[7] M. R. Nouni, S. C. Mullick, and T. C. Kandpal, "Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply," *Renew. Sustain. Energy Rev.*, vol. 12, no. 5, pp. 1187–1220, 2008. doi: https://doi.org/10.1016/j.rser.2007.01.008.

[8] United Nations, "Climate Change.",2021 [Online]. Available: https://www.un.org/en/climatechange.

[9] Intergovernmental Panel on Climate Change (IPCC), Ed., *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2023.doi:https://doi.org/10.1017/9781009157926

[10] United Nations Development Programme, "UN Climate Promise." [Online]. Available: https://climatepromise.undp.org/

[11] Z. Abed-El-Hadi and W. S. Al-Fassam, "Analysis of solar photovoltaic-powered village electrification at Abou-Sorra in Damascus region," *Renew. Energy*, vol. 14, pp. 119–128, 1998. doi: https://doi.org/10.1016/S0960-1481(98)00057-3.

[12] G. J. Dalton, D. A. Lockington, and T. E. Baldock, "Case study feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations," *Renew. Energy*, vol. 34, no. 4, pp. 1134–1144, 2009. doi: https://doi.org/10.1016/j.renene.2008.06.018.

[13] N. Siweya, "Carbon tax to lower emissions: the likely impact of carbon emissions tax on households in South Africa," *Afr. Multidiscip. Tax J.*, vol. 2021, no. 1, pp. 211–227, 2022. doi: https://doi.org/10.47348/AMTJ/2021/i1a12.

[14] H. Nehrir, C. Wang, K. Strunz, and H. Aki, "A Review of Hybrid Renewable/Alternative Energy Systems for Electric Power Generation: Configurations, Control, and Applications," in *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, USA, 2012. doi: https://doi.org/10.1109/pesgm.2012.6344852.

[15] H. A. Kazem, T. Khatib, and K. Sopian, "Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman," *Energy and Buildings.*, vol. 61, pp. 108–115, 2013. doi: https://doi.org/10.1016/j.enbuild.2013.02.011.

[16] H. A. Kazem, "Renewable energy in Oman: Status and prospects," *Renew. Sustain. Energy Rev.*, vol. 15, pp. 3465–3469, 2011. doi: https://doi.org/10.1016/j.rser.2011.05.015.

[17] H. A. Kazem and M. T. Chaichan, "Status and prospects of renewable energy in Iraq," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 6007–6012, Oct. 2012. doi: https://doi.org/10.1016/j.rser.2012.03.058.

[18] S. Singh, S. C. Kaushik, and R. K. Chauhan, "Feasibility study of an islanded microgrid in a rural area consisting of PV, wind, biomass, and battery energy storage system," *Energy Conversion and Management*, vol. 128, pp. 178–190, 2016. doi: https://doi.org/10.1016/j.enconman.2016.09.046.

[19] S. O. Frimpong, E. A. Frimpong, and A. A. Asiedu, "Economic and reliability determination of sustainable renewable mix based on social spider prey optimization algorithm," *Soft Computing*, vol. 27, pp. 10687–10718, May 2023. doi: https://doi.org/10.1007/s00500-023-08231-8.

[20] S. Mandal, K. K. Mandal, and S. K. Mandal, "Modeling of photovoltaic systems using Modified Elephant Swarm Water Search Algorithm," *Int. J. Model. Simul.*, vol. 40, no. 6, pp. 436–455, 2020. doi: https://doi.org/10.1080/02286203.2019.1650488.

[21] S. Sinha and S. S. Chandel, "Review of recent trends in optimization techniques for solar photovoltaic–wind-based hybrid energy systems," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 755–769, 2015. doi: https://doi.org/10.1016/j.rser.2015.05.040.

[22] V. K. R. Kalananda, *Intelligent Paradigms for Smart Grid and Renewable Energy Systems*. Singapore: Springer, 2021. doi: https://doi.org/10.1007/978-981-15-9968-2.

