Published in Journal of Energy Storage with doi: 10.1016/j.est.2022.104343

An Improved Arithmetic Optimization Algorithm for Design of a Microgrid with Energy Storage System: Case Study of El Kharga Oasis, Egypt

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Abstract: The microgrid design problem needs efficacy tools to reach good results with optimal convergence characteristics. Stochastic metaheuristic algorithms are the best choice to address complex problems. This paper proposes new hybrid renewable energy systems (HRES) design, composed of PV, wind turbine, diesel generator, and battery system. The objective function is minimizing the total net present cost, which includes all expenses during the project lifetime; the optimization respects other aspects, technical and ecologic. The improved algorithm is called IAOA that developed by modifying the original Arithmetic Optimization Algorithm (AOA) using the leading operators of the Aquila Optimizer (AO). The modified version is conducted to improve the search ability of the original AOA and avoid its weaknesses like being trapped in a local search. Moreover, the proposed IAOA makes a learning stage from the search process of the AO to enhance the research history of the AOA. Two HRES scenarios are suggested, the first is based on using PV/wind/diesel/battery, while the second scenario consists of PV/diesel/battery. This proposed HRES is located in El Kharga Oasis in Egypt with latitude of 25.42 and longitude of 30.581. The obtained results prove that the proposed IAOA gives better results compared with the other well-known algorithms, namely the original algorithm of AOA, Equilibrium Optimizer (EO), Gray Wolf Optimization (GWO), Artificial Electric Field Algorithm (AEFA), and Harris Hawks Optimization (HHO). It is recognized that the proposed IAOA is a promising alternative to solve hybrid renewable energy systems.

Keywords: Arithmetic optimization algorithm (AOA); hybrid renewable energy system (HRES); microgrid design; optimization algorithm.

Nomenclature

AEFA	Artificial Electric Field Algorithm
AO	Aquila Optimizer
AOA	Arithmetic Optimization Algorithm
EO	Equilibrium Optimizer
GWO	Grey Wolf Optimizer
HHO	Harris Hawks Optimization
HRES	Hybrid renewable energy system
IWO	Invasive Weed Optimization
LCOE	Levelized Cost of Energy
NPC	Net Present Cost
PV	Photovoltaic
WT	Wind turbine

Symbols

$A_g,\ B_g$	Constants of the linear consumption of the fuel (L/kW)
A_{pv}	PV area (m^2)
A_{wind}	Swept area of the wind turbine (m^2)
C_{BESS}	Capacity of BESS (kWh)
C_{bat}	Investment cost of BESS ($)
$C_{PV,WT}$	Investment cost of PV and wind generators ($)
$C_f(t)$	Cost of the consumed quantity of fuel ($/year)
C_{inv}	Inverter investment cost ($)
C_p	Maximum power coefficient (%)
E_{bmin}	Min battery energy in discharge (kWh)
E_l	Energy Load (kWh)
FC_{dg}	Fuel cost ($)
F_{dg}	Fuel consumption (L/h)
$F_{dg}(t)$	Consumed quantity of fuel (L)
N_{run}	Diesel run number
OM_{BESS}	O&M (contain the replacement) costs of the BESS ($)
OM_{Inv}	O&M cost of the inverter ($)
$OM_{PV,WT}$	Operation & maintenance costs ($)
OM_{dg}	Maintenance and Operation cost of diesel generator ($)
$P_{dg,out}$	Output power of diesel generator (kW)
P_{dg}	Rated power of diesel generator (kW)
P_{inv}	Rated power of the inverter (kW)
P_{load}	Load power (kW)
P_{pv}	Output power of PV (kW)
P_r	Rated power (kW)
P_{re}	Output power of renewable energy sources (kW)
P_w	Annual working of system (kWh/Year)
P_{wind}	Output wind power (kW)
R_{dg}	Annual replacement cost of diesel ($)
R_{diesel}	Diesel replacement cost ($/kW)
T_a	Ambient temperature (°C),
T_r	Photovoltaic cell reference temperature (°C).
i_r	Interest rate (%)
p_f	Fuel price ($/L)
v_{ci}	Cut-in speed (m/s)
v_{co}	Cut-out speed (m/s)
v_r	Rated wind speed (m/s)

η_b	Efficiency of the battery (%)
η_i	Efficiency of the inverter (%)
η_{pv}	Efficiency of the PV (%)
η_r	Reference efficiency, η_t is the efficiency of the MPPT equipment,
θ_{Inv}	Annual O&M cost of the inverter ($/year)
$\theta_{PV,WT}$	Annual operation & maintenance of PV and wind ($/m^2/year)
θ_{bat}	Annual O&M cost of BESS ($/m^2/year)
θ_{dg}	Annual O&M cost of diesel ($/hr)
$\lambda_{PV,WT}$	Initial cost of PV and wind ($/m^2)
λ_{bat}	BESS initial cost ($/kWh)
λ_{dg}	Diesel initial cost ($/kW)
λ_{inv}	Inverter initial cost ($/m^2)
A	Availability index (%)
AD	Autonomy daily of the battery (day)
C	Investment cost ($)
CRF	Capital recovery factor
DOD	Depth of discharge (%)
I	Solar irradiation (kW/m^2)
$LCOE$	Levelized cost of energy ($/kWh)
$LPSP$	Loss of power supply probability (%)
$NOCT$	Nominal operating cell temperature (°C),
NPC	Net Present Cost ($)
OM	Operation and maintenance cost ($)
R	Replacement cost ($)
RF	Renewable Fraction (%)
v	Wind velocity (m/s)
β	Temperature coefficient of the efficiency
δ	Inflation rate (%)
μ	Escalation rate (%)
ρ	Air density (Kg/m^3)

1. Introduction

The microgrid system is one of the most recommended solutions for proper electrification, mainly in the non-electrified area. Many problems are treated in the hybrid renewable energy system (HRES), which the first and the vital subject is finding the optimal design and sizing of the HRES with the appropriate configuration. The following papers [1-6] treat the different subjects in the HRES; Ref. [1] presents a review of the control and stability aspects of the microgrid architectures. Ref. [2] presents an investigation of the microgrid technology compatible in Thailand and then explores the policy key drivers of microgrids in the country. Ref. [3], presents a review about planning, operation, and control DC microgrid. Ref. [4] presents a review of control techniques of the power management of the isolated DC microgrid. Ref. [5] presents a review for smart inverters of microgrid applications. Moreover, a study of predictive control for microgrid applications has been presented in [6]. Ref. [7] presents a review of 550 papers to create a matrix of literature database which found that the stand-alone systems and residential are the most applications. Likewise, they discovered that photovoltaic is preferred for its low installed power.

The microgrid's design and sizing problem are called the HRES, and the design problem is already considered in the literature in many papers. In [8], the report designs a hybrid microgrid system composed of PV, wind turbine, diesel, and battery. The project is investigated in Yanbu city, Saudi Arabia, dedicated to feeding a set of houses considering the load uncertainty. The design problem is treated using the multi-objective algorithm called MOEA/D, which considers the LPSP and energy cost as objective functions. Another paper that treated the microgrid design in Yanbu, Saudi Arabia, is presented in [9]; the paper optimizes the NPC as an objective function using the recent Giza Pyramids Construction algorithm (GPC), considering the LPSP index as constraint. Ref. [10] presents an HRES, a synergy between PV, wind, and biomass. This system is dedicated to responding to 100% load demand using 100% renewable energy resources. Ref. [11] presents a new method to find the better compromise of the multiple multiobjective algorithms, and the procedure is based on a statistical technique of Six-Sigma. Three algorithms are considered: MOPSO, PESA II, and SPEA2. The case study is dedicated to optimizing an HRES based on PV, wind, diesel, and battery in Rabat, Morocco, the reliability index used is the LPSP. Ref [12] presents a power management control of the hybrid wind/photovoltaic/diesel/battery system using fuzzy logic control. Ref [13], used the harmony search algorithm to optimally design the PV/wind/diesel system and compare two storage techniques: the battery and fuel cell storage devices.

