Optimal Sizing and Design of a Photovoltaic-Wind-Fuel Cell Storage System Using Zebra Optimization Algorithm

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Abstract

An optimum design of Photovoltaic-wind turbine-fuel cell hybrid energy systems (HRES) linked to a stand-alone micro-grid to meet the energy requirements of industrial and residential buildings in the Egyptian city of Siwa with anew algorithm introduced in this paper. The main photovoltaic (PV) and wind turbine (WT) hybrid renewable energy systems (HRESs) provide an affordable means of distributing power in these areas and then there is surplus power, it is efficiently channeled towards the electrolyzer to produce hydrogen. When the generated power cannot provide sufficient power, stored hydrogen is furnished to a proton exchange membrane fuel cell which, smoothly and without interruption, supplies the load. Fuel cells serve as supplemental sources intended to balance out power fluctuations and provide a steady supply of electricity to the load. The Zebra algorithm (ZOA) is used to determine the hybrid system's ideal size and compare results with Cuckoo Search algorithm (CSA). To match the load of the site with high operational reliability, a fitness function is employed loss of power supply probability (LPSP). To have a high-performance, dependable system, the optimization problem's choice variables such as the quantity of PV arrays and WTs are optimized. Based on the findings, 150 FCs, 113 wind turbines, and 82 PV arrays make up the ideal HRES system. The optimization performance has been excellent, even when the unmet load is zero with lowest COE.

Introduction

Developing renewable energy is essential for the energy transition and for cutting greenhouse gas emissions [1]. Global pollution in 2020 dropped by 5.9% from 2019 due to the coronavirus epidemic, which also markedly cut global energy consumption [2]. As a result, there has been a greater focus on hybrid renewable energy systems (HRES), which encompass either one or more renewable energy sources (RE). To raise system efficiency and boost power supply reliability, several energy sources are being used, such as wind, solar, fuel cells (FCs), hydropower, biomass, and biogas. Additionally, FCs are employed as a backup storage device because their efficiency is higher than those of batteries [3–7]. The majority of HRESs are utilized either alone or in conjunction with an electrical grid. In remote areas, stand-alone systems are utilized to cover consumption [8]. Therefore, efforts were focused on using hybrid renewable energy systems (HRES), which use clean renewable energy sources like solar electricity, wind, biomass, hydropower, and fuel cells, to increase the stability of the power supply. Moreover, HRESs can be used to bridge the gap between supply and demand loads or to send electricity to remote places due to the rapidly increasing need for power and the incapacity of conventional plants to meet it [9–17].

These days, several studies describe and assess how to model, size, and simulate hybrid systems such as RE with FCs and use a suggested optimization technique to increase system reliability while lowering energy costs [18–22]. In the literature, F. S. Mahmoud et al. (2022) [23] have several optimization techniques that aim to find the best solution to HRES. For the best sizing of HRESs in combination with a grid under uncertainty, the marine predators’ algorithm (MPA) and the seagull optimization algorithm (SOA) was integrated. R. J. Rathish et al. (2021) [24] use of the strong Pareto evolutionary algorithm demonstrated the best way to combine photovoltaic (PV), wind, and diesel
energy sources to minimize CO2 emissions and acquire the lowest possible overall cost of a hybrid system. A. Maleki et al. (2015) [25] best design of a solar/wind system with a storage battery bank was determined by applying the genetic algorithm (GA) method to minimize the loss of power supply probability (LPSP) and the overall cost of the system. M. J. Hadidian-Moghaddam et al. (2016) [26] Additionally, grey wolf optimization (GWO) was used to adopt the best design for a PV/wind turbine/battery hybrid system to reduce annual total cost and increase system reliability. M. Bilal et al. (2022) [27] show several hybrid energy system configurations that can be used to meet the power needs of the electric vehicle charging station (EVCS) that is located in Delhi, India's northwest. Additionally, the levelized cost of energy and total net present cost are minimized through the application of the modified slap swarm algorithm (MSSA).