[23] D. Karaboga and B. Akay, "A comparative study of Artificial Bee Colony algorithm," *Applied Mathematics and Computation*, vol. 214, no. 1, pp. 108–132, Aug. 2009. doi: https://doi.org/10.1016/j.amc.2009.03.090.

[24] M. J. Hussein, O. T. Khazraji and A. M. Almawla, "Optimization Algorithms and Modeling Techniques for Hybrid Renewable Energy Systems: A Mini Review," *Engineering and Technology Journal*, vol. 44, no. 2, pp. 55-77, 2026. https://etj.researchcommons.org/journal/vol44/iss2/4/

[25] Y. Xu, P. Fan, and L. Yuan, "A Simple and Efficient Artificial Bee Colony Algorithm," *Math. Probl. Eng.*, vol. 2013, pp. 1–9, 2013. doi: https://doi.org/10.1155/2013/526315.

[26] D. Karaboga, "Artificial Bee Colony (ABC) Algorithm," *Scholarpedia*, vol. 5, no. 3, p. 6915, 2010. [Online]. available: http://www.scholarpedia.org/article/Artificial_bee_colony_algorithm

[27] D. Karaboga and B. Basturk, "A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm," *Journal of Global Optimization*, vol. 39, no. 3 pp. 459–471, Apr. 2007. doi: https://doi.org/10.1007/s10898-007-9149-x.

[28] B. Diouf and R. A. Diouf, "Initiative for 100% rural electrification in developing countries: Case study of Senegal," *Energy Policy*, vol. 59, pp. 926–930, 2013. doi: https://doi.org/10.1016/j.enpol.2013.04.012.

[29] R. Salih, "Seasonal Optimum Tilt Angle of Solar Panels for 100 Cities in the World," *Al-Mustansiriyah J. Sci.*, vol. 34, no. 1, pp. 104–110, 2023. doi: https://doi.org/10.23851/mjs.v34i1.1250.

[30] A. Ahmed, S. A. O. Al-Mamoori, and M. A. Al-Maliki, "The Role of Teleconnection Patterns on Wind Speed of Iraqi Kurdistan Region," *Al-Mustansiriyah J. Sci.*, vol. 34, no. 2, pp. 8–18, 2023. doi: https://doi.org/10.23851/mjs.v34i2.1249.

[31] T. Adefarati and R. C. Bansal, "Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources," *Applied Energy*, vol. 236, pp. 1089–1114, 2019. doi: https://doi.org/10.1016/j.apenergy.2018.12.050.

[32] NREL, "The National Renewable Energy Laboratory." [Online]. Available: https://www.nrel.gov/

[33] R. N. Hasanah, T. C. L. Putra, and S. T. Wicaksono, "Power Controller for Hybrid AC/DC House," *AIP Conf. Proc.*, vol. 2228, no. 1, p. 020001, 2020. doi: https://doi.org/10.1063/5.0000897.

[34] F. Alturki, H. M. H. Farh, A. A. Al-Shamma'a, and A. M. Noman, "Techno-Economic Optimization of Small-Scale Hybrid Energy Systems Using Manta-Ray Foraging Optimizer," *Electronics*, vol. 9, no. 12, p. 2045, 2020. doi: https://doi.org/10.3390/electronics9122045.

[35] M. Papapetrou and G. K. Kosmadakis, "Resource, environmental, and economic aspects of SGHE," in *Salinity Gradient Heat Engines*, Cambridge, U.K.: Elsevier, 2022, ch. 9, pp. 319–353. doi: https://doi.org/10.1016/B978-0-08-102847-6.00006-1.

[36] Iraqi Ministry of Electricity, "Iraqi Ministry of Electricity." [Online]. Available: https://moelc.gov.iq/ .

[37] A. Q. Mohammed, K. A. Al-Anbarri, and R. M. Hannun, "Using Particle Swarm Optimization To Find Optimal Sizing Of PV-BS And Diesel Generator," *J. Eng. Sustain. Dev.*, vol. 25, no. 3, pp. 51–59, May 2021. doi: https://doi.org/10.31272/jeasd.25.3.6.