The proposition of the improved or the new algorithms is very popular recently. Many papers that treated the microgrid system problems are used and compared a proposed algorithm in literature. Ref [14] develops and presents a hybrid framework based on a hybrid heuristic to define the optimal size and location of a stand-alone PV/battery scheme, the reliability is calculated using the desired loss of power supply probability. Ref [15] presents an optimal hybrid system of wind/hydrogen, based on a global dynamic harmony search (GDHS) optimization algorithm to optimize the cost and reliability (loss of power supply reliability, which is the LPSP) of the system. In [16], a hybrid algorithm between Jaya and teaching learning-based optimization (TLBO) is hybridized and applied to find the optimal sizing of the PV/wind/battery HRES by minimizing the total annual cost (TAC) as the objective function and the LPSP as constraint. Ref. [17] presents a hybrid algorithm of invasive weed optimization (IWO) and backtracking search optimization (BSA); the project is investigated in the Dakhla region in Morocco. The objective is to obtain the optimal design of the HRES to feed loads with economic costs and good LPSP. Ref. [18] proposed an improved gray wolf algorithm (GWO) to resolve the electrical energy storage system's microgrids' placement and sizing problem. Ref. [19] proposed a hybrid algorithm between the particle swarm optimization (PSO) and the bat algorithm (BA), the proposed algorithm named BAPSO. The algorithm is used to optimize the capacity configuration composed of PV and battery. Ref. [20] introduces an improved algorithm of the Bonobo Optimizer (BO), based on the quasi-oppositional technic. The proposed algorithm was used to solve the design problem of HRES respecting the LPSP factor in Aswan, Egypt, the HRES including PV, wind turbine, and battery, with a diesel generator. The QOBO proposed is compared to the traditional BO, Harris Hawks Optimization (HHO), Artificial Electric Field Algorithm (AEFA), and Invasive Weed Optimization (IWO).

In Ref. [21], an improved Artificial Ecosystem Optimization (IAEO) has been applied for the optimal design of a grid-connected and stand-alone HRES consisting of PV/Wind Turbine/Fuel Cell/hydrogen tank and respecting the LPSP factor in Ataka region, Suez Gulf, Egypt. The obtained results prove that the proposed IAEO has the best results compared to the other well-known algorithms, namely the original AEO, PSO, Salp Swarm Algorithm (SSA), and GWO. Ref. [22] analyzed an off-grid PV/WT/battery HRES for optimal component design in Oujda city in Morocco. Modified Electric System Cascade Analysis method (MESCA) has been applied for solving the optimization problem, and the obtained results have been compared with the results from Homer software, the reliability index used is the LPSP. Ref. [23] assessed a hybrid power system's optimal size and location respecting a good LPSP reliability based on a PV array, diesel generator, and battery storage unit using a novel hybrid algorithm consisting of an improved harmony search, simulated annealing, and geographic information system (IHS-SA-GIS). Ref. [24] evaluated an optimization design of a hybrid system based on the PV panels and battery storage units located in Davarzan city, Iran, to reduce the total life cycle cost and achieve the desired LPSP. This study presented a new IHS technique to solve the optimal sizing problem for the proposed hybrid system. Ref. [25] implemented an improved ant colony optimization (ACO) algorithm to optimize an isolated hybrid power system consisting of PV, wind turbine, battery units, and hydrogen system on an island of Zhejiang, China. The objective function of this stand-alone system was to minimize the total annual cost of the system and maximize system reliability represented by the LPSP.

According to the given studies, the engineering problems, especially the energy issues, have been successfully solved by various optimization algorithms. The presented results illustrated the need and possibility to find new and improved methods to deal with particular energy problems, which motivates us to propose a new, improved variant of the Arithmetic Optimization Algorithm based on the leading search operator of the Aquila Optimizer. We selected the given algorithms according to their stunning performance in dealing with several mathematical and engineering design problems.

The HRES are recognized as attractive stand-alone power operations for producing electricity in remote regions because of the progress in renewable energy systems and consequent petroleum output costs. HRES typically contains more than one renewable energy origin to improve system performance and more prominent equilibrium in energy supply. Thus, the HRNS has several parameters that must be optimized carefully by robust search methods to reach the main objectives. This paper presents an improved Arithmetic Optimization Algorithm-based on the leading search operators of Aquila Optimizer. The proposed method is called IAOA, which has been adapted to tackle the main weaknesses of the original techniques. The main recognized disadvantages of the tested methods are coverage fast or sometimes slow to the targeted search space, and it does not make a proper equilibrium between the search stages. This requires a new modified method to address the mentioned problems by creating a suitable operator for each one. The improved algorithm of IAOA is investigated in the HRES design, composed of PV, wind, diesel, and battery. To validate the efficacy of the proposed IAOA, five well-known algorithms are used in the comparison of the results, which are 1) Equilibrium Optimizer (EO), 2) GWO, 3), AEFA 4) HHO, and 5) AOA. The proposed IAOA proved its ability to deal with the problem. It obtained excellent results compared to several well-known methods in solving the same problems. Moreover, the results revealed that, with the improvement of existing processes, the different goals of HRES are accomplished. The following points can summarize the main contributions of the paper:

- Proposing an improved version of the conventional AOA algorithm to improve its performance;
- Applying the conventional AOA and proposed IAOA algorithms for the optimal design of a hybrid microgrid system including RES (photovoltaic panels, wind turbines, and batteries) with diesel generators;
- Considering the reliability, availability, and the renewable fraction constraints in the designed Microgrid;
- Evaluating the proposed IAOA algorithm's efficiency and its performance on different HRES configurations.

The rest of the paper is organized as follows. Section 2 presents the proposed IAOA method. Section 3 and 4 presents the technical and economic modeling of all systems. Section 5 gives an overview of the project location and its meteorological data. Then, Section 6 presents the results and discussion, and section 7 summarizes the study with the conclusion.

2. The proposed Improved Arithmetic Optimization Algorithm

2.1. Arithmetic Optimization Algorithm

The Arithmetic Optimization Algorithm (AOA) was proposed by Abulaigah et al. in 2021 [26], inspired by the math operators in science (i.e., Multiplication, Division, Subtraction, and Addition). The search phrases of the AOA are described as follows.

The initial solutions of AOA are given as Matrix (1).

$$X_i = \begin{bmatrix} x_1^1 & x_1^1 & \cdots & x_{1,D}^1 \\ x_1^2 & x_2^2 & \dots & x_D^2 \\ \vdots & \ddots & \ddots & \vdots \\ x_1^N & x_D^N & \dots & x_D^N \end{bmatrix} \quad (1)$$

The search operator of each iteration is selected using the Math Optimizer Accelerated (MOA) as in Equation (2).

$$MOA(C\_Iter) = Min + C\_Iter \times \left(\frac{Max - Min}{M\_Iter}\right) \quad (2)$$

The accelerated function's minimum and maximum values are called Min and Max, respectively. Where $MOA(C\_Iter)$ is the MOA calculated for each iteration, M_Iter is the total iterations. C_Iter is the current iteration.

Exploration phase

AOA's exploration stage explores in different places. It operates two search methods (D and M) as in Equation (3). If r1>MOA, where r1 is a random number, this step (M) is allowed; otherwise, the other operator (M) is allowed.

$$x_{i,j}(C\_Iter + 1) = \begin{cases} best(x_j) \div (MOP + \epsilon) \times \left((UB_j - LB_j) \times \mu + LB_j\right), r2 < 0.5 \\ best(x_j) \times MOP \times \left((UB_j - LB_j) \times \mu + LB_j\right), otherwise \end{cases} \quad (3)$$

Where $x_{i,j}(C\_Iter)$ is the j_{th} location of the i_{th} solution, and $best(x_j)$ is jth location in the best-obtained location in the i_{th} solution, μ is a control value fixed to 0.5 [27].

$$MOP(C\_Iter) = 1 - \frac{C\_Iter^{\left(\frac{1}{\alpha}\right)}}{M\_Iter^{\left(\frac{1}{\alpha}\right)}} \quad (4)$$

Where $MOP(C\_Iter)$ is the value of the MOP at the t_{th} iteration, α is a control value fixed to 0.5

Exploitation phase

If r3 < 0.5, the S operator is used; otherwise, the A is used, as given in Equation (5).

$$x_{i,j}(C\_Iter + 1) = \begin{cases} best(x_j) - MOP \times \left((UB_j - LB_j) \times \mu + LB_j\right), r3 < 0.5 \\ best(x_j) + MOP \times \left((UB_j - LB_j) \times mu + LB_j\right), otherwise \end{cases} \quad (5)$$

2.2. Aquila Optimizer

The mathematical model of the AO is given as follows.

Expanded exploration

The expanded exploration is determined in Equation (6) [28].

$$X_1(t+1) = Xbest(t) * \left(1 - \frac{t}{T}\right) + (X_m(t) - Xbest(t) * rand) \quad (6)$$

Where $X_1(t+1)$ is the solution for the next iteration. (X_1). The best solution is $Xbest(t)$*$(1 - t/T)$ is a control value of the exploration, $X_m(t)$ is mean value of the current solutions. The current and total iterations are given by t and T, respectively.

$$X_M(t) = \frac{1}{N}\sum_{i=1}^{N} X_i(t), \forall j = 1 \ldots\ldots Dim \quad (7)$$

Where Dim is the dimension size and N is the population size.