In the past few years, M.J. Khan et al. (2022) [28] FCs have drawn increased attention as storage devices and have been crucial to HRES in providing load with continuous power. A.A.Z. Diab et al. (2019) [29] when compared to batteries, FCs offer a number of advantages, such as low temperatures, excellent efficiency, and no toxic emissions. In this study, when the generated power from PV and wind energy more than the load demand, the excess power sent to electrolyzer system that produces hydrogen, which is stored in tanks to be used later to power fuel cells (FCs) that generate electricity when load demand less than the generated power. Additionally, the mass of hydrogen tanks, the number of PV arrays, wind turbines, and the rated power of FCs, inverters, and electrolyzers should all be optimized for the best possible sizing. The modelling of the hybrid system components to meet load requirements, achieve maximum system reliability, and achieve least generated energy cost are the three most important challenges in this work. Due to the intricacy of the hybrid system's optimization, new methods for resolving optimization issues were developed, including Zebra optimization algorithm. Through hourly temperature, solar radiation, and wind speed calculations, the practicality of the suggested methodologies has been verified using the Siwa Osias of Egypt as a case study.

It is evident from the literature assessment that hybrid renewable energy systems and their optimal sizing are the researchers' main areas of interest. Driven by the concerns of the literature review, the primary goals and contributions of this work are:

- The Egyptian city of Siwa has developed its residential and industrial units with the best PV/WT/FC HRES.
- A novel new metaheuristic technique known as the Zebra algorithm has been used to address the optimization issue. The size number of PV arrays, WTs, are used as choice variables in the optimization problem. On the other hand, the fitness function is the LPSP minimization and estimated the number of FCs.
- The energy analysis cost for the ideal system size has been established.
- We have analyzed the performance of the Zebra approach by examining its resilience and convergence curves through statistical analysis of 100 independent runs.
The study is structured as follows: part 2 (the modeling of the hybrid system) comes after the introduction. The methodology is introduced in Section 3. The application and outcomes are covered in Section 4. Optimization Zebra algorithm is in Section 5. Section 6 provides the conclusion at the end.

**Modeling of hybrid PV/WT/FC system**

The modeling of the content of PV/WT/FC is indicated in Fig. 1. System consists of AC bus and DC bus, which provide the best performance to the model, to directly supply power from WTs to the AC load. The energy interest of the consumer is satisfied by using the energy produced by PV and WTs, which are double sources. The residual energy is sent to the electrolyzer and stored in the hydrogen tank when the generated does not satisfy the load, the load feeds from the fuel cell. The HRES parameters are determined by using Table 1.
Table 1
HRES (PV/WT/FC) parameters [30–32], [23].

<table>
<thead>
<tr>
<th>Hybrid system components</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>Panel model</td>
<td>BBS24MF400 (Mono PERC)</td>
</tr>
<tr>
<td></td>
<td>Maximum power of panel</td>
<td>400 W</td>
</tr>
<tr>
<td></td>
<td>Open circuit voltage of panel</td>
<td>50.49 V</td>
</tr>
<tr>
<td></td>
<td>Short circuit current of panel</td>
<td>9.98 A</td>
</tr>
<tr>
<td>WT</td>
<td>Model</td>
<td>REYAH - H50</td>
</tr>
<tr>
<td></td>
<td>Rated power</td>
<td>50 kW</td>
</tr>
<tr>
<td></td>
<td>Start-up wind speed</td>
<td>3 m/s</td>
</tr>
<tr>
<td></td>
<td>Rated wind speed</td>
<td>10 m/s</td>
</tr>
<tr>
<td></td>
<td>Survival wind speed</td>
<td>50 m/s</td>
</tr>
<tr>
<td></td>
<td>Wheel diameter</td>
<td>17.6 m</td>
</tr>
<tr>
<td>FC</td>
<td>Model</td>
<td>Fuel cell stack EH-81</td>
</tr>
<tr>
<td></td>
<td>Rated power</td>
<td>100 kW</td>
</tr>
<tr>
<td></td>
<td>Voltage range</td>
<td>231–513 V</td>
</tr>
<tr>
<td></td>
<td>Peak current</td>
<td>450A</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>Model</td>
<td>PEM</td>
</tr>
<tr>
<td></td>
<td>Rated power</td>
<td>300 kW</td>
</tr>
<tr>
<td></td>
<td>Voltage</td>
<td>415V</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Converter</td>
<td>Rated power</td>
<td>150 kW</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>90%</td>
</tr>
</tbody>
</table>

2 − 1.