Narrowed exploration

The narrowed exploration is determined in Equation (8).

$$X_2(t+1) = Xbest(t) * Levy(D) + X_R(t) + (y - x) * rand \quad (8)$$

$Levy(D)$ is the levy flight function determined by Equation (9). $X_R(t)$ is a random solution.

$$Levy(D) = s * \frac{u * \sigma}{|\nu|^{\frac{1}{\beta}}} \quad (9)$$

Where s is a fixed value equal to 0.01, u, and ν are random numbers between 0 and 1, and σ is computed by Equation (10).

$$\sigma = \left(\frac{\Gamma(1+\beta) * sine(\frac{\pi\beta}{2})}{\Gamma\left(\frac{1+\beta}{2}\right) * \beta * 2^{(\frac{\beta-1}{2})}}\right) \quad (10)$$

In Equation (8), the spiral shape is given by y and x, as follows.

$$y = r * \cos(\theta) \quad (11)$$

$$x = r * sine(\theta) \quad (12)$$

$$r = r1 + U * D1 \tag{13}$$

$$\theta = -w * D1 * \theta 1 \tag{14}$$

$$\theta 1 = \frac{3 * \pi}{2} \tag{15}$$

Expanded exploitation: The expanded exploitation is determined in Equation (16).

$$X_3(t+1) = \left(Xbest(t) - X_M(t)\right) * \quad \alpha - rand + \left((UBj - LBj) * rand + LBj\right) * \delta \tag{16}$$

α and δ are the exploitation parameters fixed to 0.1.

Narrowed exploitation: The narrowed exploitation is determined in Equation (16).

$$X_4(t) = QF * \quad Xbest(t) - (G_1 * X(t) * rand) - G_2 * Levy(D) + rand * G_1 \tag{17}$$

The QF is determined by Equation (15). G1 is calculated by Equation (19). G2 is calculated by Equation (20) [36].

$$QF(t) = \quad t^{\left(\frac{2*rand-1}{(1-T)^2}\right)} \tag{18}$$

$$G_{1=2*rand-1} \tag{19}$$

$$G_2 = 2 * (1 - \frac{t}{T}) \tag{20}$$

2.3. The proposed IAOA

In this section, a new improved algorithm called IAOA is presented; by modifying the original Arithmetic Optimization Algorithm (AOA) using the leading operators of the Aquila Optimizer (AO). The modified version is conducted to improve the search ability of the original AOA and avoid its weaknesses like being trapped in local search. Moreover, the proposed IAOA also makes a learning stage from the search process of the AO to enhance the research history of the AOA. The main procedure of the proposed method is given in Algorithm 1.

Algorithm 1: Improved Arithmetic Optimization Algorithm (IAOA)

```
Initialize the Arithmetic Optimization Algorithm parameters N, α, μ, etc.
Initialize the solutions' locations randomly. (Solutions: i= 1... N).
WHILE (C_Iter < M_Iter)
     Calculate the Fitness Function for the given solutions.
     Find the best solution so far.
     Update the MOA parameter using Equation (2).
     Update the MOP parameter using Equation (4).
     FOR (i=1 to Solutions)
        FOR (j=1 to Locations)
If rand < 0.5
 Generate random values between [0, 1] (r1, r2, and r3)
     IF (r1>MOA)
           IF (r2>0.5)
              Update the current solution using the first part in Equation (3).
          ELSE
              Update the current solution using the second part in Equation (3).
          ENDIF
     ELSE
          IF (r3>0.5)
              Update the current solution using the first part in Equation (5).
          ELSE
              Update the current solution using the second part in Equation (5).
          ENDIF
     ENDIF
ELSE
Update the mean value of the current solution XM(t).
Update the x, y, G1, G2, Levy(D), etc.
IF (t≤ (2/3)*T)
   IF (rand≤0.5)
      Update the current solution using Equation (6).
   ELSE
      Update the current solution using Equation (8).
   ENDIF
ELSE
   IF (rand ≤ 0.5)
      Update the current solution using Equation (16).
   ELSE
      Update the current solution using Equation (17).
   ENDIF
ENDIF
     ENDFOR
  ENDFOR
ENDFOR
     C_Iter=C_Iter+1
ENDWHILE
Return the best solution (best_x).
```

3. Technical and Economic Modeling

This study included the construction of PV, wind, diesel, and battery units for the proposed HRES. Modeling of systems components is a necessity for obtaining the optimum size; a detailed modeling of the suggested stand-alone grid layout is depicted in Figure 1. The system controller block diagram is presented in Figure 2. As shown, the main power is generated from PV and wind units to meet the load demand. If the power from the PV and wind units with battery storage is unable to meet energy demand, a diesel generator will be used to cover the lack in power. If the power generated by the PV and wind units exceeds the load power needed, the excess power will be used to charge the battery. The power generated by the PV and wind units will be discarded when the battery reaches its maximum charging level, this dissipated power is consumed by the dummy load.

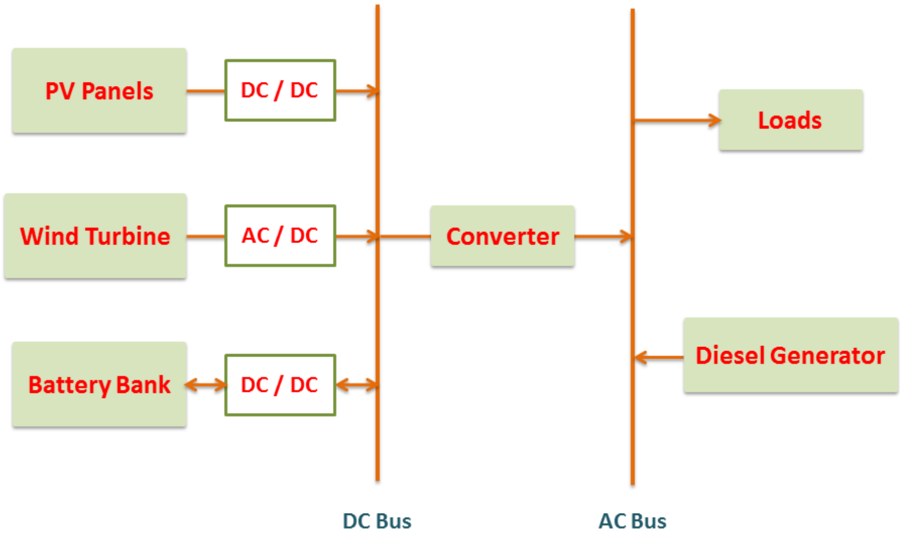


Figure 1. The block diagram Configuration of The Proposed Hybrid System

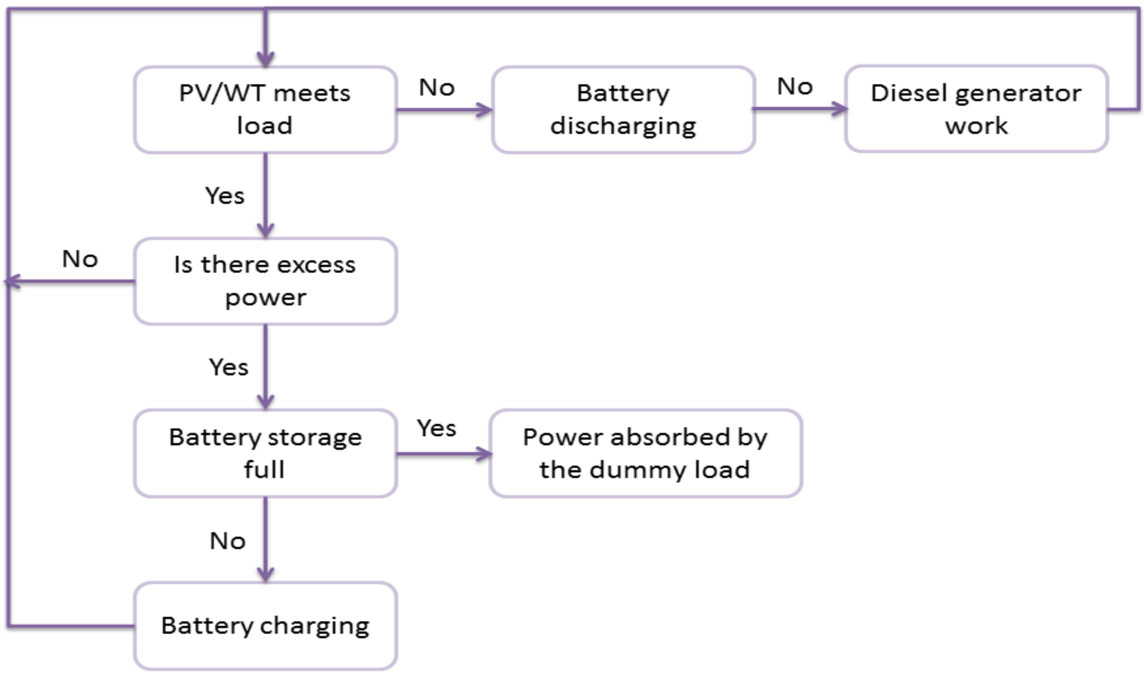


Figure 2. The controller block diagram of The Proposed Hybrid System

3.1. PV Panel Modeling

The PV output power is calculated as follows [29, 30]:

$$P_{pv} = I\langle t\rangle \times \eta_{pv}\langle t\rangle \times A_{pv} \tag{21}$$