2 − 1. Modeling of PV system
One can compute the PV panel output power ($P_{PVp}$) in the following way [33–34]:

$$P_{PVp} = \frac{S_{Glo}}{S_{Stand}} \times P_{PVr-cap} \times f_{de-pv} \times (1)$$

The following formula yields the total energy generated (kWh) from a photovoltaic system ($P_{PVp-tot}$).
\[ PV_{Pp-tot} = N_{PV} \times PV_{Pp} \] (2)

Where;

- \( S_{Glo} \) is the panel's worldwide incident solar radiation (kWh/m²),
- \( S_{Stand} \) is standard of solar radiation (1 kWh/m²),
- \( P_{PV-cap} \) is rated capacity of PV array (kW),
- \( f_{de-pv} \) is derating factor of PV,
- \( N_{PV} \) is the number of PV arrays.

### 2–2. Modeling of WT system

This is how the WT generated power \( P_{windT} \) is calculated.[35],

\[
P_{windT} = \begin{cases} 
P_{rwt} \times \frac{v^3 - v_{low-cut}^3}{v_{r}^3 - v_{low-cut}^3} v_{slow-cut} \leq v \leq v_{r} \\ P_{rwt} \times n\nu_{r} \leq v \leq v_{upcut} \\ 0 \text{ otherwise} \end{cases} \tag{3}
\]

Where;

- \( P_{rwt} \) is the wind turbine's nominal power,
- \( v \) is speed of the wind,
- \( v_{slow-cut} \) is the slow cut speed,
- \( v_{upcut} \) is the speed at which the upcut occurs,
- \( v_{r} \) is the nominal power of wind speed.

The turbine hub height can be used to determine the variance in wind speed in the following ways:

[3], [35],

\[
\frac{v_{av\_h}}{v_{av\_hr}} = \left( \frac{h}{h_{r}} \right)^{\epsilon} \tag{4}
\]

Where;

- \( v_{av\_h} \) (m/s) is the wind speed on average at hub height \( h \) (m).
\( v_{av,hr} \) (m/s) is the mean wind speed at the height \( h_r \) (m).

\( \epsilon \) is roughness factor that has the values from 0.14 to 0.25.

The following formula is used to calculate the total generated power (kW) from WTs \( (P_{\text{WindT-total}}) \).

\[
P_{\text{WindT-total}} = N_{\text{WT}} \times P_{\text{windT}} \tag{5}
\]

Where, \( N_{\text{WT}} \) is number of WTs.

### 2.3. Modeling of Electrolyzers

By running a direct current (DC) across two electrodes to separate water into hydrogen (from the anode side) and oxygen (from the cathode side), the electrolyzer to produce hydrogen is fed by the extra energy produced by PVs and wind sources (See Eq. (6)) [29]. Subsequently, the hydrogen generated is kept in high-pressure tanks [36].

\[
\text{Electricity} + H_2O = H_2 + \frac{1}{2} O_2 \tag{6}
\]

The following equation shows the power output that is transferred from the electrolyzer to the hydrogen tank [29].

\[
P_{\text{out-ele}} = P_{\text{in-ele}} \times \tau_{\text{ele}} \tag{7}
\]

Where;

- \( P_{\text{out-ele}} \) is the electrolyzer’s output power (kw),
- \( P_{\text{in-ele}} \) is its input power (kw),
- \( \tau_{\text{ele}} \) is the electrolyzer’s constant efficiency,

### 2.4. Modeling of \( H_2 \) Tank

When power output from PVs and wind sources is low during peak hours, FCs are fed the necessary amount of hydrogen to make up for any shortage in the needed power. The following is an illustration of the hydrogen energy at any \( (t) \):

\[
E_{\text{tank}H_2}(\Delta t) = E_{\text{tank}H_2}(t - 1) + (P_{\text{out-ele}} - \frac{P_{\text{sup-fc}}(t)}{\tau_{\text{tank}}} \times \Delta t) \tag{8}
\]

Where;

- \( E_{\text{tank}H_2}(\Delta t) \), \( E_{\text{tank}H_2}(t - 1) \) are the energy stored in the tank at times \( t \) and \( (t - 1) \),
- \( P_{\text{sup-fc}}(t) \) is the power given to the FCs,
\( \tau_{tank} \) is the efficiency of the hydrogen tank, is assumed to be 95\% during all operations.

The following estimate can be used to determine the mass of hydrogen generated by the electrolyzes [29]:

\[
M_{ankH_2} (\Delta t) = \frac{E_{tankH_2} (\Delta t)}{HHV} \tag{9}
\]

Where;

\( HHV \) is the hydrogen's higher heating value, which is 39.7 kWh/m\(^2\).

### 2.5. Modeling of FC

An FC is made up of two electrons (the anode and cathode) and an electrolyte that sits in between. It is used to convert chemical energy to electrical DC energy using an electrolyzer. In addition to being simpler, requiring less maintenance, and having a higher efficiency than batteries, it is also a green energy source that produces no pollutants [37–39].

Equation (10) can be used to calculate the power generated by FC in the following manner and number of fc can be calculated form Eq. (11) [22]:

\[
P_{out\_fc} (t) = P_{sup\_fc} (t) \times \tau_{fc} \tag{10}
\]

\[
N_{fc} = \frac{\max(P_{fc})}{P_{fc\_rated}} \tag{11}
\]

Where;

\( \tau_{fc} \) is FC efficiency,

### 2.6. Modeling of DC/AC Converter

Since the loads require alternating current (AC) power, the power generated by the PVs and wind turbines is required for the conversion of DC power to AC power. Eq. (12) is utilized to compute the inverter's output power.

\[
P_{out\_invr} = (P_{out\_fc} (t) \times P_{gen}) \times \tau_{invr} \tag{12}
\]

Where;

\( P_{gen} \) is the amount of power generated by RES.

\( \tau_{invr} \) is the efficiency of the inverter taken to be constant at 90\%.

### Methodology

#### 3 – 1. Objective function
The major objective function of the hybrid system in this work is to minimize the COE and LPSP with decision variables:

\[ N_{PV}^{min} \leq N_{PV} \leq N_{PV}^{max} \] (13)
\[ N_{WT}^{min} \leq N_{WT} \leq N_{WT}^{max} \] (14)

Where \( N_{PV} \) is the number of photovoltaic arrays; \( N_{WT} \) is the number of wind turbines;

We must take this into consideration to prevent issues with electrolyzer charging and FC device discharge, the generated power needs to be limited.

\[ M_{tank_{H2-min}} \leq M_{tank_{H2}} (t) \leq M_{tank_{H2-max}} \] (15)

where \( M_{tank_{H2-min}} \) represents the lowest capacity of the hydrogen tanks and \( M_{tank_{H2-max}} \) represents the maximum capacity of the H2 tanks.

3.2. Loss of power supply probability

The evaluation of the proposed energy system's reliability relies on the Loss of Power Supply Probability (LPSP). It is crucial to ensure that the LPSP does not exceed a certain threshold, as indicated by \( \epsilon_{LP} \) [23]. To determine the LPSP value, the following equation is utilized.

\[ LPSP = \frac{P_{load} - P_{generated}}{P_{load}} = \frac{P_{load} - (P_{PV} + P_{Wt} + P_{fc})}{P_{load}} \] (16)

The power generated from WT is denoted by \( P_{Wt} \), the power generated from PV by \( P_{PV} \), the total generated power by \( P_{generated} \), the load power by \( P_{load} \) and \( P_{fc} \) is the power of fuel cell.

3.3. Cost of Energy (COE)

The annual total cost of the hybrid system is the same as the total cost of the PV, wind turbine, FCs, electrolyzer, H2 tank, and converters components of the suggested system [23].

\[ C_{t-an} = C_{ca-an} + C_{re-an} + C_{o-m-an} \] (17)

Where;

\( C_{t-an} \) is the hybrid system's total annual cost.

\( C_{ca-an} \) is the annual capital cost of each system component.

\( C_{re-an} \) is the annual cost of replacement.