Where I represents the irradiation, η_{pv} represents the efficiency of PV; A_{pv} is the area of PV. The efficiency of PV can be calculated based on reference efficiency (η_r), the efficiency of MPPT (η_t), temperature coefficient (β), ambient temperature (T_a), PV cell reference temperature (T_r), and nominal operating cell temperature (NOCT).

$$\eta_{pv}(t) = \eta_r \times \eta_t \times \left[1 - \beta \times (T_a\langle t\rangle - T_r) - \beta \times I\langle t\rangle \times \left(\frac{NOCT - 20}{800}\right) \times (1 - \eta_r \times \eta_t)\right] \tag{22}$$

3.2. Wind System Modeling

The wind turbine output power can be calculated following these conditions [31, 32]:

$$P_{wind} = \begin{cases} 0, & v\langle t\rangle \le v_{ci}, v\langle t\rangle \ge v_{co} \\ a \times V\langle t\rangle^3 - b \times P_r, & v_{ci} < v\langle t\rangle < v_r \\ P_r, & v_r \le v\langle t\rangle < v_{co} \end{cases} \tag{23}$$

Where V represents the wind velocity, P_r is rated power, v_{ci} is cut-in, v_{co} represents cut-out, and v_r is the rated wind. a and b are constant values that expressed as:

$$\begin{cases} a = P_r/({v_r}^3 - {v_{ci}}^3) \\ b = {v_{ci}}^3/({v_r}^3 - {v_{ci}}^3) \end{cases} \tag{24}$$

The Rated power of wind turbine can be calculated as:

$$P_r = \frac{1}{2} \times \rho \times A_{wind} \times C_p \times {v_r}^3 \tag{25}$$

Where ρ is the air density, A_{wind} represents the swept area of the wind turbine, C_p is the maximum power coefficient (from 0.25 to 0.45).

3.3. Diesel System Modeling

The diesel rated power can be calculated as [33]:

$$P_{dg} = \frac{F_{dg}\langle t \rangle \; - \; A_g \times P_{dg,out}}{B_g} \tag{26}$$

Where F_{dg} represents the fuel consumption, $P_{dg,out}$ is the output power of diesel generator, A_g and B_g are two constant values that represent the linear fuel consumption.

3.4. Battery System Modeling

The battery capacity of battery can be calculated as [33]:

$$C_{BESS} = \frac{E_l \times AD}{DOD \times \eta_i \times \eta_b} \tag{27}$$

Where E_l is the load demand, AD is the autonomy of the battery, DOD represents the depth of discharge, η_i and η_b represents the inverter and battery efficiency, respectively.

4. Objective Function and Constraints

4.1. Net Present Cost

The NPC represents an economic factor, which is considered as the objective function in this study. This paper aims to minimize the NPC's sum of all costs during the project lifetime. The NPC is calculated as [34, 35]:

$$NPC = C + OM + R + FC_{dg} \tag{28}$$

Where C represent the capital cost, OM is the Operation and maintenance costs, R is the replacement cost, and FC_{dg} is the fuel cost.

3.1.1. PV and WT Costs

The modeling of PV and WT costs is similar. The capital cost of the PV or Wind turbine ($C_{PV,WT}$) is calculated based on their initial cost ($\lambda_{PV,WT}$) and the area ($A_{PV,WT}$) [35]:

$$C_{PV,WT} = \lambda_{PV,WT} \times A_{PV,WT} \tag{29}$$

The operation and maintenance costs ($OM_{PV,WT}$) are calculated as:

$$OM_{PV,WT} = \theta_{PV,WT} \times A_{PV,WT} \times \sum_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{30}$$

where, $\theta_{PV,WT}$ is the annual operation and maintenance costs for each component, $\boldsymbol{N}$ is the project lifetime. The replacement costs are null because the project lifetime and the PV or WT lifetime are the same.

3.1.2. Diesel Costs

The costs of the diesel generator are modeled as follows [34]:

$$C_{dg} = \lambda_{dg} \times P_{dg} \tag{31}$$

$$OM_{dg} = \theta_{dg} \times N_{run} \times \sum_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{32}$$

$$R_{diesel} = R_{dg} \times P_{dg} \times \sum_{i=7,14\dots} \left(\frac{1+\delta}{1+i_r}\right)^i \tag{33}$$

$$C_f(t) = p_f \times F_{dg}\langle t\rangle \tag{34}$$

$$FC_{dg} = \sum_{t=1}^{8760} C_f\langle t\rangle \times \sum_{i=1}^{N} \left(\frac{1+\delta}{1+i_r}\right)^i \tag{35}$$

where, C_{dg} is the diesel investement cost, λ_{dg} is the initial diesel cost, OM_{dg} represents the operation and replacement cost, θ_{dg} is the annual O&M cost of diesel, N_{run} is the number of diesel-run in the year, R_{diesel} is the diesel replacement cost, R_{dg} represents the annual replacement cost of diesel, p_f is the cost of the fuel, F_{dg} is the consumed quantity of fuel and FC_{dg} is the total fuel cost.

3.1.3. BESS Costs

The initial and O&M (contain the replacement) costs of the BESS are expressed as follows [35]:

$$C_{BESS} = \lambda_{bat} \times C_{bat} \tag{36}$$

$$OM_{BESS} = \theta_{bat} \times C_{bat} \times \sum_{i=1}^{T_B} \left(\frac{1+\mu}{1+\delta}\right)^{(i\_1)N_{bat}} \tag{37}$$

where, λ_{bat} is the BESS initial cost and θ_{bat} is the annual O&M cost of BESS.

3.1.5. Inverter Costs

The inverter investment and O&M costs are represented as [34]:

$$C_{inv} = \lambda_{inv} \times P_{inv} \tag{38}$$

$$OM_{Inv} = \theta_{Inv} \times \sum_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{39}$$

where, λ_{inv} is the inverter initial cost and θ_{Inv} is the annual O&M cost of the inverter.

4.2. LCOE Index

The LCOE represent the price of energy, is a critical factor, which is calculated as [33]:

$$LCOE = \frac{NPC \times CRF}{\sum_{t=1}^{8760} P_{load}\langle t\rangle} \quad (40)$$

where CRF: Capital Recovery Factor (convert the initial cost to annual capital cost); P_{load}: Power load. The CRF is calculated as:

$$CRF(ir, R) = \frac{i_r \times (1 + i_r)^R}{(1 + i_r)^R - 1} \quad (41)$$

4.3. LPSP Index

The reliability is an important index to design the microgrids, many indexes are used such as the LOLE, LOEE, and ELF [37, 38, 39]. However, the best index and the most used for its efficacy is the LPSP. The LPSP is a technical index, it's used to indicate the reliability of the microgrid system. The LPSP is calculated as follows [33]:

$$LPSP = \frac{\sum_{t=1}^{8760}\left(P_{load}\langle t\rangle - P_{pv}\langle t\rangle - P_{wind}\langle t\rangle + P_{dg,out}\langle t\rangle + E_{bmin}\right)}{\sum_{t=1}^{8760} P_{load}\langle t\rangle} \quad (42)$$

4.4. Renewable Energy Index

Renewable energy (RF) is calculated to determine the renewable energy percent penetrated the microgrid system. The RF is expressed as [33]:

$$RF = \left(1 - \frac{\sum_{t=1}^{8760} P_{dg,out}\langle t\rangle}{\sum_{t=1}^{8760} P_{re}\langle t\rangle}\right) \times 100 \quad (43)$$

Where P_{re}: sum of renewable energy powers.