\( C_{o-m-an} \) is annual maintenance and operating costs for every system component.
The calculation for annual capital cost is as follows:

\[ C_{ca_{an}} = C_{ca_{an-pv}} + C_{ca_{an-wt}} + C_{ca_{an-fc}} + C_{ca_{an-ele}} + C_{ca_{an-h2}} + C_{ca_{an-invr}} \] (18)

The cost of each individual component in the entire system for one year is depicted in Eq. (19).

\[
\begin{bmatrix}
C_{ca_{an-pv}} &= C_{ca_{pv}} \times CRF(i, L_{pv}) \\
C_{ca_{an-wt}} &= C_{ca_{wt}} \times CRF(i, L_{wt}) \\
C_{ca_{an-fc}} &= C_{ca_{fc}} \times CRF(i, L_{fc}) \\
C_{ca_{an-ele}} &= C_{ca_{ele}} \times CRF(i, L_{ele}) \\
C_{ca_{an-h2}} &= C_{ca_{h2}} \times CRF(i, L_{h2}) \\
C_{ca_{an-invr}} &= C_{ca_{invcr}} \times CRF(i, L_{inlr})
\end{bmatrix}
\]

where the initial capital costs of the wind turbine module, FC, hydrogen tanks, electrolyzers, PV module, and converter are denoted by the letters \( C_{ca_{wt}}, C_{ca_{fc}}, C_{ca_{ele}}, C_{ca_{h2}}, C_{ca_{pv}}, \) and \( C_{ca_{invcr}} \) correspondingly. The lifetimes of the WTs, FCs, hydrogen tanks, electrolyzers, PV module, and converter are, in order, \( L_{wt}, L_{fc}, L_{ele}, L_{h2}, L_{pv}, \) and \( L_{invr}. \) The annual interest rate is denoted by \( i. \)

The investment cost is converted to the capital cost using the Capital Recovery Factor (CRF). To calculate CRF, Eq. (20) is considered.

\[ CRF(i, L_{i}) = \frac{i(1+i)^{L_{i}}}{i(1+i)^{L_{i}} - 1} \] (20)

- **Annual replacement cost:** this expense arises when the component lifetime is less than the project lifetime.

\[ C_{re_an} = C_{re_i} \times \frac{(L - L_{i})}{L} \] (21)

- **Annual operation and maintenance costs:** These are the expenses incurred when a hybrid system component needs to be repaired or when it is necessary to operate a component.

\[ C_{o_m_an} = C_{o_m_an-pv} + C_{o_m_an-wt} + C_{o_m_an-fc} + C_{o_m_an-ele} + C_{o_m_an-h2} + C_{o_m_an-invr} \] (22)

The following formula is used to calculate COE of the hybrid power systems:

\[ COE = \frac{C_{t-an}}{P_{load}} \] (23)

**Zebra optimization algorithm**
The basic idea behind Zebra optimization algorithm (ZOA) is to simulate the social behavior found in zebra herds in the natural. Sixty-eight benchmark functions of various unimodal, high-dimensional multimodal, fixed-dimensional multimodal, CEC2015, and CEC2017 models have been used to test ZOA performance [40]. A pioneer zebra facilitates the movement of other zebras towards the food source during the foraging process. As a result, the pioneer zebra leads the herd of other zebras as they go over the plains. The zebras’ main defense against predators is to flee in a zigzag manner. But occasionally, they try to scare or confound the predator by congregating. The proposed ZOA design draws its fundamental inspiration from mathematical modeling of these two types of intelligent zebra behavior.

4.1. ZOA mathematical model

4.1.1 initialization

Zebras are part of the population of ZOA, a population-based optimizer. Each zebra is a potential solution to the issue from a mathematical perspective, and the plain where the zebras are located is the problem's search space. The values for the decision variables are determined by each zebra's location inside the search space. As a result, a vector may be used to describe each zebra as a member of the ZOA, with the values of the issue variables being represented by the vector's elements. A matrix can be used to numerically model the zebra population [40]. The zebras’ starting locations inside the search area are chosen at random. The population matrix for ZOA can be found in (24).

\[
Z = \begin{bmatrix}
Z_1 \\
\vdots \\
Z_i \\
\vdots \\
Z_N
\end{bmatrix}_{N \times m} =
\begin{bmatrix}
z_{1,1} & \cdots & z_{1,j} & \cdots & z_{1,m} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
z_{i,1} & \cdots & z_{i,j} & \cdots & z_{i,m} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
z_{N,1} & \cdots & z_{N,j} & \cdots & z_{N,m}
\end{bmatrix}_{N \times m}
\]  

(24)

Where;

\( N \) is the number of population members (zebras).