4.5. Availability Index

The availability factor (A) is assumed as an index of the customer's satisfaction; it measures the ability of the Microgrid to convert the total energy to load charge. The availability is calculated as [35]:

$$A = 1 - \frac{DMN}{\sum_{t=1}^{8760} P_{load}\langle t\rangle} \quad (44)$$

$$DMN = P_{bmin}\langle t\rangle - P_b\langle t\rangle - \left(P_{pv}\langle t\rangle + P_{wind}\langle t\rangle + P_{dg,out}\langle t\rangle - P_{load}\langle t\rangle\right) \times u\langle t\rangle \quad (45)$$

where P_{bmin}: battery min state; P_b: battery power; u: fixed value that equals 1 when the load isn't satisfied and 0 otherwise.

4.6. Constraints

The constraints are introduced to tuning the microgrid system factors and help to improve the microgrid services quality. In this work, the constraints proposed are:

$$\begin{cases} 0 \le A_{pv} \le A_{pv}^{max} \\ 0 \le A_{wind} \le A_{wind}^{max} \\ 0 \le P_{dg} \le P_{dg}^{max} \\ 0 \le C_{BESS} \le C_{BESS}^{max} \\ LPSP \le LPSP^{max} \\ RF^{min} \le RF \\ A^{min} \le A \\ AD^{min} \le AD \end{cases} \tag{46}$$

5. Location of project study

The HRES design is investigated in El Kharga Oasis, Egypt, with a coordinate (latitude of 25,42 and longitude of 30,581). It is essential to consider the El Kharga region, mainly the solar irradiation; its location is indicated in Figure 3. The load and the meteorological conditions are presented in Figures 4-9.

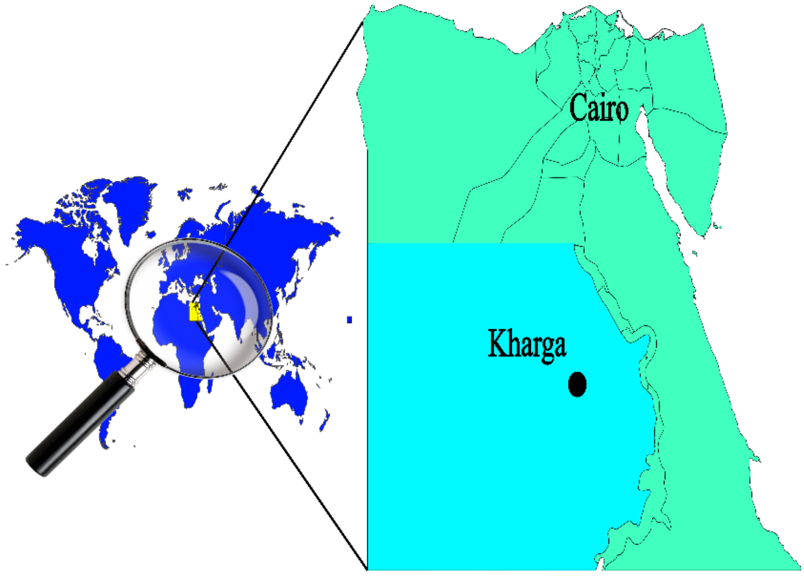


Figure 3. Maps location of El Kharga region, Egypt.

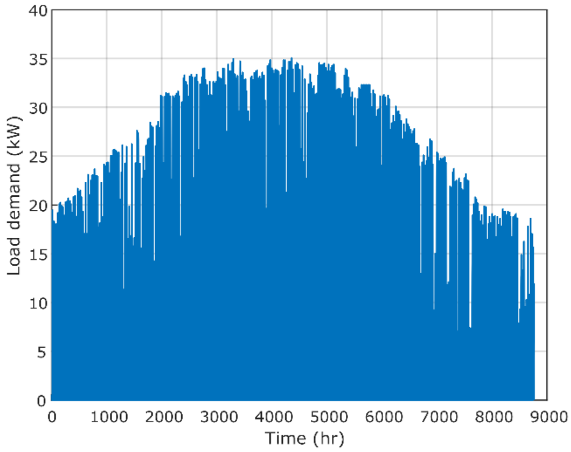


Figure 4. Load curve.

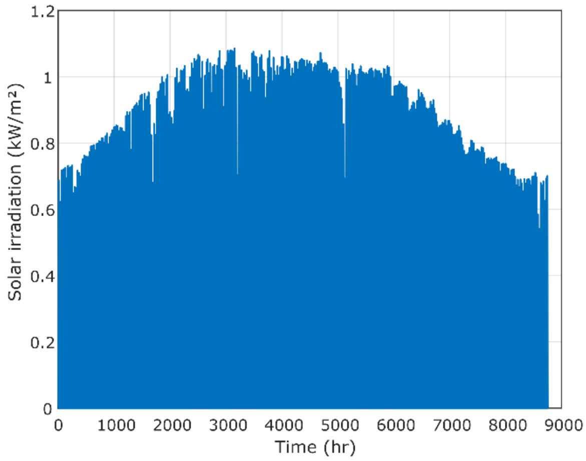


Figure 5. Solar radiation of the project localization.

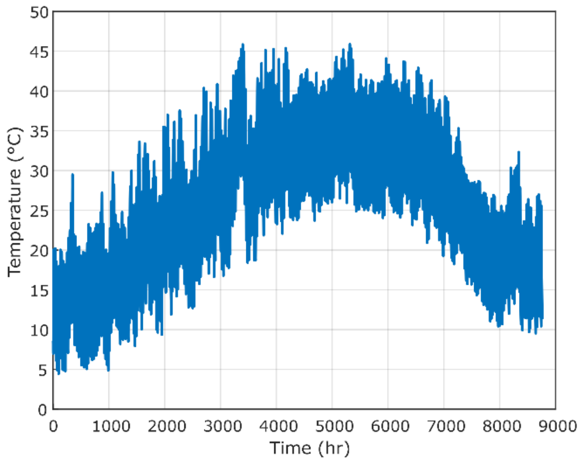


Figure 6. Temperature data.

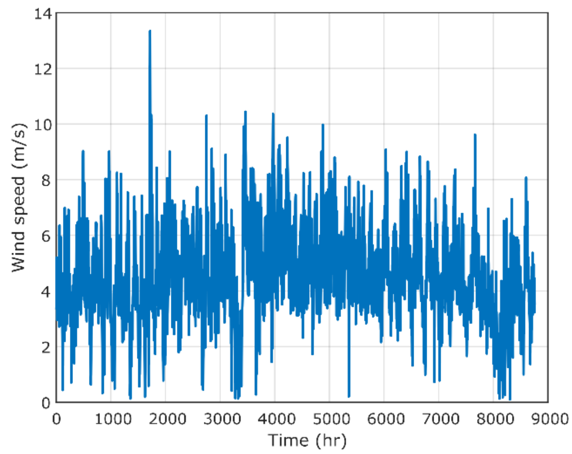


Figure 7. Wind speed data.

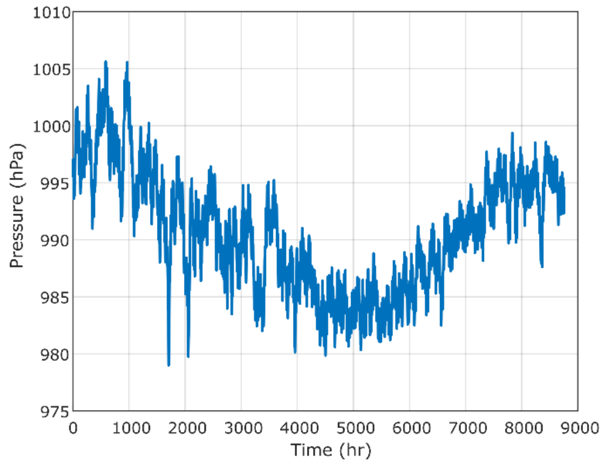


Figure 8. Curve of the pressure.

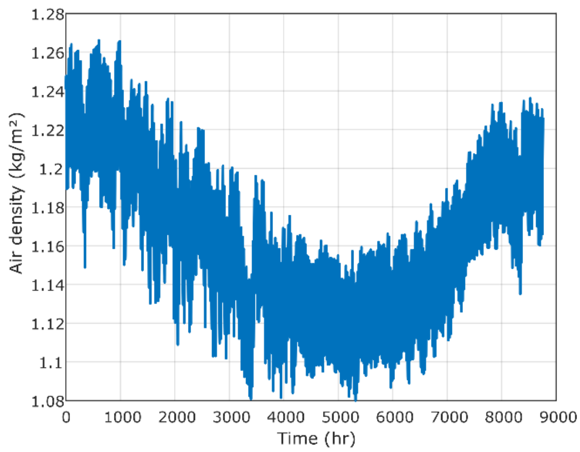


Figure 9. Curve of the air density.

6. Results and discussion

The HRES design is a complex problem that requires the consideration of many technical, economic, and ecologic aspects. To assure good results, choosing the best tools is essential; otherwise, there are many software such as Homer and iHoga, but they are limited for many reasons; for that, the researchers prefer to propose their framework, and others proposed their framework on new algorithms. Likewise, this paper presents a new algorithm, an improved version of the AOA algorithm, called IAOA. To prove the efficacy of the IAOA algorithm to resolve the complex problems, we have used it to design the HRES based on two configurations; 1) PV/wind/diesel/battery, and 2) PV/ diesel/battery. The project is dedicated to feeding power for a house in the El Kharga region, Egypt. All the economic and technical data are presented in the Appendix in Table A1.

6.1. PV/wind/diesel/battery HRES design

The first investigated configuration is the PV/wind/diesel/battery, which profits from the synergy between the PV and the wind turbine that their sources complement. From table 1, the best project investment is obtained by the proposed algorithm of IAOA, with an NPC of 286874 \$, equivalent to 0.23 \$/kWh as the energy cost. The constraints are respected with 4.11% LPSP, a renewable fraction of 83.75 %, and 99.81% power availability. Five algorithms are used to compare, which obtained the NPC of 311660, 290950, 304244, 302632, and 347232 \$ for EO, GWO, AEFA, HHO, AOA algorithms, respectively.

Table 2 presents the optimal sizing of all used algorithms, which the best-founded algorithm is the IAOA, with a size of 144.7 m^2 PV area, 252.3 m^2 swept wind area, 11.77 kWh of battery capacity, and 16.77 kW of nominal diesel power.

Table 1. Results of the PV/wind/diesel/battery HRES.

Algorithm	NPC (\$)	LCOE (\$/kWh)	LPSP (without)	RF (%)	Availability (%)
EO	311660	0.2508	0.0301	87.4157	99.8629
GWO	290950	0.2342	0.0472	91.5149	99.7187
AEFA	304244	0.2449	0.0207	73.9630	99.9214
HHO	302632	0.2436	0.0249	81.9936	99.8510
AOA	347232	0.2795	0.0033	83.2906	99.9934
IAOA	286874	0.2309	0.0411	83.7537	99.8149

Table 2. Sizing Results of the PV/wind/diesel/battery HRES.

Algorithm	PV (m²)	Wind (m²)	Battery (kWh)	Diesel (kW)
EO	241.0163328	135.5709	10.4650	16.3885
GWO	134.8229	485.5938	23.8167	16.1294
AEFA	110.8015	240.0332	4.4150	18.9074
HHO	130.1344	287.0268	17.9908	18.3759
AOA	89.4146	503.0606	0.3122	22.5764
IAOA	144.7078	252.331	11.7795	16.7740

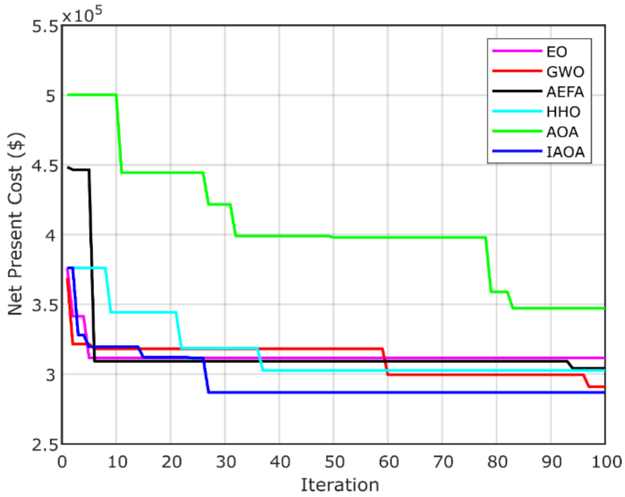


Figure 10. NPC convergence of PV/wind/battery/diesel HRES.

Figure 10 presents an overview of all algorithms' convergence curve results, and from the figure, it can be noticed that the IAOA gives a better convergence solution. Figure 11 presents the output power of 24 hours, from 1000 to 1024 hours, of all used algorithms. We observe from figure 11 that the output power curve of PV and wind, diesel, and battery are well managed, the PV is the pillar system, and the battery is used to achieve consumer satisfaction economically and technic. Figure 12 shows the financial results of each design using all algorithms as mentioned above. We notified that the cost of diesel is prohibitive, but it is considered for its vital role to satisfy the predefined constraints.

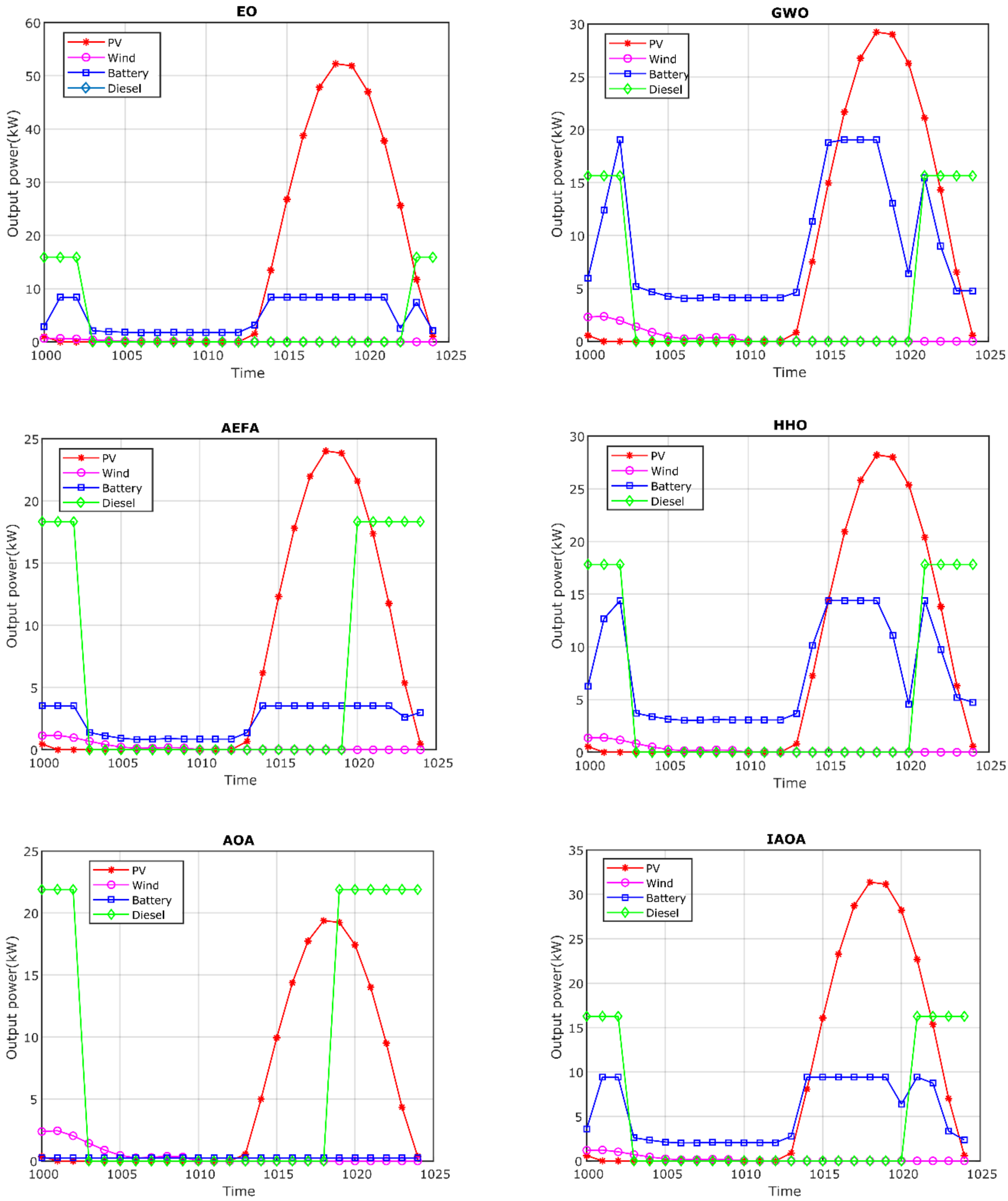


Figure 11. Output power of PV, wind, battery, diesel on time of 1000 to 1024 hr.