\( m \) is the number of choice variables.

\( Z \) is the zebra population.

\( z_i \) is the \( ith \) zebra.

\( z_{i,j} \) is the answer for the \( jth \) problem variable provided by the \( ith \) zebra.

Every zebra symbolizes a potential resolution to the optimization issue. As a result, the suggested values of each zebra for the issue variables may be used to assess the objective function. By utilizing Eq. (25),
the values acquired for the objective function are provided as a vector.

\[
F = \begin{bmatrix}
F_1 \\
\vdots \\
F_i \\
\vdots \\
F_N
\end{bmatrix}_{N \times 1} = \begin{bmatrix}
F(Z_1) \\
\vdots \\
F(Z_i) \\
\vdots \\
F(Z_N)
\end{bmatrix}_{N \times 1}
\] (25)

Where;

\(F\) is objective function value as a vector.

\(F_i\) is the objective function value acquired for the \(i\)th zebra.

The best candidate solution for the given issue is found by comparing the values obtained for the objective function, which effectively analyses the quality of their associated candidate solutions. The zebra with the lowest objective function value is the best possible solution in minimization issues.

On the other hand, the optimal candidate zebra in maximization issues is the one with the highest value of the objective function. The best candidate solution must be found in each iteration as the zebras' locations and, as a result, the values of the goal function, are modified in each iteration.

ZOA members have been updated using two of the zebra's natural behaviors. The first of these two behavioral patterns is foraging, and the second is predator defense mechanisms. Members of the ZOA population are therefore updated twice throughout each cycle.

4.1.2. Phase 1: Foraging Behavior

Using models of zebra behavior during foraging, population members are updated in the first phase. The plains zebra, one of the zebra species, offers habitat to other species that require shorter and more nutrient-rich grasses below. The best zebra in the population is known as the pioneer zebra in ZOA, and it guides other zebras in the population towards its location in the search space [40]. Therefore, Eqs. (26) and (27) may be used to mathematically simulate how zebras' positions are updated throughout the foraging phase.

\[
z_{i,j}^{new,P1} = z_{i,j} + r \cdot (P_X_j - I \cdot x_{i,j})
\] (26)

\[
Z_i = \begin{cases} 
Z_{i}^{new,P1} & F_i^{new,P1} < F_i \\
Z_i & \text{else}
\end{cases}
\] (27)

Where;

\(P_X\) is the best member represent the pioneer zebra.
$PX_j$ is $jth$ dimension.

$r$ is a random number within a specific range $[0; 1]$.

### 4.1.3. Phase 2: Defense Strategies Against Predators

The second step involves updating the position of ZOA population members in the search space using models of the zebra's defense mechanism against predator assaults. The mode $S1$ in Eq. (28) can be used to simulate this tactic. When a zebra is attacked by another predator, the other zebras in the herd move towards it to create a protective structure that will intimidate and confuse the attacker. The mode $S2$ in Eq. (28) is used to mathematically represent this zebra technique. Zebras update their positions, and if a new location has a higher value for the goal function, the zebra is allowed for the update. Eq. (29) is used to simulate this updating circumstance.

$$z_{i,j}^{new,P2} = \begin{cases} 
S1 : x_{i,j} + R \cdot (2r - 1) \\
(1 - \frac{t}{T}) \cdot x_{i,j}P_s \leq 0.5 \\
S2 : x_{i,j} + r \cdot (AZ_j - I) \cdot x_{i,j}else 
\end{cases}$$

$$Z_i = \begin{cases} 
Z_i^{new,P2}F_i^{new,P2} < F_i \\
Z_ielse 
\end{cases}$$ (29)

Where;

- $Z_i^{new,P2}$ is the updated status of the $ith$ zebra in accordance with the second phase.
- $z_{i,j}^{new,P2}$ is the value of the $jth$ dimension.
- $F_i^{new,P2}$ is objective function's value.
- $t$ is contour of iteration.
- $T$ is the biggest number of used iterations.
- $R$ is constant value represents 0.01.
- $P_s$ is the probability of selecting one of two randomly generated strategies in the interval $[0; 1]$
- $AZ$ is the assaulted zebra's status.