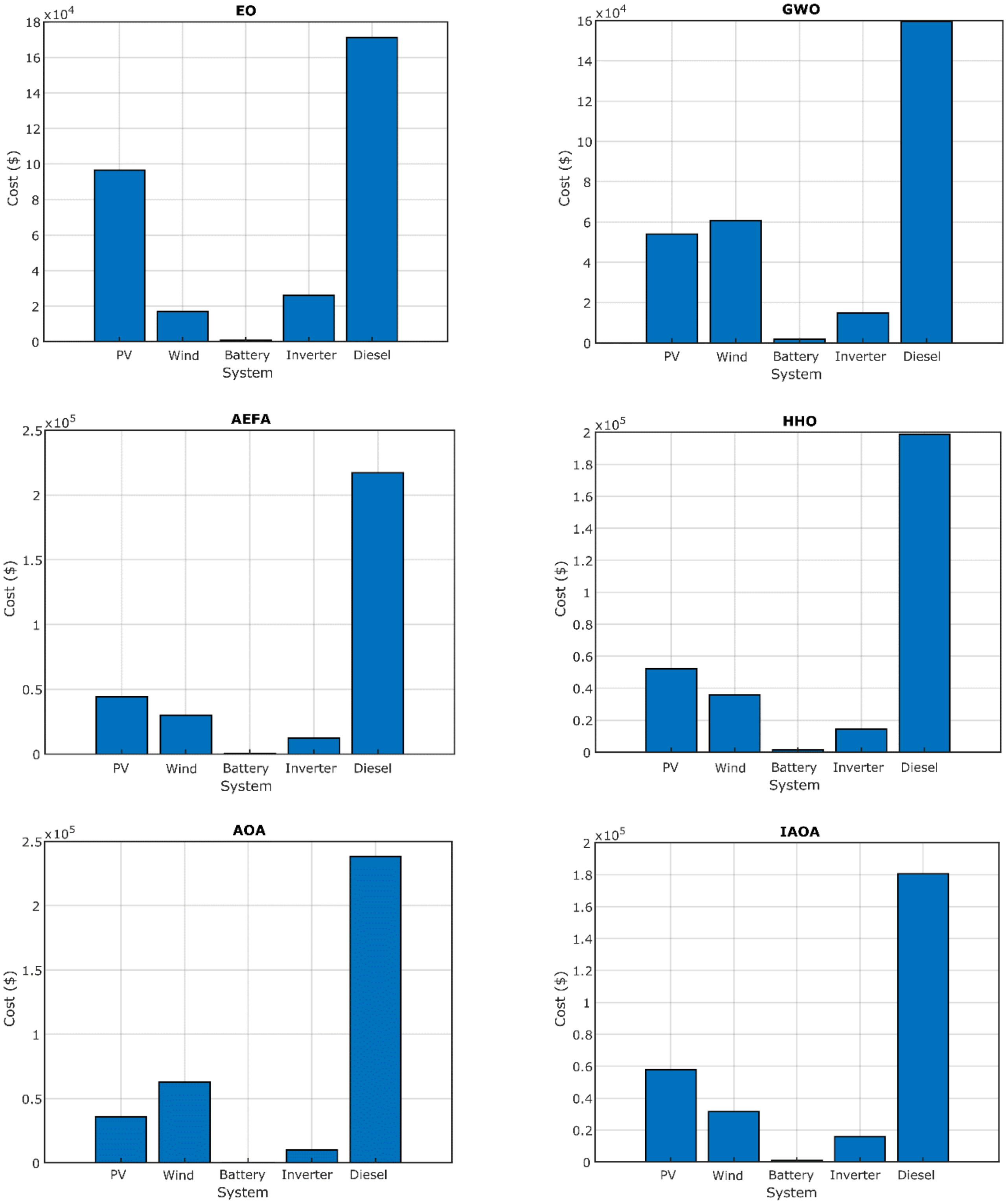


Figure 12. Costs results of PV/wind/diesel/battery HRES design using; 1) EO, 2) GWO, 3) AEFA, 4) HHO, 5) AOA, 6) IAOA.

6.2. PV/diesel/battery HRES design

The second configuration is the PV/diesel/battery HRES, used without the wind turbines. The results show that the best investment project is found using the improved algorithm of IAOA with a cost of 322674 $, equivalent to a cost of energy of 0.2597 $/kWh; all results are presented in Table 3, in which the constraints are respected. Table 4 shows the sizing results, which the best configuration requires 232 m² of the PV area, and 17 kW of diesel capacity, without using the battery.

The algorithm convergence curves are presented in Figure 13, in which the IAOA shows an excellent aptitude to find the best solution. Figure 14 illustrates daily output power, from 1000 to 1024 hr, to understand the power management's behavior. The figure shows correctly that power management is used in the best way. Figure 15 presents a detailed study of the costs required during the project's lifetimes. From this figure, we can observe that the diesel cost is prohibitive, but it is essential to achieve a better performance of the HRES. We concluded from the obtained results that the performance of the proposed method is promising due to the given modifications, which assist the conventional method in finding new solutions and search areas. Besides, it can change between the search processes to determine better results and avert the searching problems.

Table 3. Results of the PV/diesel/battery HRES.

Algorithm	NPC ($)	LCOE ($/kWh)	LPSP (without)	RF (%)	Availability (%)
EO	323811	0.2606	0.0494	76.8566	99.7886
GWO	329141	0.2649	0.0483	79.0640	99.7954
AEFA	328545	0.2644	0.0491	70.6687	99.7637
HHO	331734	0.2670	0.0473	70.4893	99.7441
AOA	364061	0.2930	0.0399	85.3549	99.8349
IAOA	322674	0.2597	0.0483	74.6241	99.7929

Table 4. Sizing Results of the PV/diesel/battery HRES.

Algorithm	PV (m²)	Battery (kWh)	Diesel (kW)
EO	243.8610	1.4690	16.9262
GWO	260.916	2.1897	16.8029
AEFA	218.5093	19.4358	17.7314
HHO	219.3146	24.63664	17.94707
AOA	341.1882	14.7448	16.76348
IAOA	232.6805	0	17.07597