### 4.1.4 Applied ZOA algorithm

The population members are updated depending on the first and second phases at the end of each ZOA cycle. Up to the algorithm's complete implementation, the algorithm population is updated depending on Eq. (26) to (29). Through several cycles, the best candidate solution is updated and stored. ZOA presents
the top contender as the best answer to the given problem when it has been completely developed. In Fig. 2, the ZOA processes are displayed as flowcharts.

Analysis of results

5.1 Meteorological data of case study

This study takes into consideration a specific services site in the Egyptian Oasis Siwa (29.150 N, 25.539 E). The capacity and continuity of the energy supply are limited since the facility is connected to a low-reliability electrical system. The location offers the following services: manufacturing, farms, and schools. In Table 2, the load data are displayed. The average load profile used in the chosen case study zone over the course of a year is shown in Fig. 3. With a connected load of 103 MW, the maximum load is around 100 MW.

<table>
<thead>
<tr>
<th>Load data of schools</th>
<th>Device</th>
<th>Power (W)</th>
<th>Quantity</th>
<th>Total load power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>100</td>
<td>43000</td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td>Appliances (class A &quot;200 W&quot;)</td>
<td>2000</td>
<td>2000</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Appliances (class B &quot;100 W&quot;)</td>
<td>1000</td>
<td>5000</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Appliances (class C &quot;75 W&quot;)</td>
<td>750</td>
<td>4000</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Appliances (class D &quot;70 W&quot;)</td>
<td>700</td>
<td>1000</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Appliances (class E &quot;50 W&quot;)</td>
<td>500</td>
<td>4000</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

The NASA Surface Meteorology and Sun Energy website was consulted for the site's local resources, which included temperature, wind speed, and sun radiation [41]. The average monthly sun radiation for the entire year is shown in Fig. 4. At 8.43 kWh/m²/day, June has the greatest daily average solar radiation and average annual solar radiation is 5.92 kWh/m²/day. The average monthly temperature for the entire year is shown in Fig. 5. The average annual temperature is 21.1°C, which may have an impact on
photovoltaic efficiency. Consequently, the high ambient temperature of 29.68°C in July may have a detrimental effect on the power generation of PV panels. The average monthly wind speed at 50 m above the earth's surface is depicted in Fig. 6 for the whole year. With an average yearly wind speed of 5.53 m/s, this region offers a lot of potential for using wind energy.

5.2 Discussion of case study results

Table 3 presents the specifications of all the elements used in HRES in this investigation. The lifetime of the system was estimated to be 25 years, the interest rate to be 6%, and the FC lifetime to be 5 years.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wind Turbine</th>
<th>PV Array</th>
<th>Electrolyzer</th>
<th>Hydrogen Tank</th>
<th>Fuel Cell</th>
<th>Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost ($)</td>
<td>118,412</td>
<td>136,912</td>
<td>52,311</td>
<td>17,004</td>
<td>71,219.2</td>
<td>12,387</td>
</tr>
<tr>
<td>Replacement cost ($)</td>
<td>52,500</td>
<td>---------</td>
<td>22,500</td>
<td>9000</td>
<td>50,000</td>
<td>7500</td>
</tr>
<tr>
<td>O&amp;M cost ($)</td>
<td>5250</td>
<td>5000</td>
<td>7500</td>
<td>2250.4</td>
<td>17,500</td>
<td>1203,02</td>
</tr>
<tr>
<td>Lifetime (year)</td>
<td>20</td>
<td>25</td>
<td>20</td>
<td>20</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

MATLAB software is utilized to simulate and apply the suggested sizing strategy, considering significant variations in the average solar radiation, the average temperature, and the average wind speed. The model takes the temperature, wind speed, and sun radiation observed data from the Oasis Siwa site as input. The number of PV arrays and WTs, which are the decision variables, have minimum and maximum constraints of 1 and 250, respectively.

Furthermore, the largest number of agents searching is 30, and the maximum is 1000 iterations. To determine the best option for each component such as the number of solar PV panels, WTs and FCs. Table 4 presents the simulation results of the suggested optimization for the two strategies. ZOA achieved the best optimum solution concluded that predicts the best COE of 0.1565 $/kWh, with the least of NPC = 1.0793 × 10^7 $ and LPSP=0 compare with CSA algorithm estimates 0.6439 $/kWh to the COE and NPC = 2.41 × 10^7 and LPSP = 5.2963 × 10^{-9} .
According to the ZOA optimization algorithms, it has been demonstrated that the proposed location offers the lowest COE. After careful analysis, it has been determined that the ideal configuration for the system consists of 82 PV arrays, 113 wind turbines, 150 FCs, electrolytes rated 300 kW of power, H2 tanks with a maximum mass of 150 kg, an FC with a rated power of 100 kW, an inverter with a rated power of 150 kW and get maximum power produced by 20 MW hydrogen production electricity by electrolysis. This optimized setup ensures efficient operation and harnesses renewable energy sources to their fullest potential.

Figures cover several aspects of the MATLAB replication and enhancement. Figure 7 shows the maximum power produced by the PV system (143 MW) and the wind (3.96 MW) for the month of July, which is the month with the highest load in our area. Figure 8 shows the difference between the load and the power produced by wind and photovoltaic systems; the load may produce up to 100 MW of power.

If the combined electrical power produced by the WT and PV solar cell array exceeds the demand from the load, the electrolyzer is utilized to make hydrogen by absorbing excess energy, which is then collected in its tanks. The FC generates energy to make up for the energy shortage during low power generation hours. Figure 9 indicate the power of electrolyzer and Fig. 10 indicate the power of FC.

The convergence of the Zebra algorithm throughout 100 separate runs of finding the best solutions for the PV/WT/FC HRES is depicted in Fig. 11. When the best solution is achieved, which is reached by the 81st iteration, the convergence is done at random and stabilizes. There are 153 FCs, 92 WTs, and 82 PV arrays in the optimized HRES.

**Conclusions**
A novel approach was used to optimize the size of the fuel cell, solar, and wind components of a hybrid renewable energy system (HRES) that is linked to a stand-alone micro grid system. The month of July was selected as the case study to address the energy requirements of Siwa, Egypt’s residential and industrial buildings. The month with the highest load demand is July. The number of solar, wind turbine, and fuel cell systems that reach good performance of loss of energy supply probability is 82, 113, and 150, respectively, according to the results of a novel metaheuristic method called the Zebra algorithm. Out of all the optimization results, the suggested zebra method also provides the ideal HRES component sizes to reduce the COE as effectively as possible while meeting load requirement. To reduce costs even further, consider using a different type of backup energy in future projects rather than batteries. Furthermore, the suggested approach may be used for various study scenarios spanning the entire year. Then, further algorithms could yield the best design for any study situation.

**Abbreviations**
Declarations

Author Contribution

Doaa Ahmed Gad wrote the main manuscript text and the idea of paper. Mokhtar and Mohamed helped writing the manuscript and figure. Adel and Ahmed reviewed the manuscript.
Data Availability

The datasets generated and analyzed during the current study are not publicly available due data cannot be shared openly but are available from the corresponding author on reasonable request.

References


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41. NASA Surface meteorology and solar energy; Available from: http://eosweb.larc.nasa.gov/sse/.
Figure 1

PV/WT/FC hybrid system proposal.
Figure 2

Flowchart of ZOA.
Figure 3

Average hourly load profile through the year.

Figure 4

Average daily radiation (kW/m²/day)
Figure 5

Average monthly temperature.

Figure 6

Average monthly wind speed.
Figure 7

Power generated from: (a) PV system, (b) WT.
Figure 8

Power generated from PV, WT and Load demand.

Figure 9

Power of Electrolyzer
Figure 10

Power of FC

Figure 11

Convergence characteristics of Zebra algorithm.