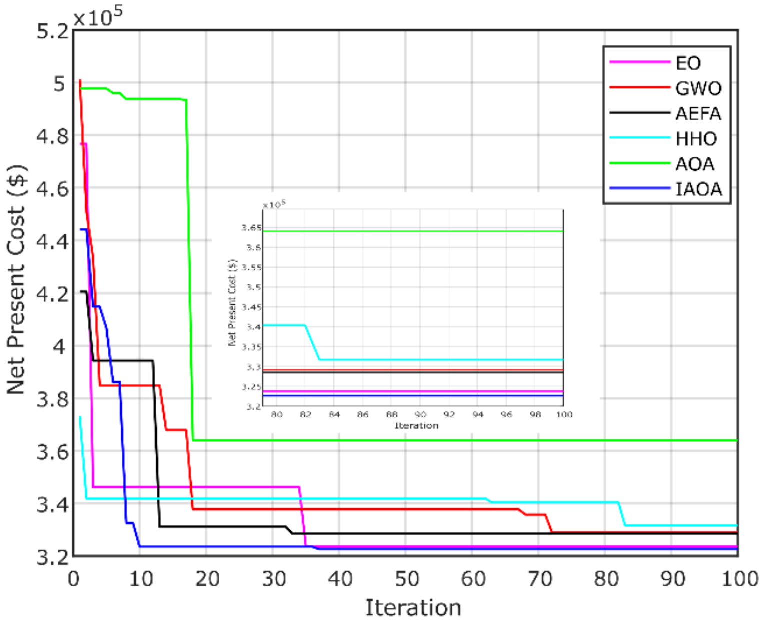
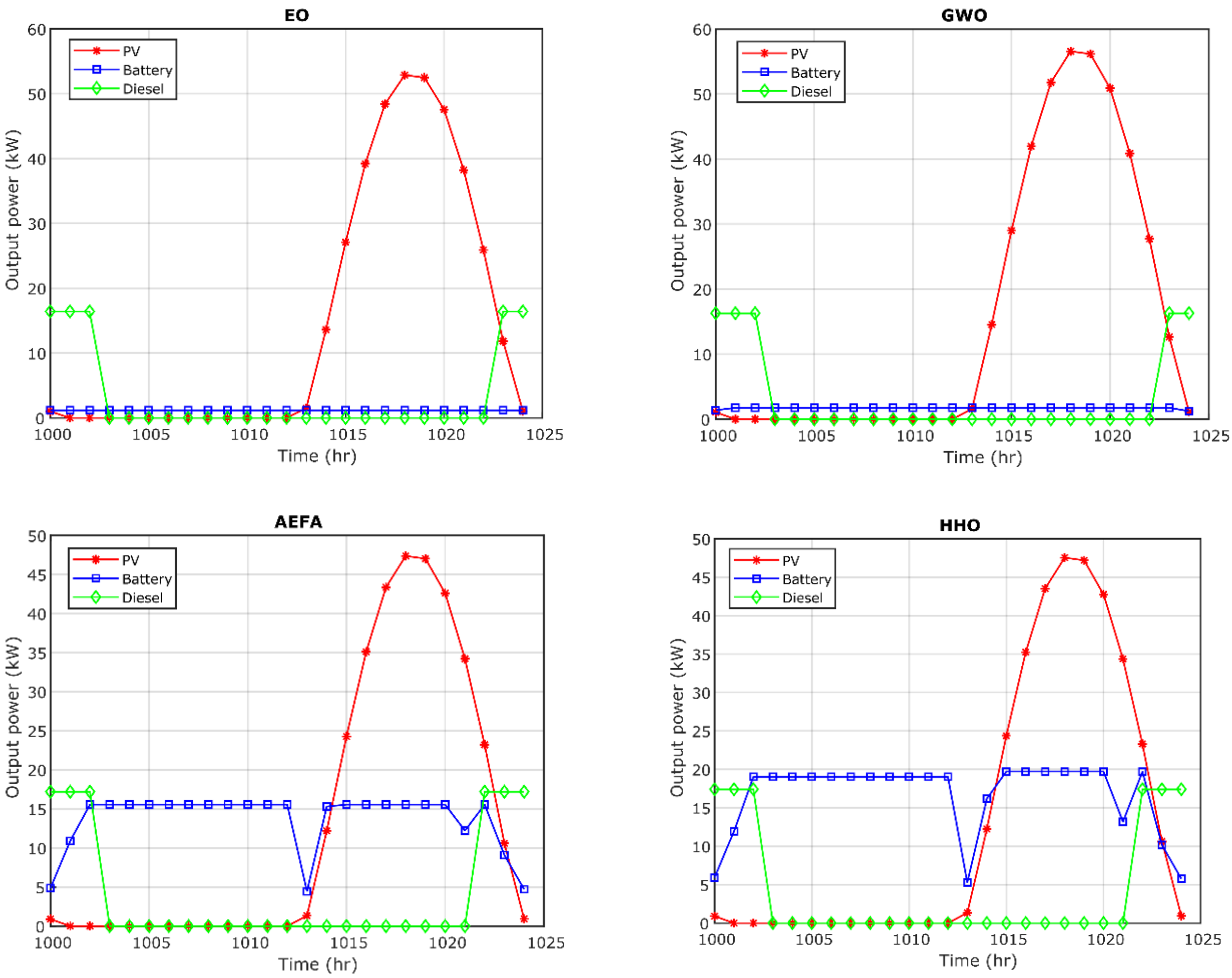


Figure 13. NPC convergence of PV/battery/diesel HRES.



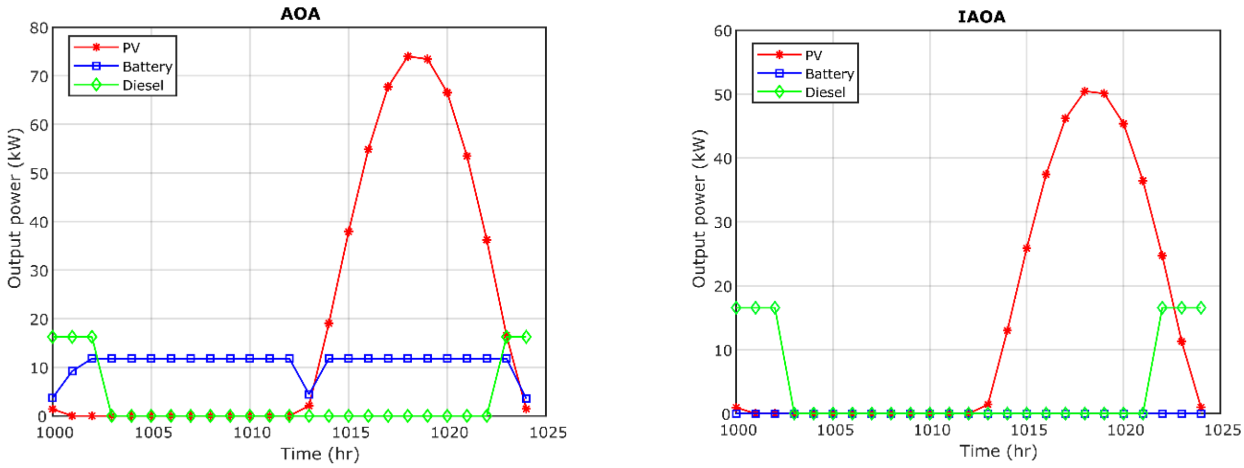
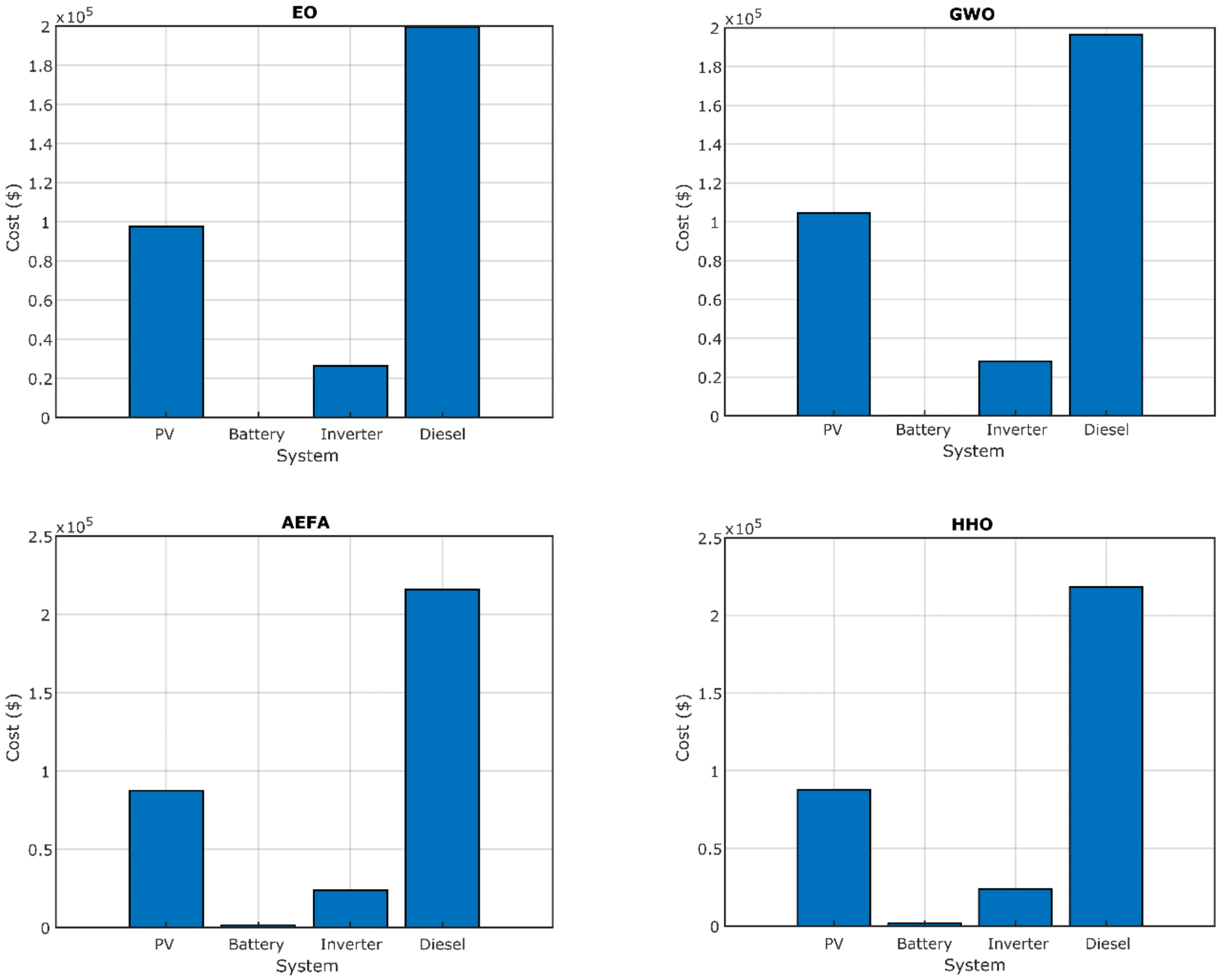


Figure 14. Output power of PV, battery, diesel on time of 1000 to 1024 hr.



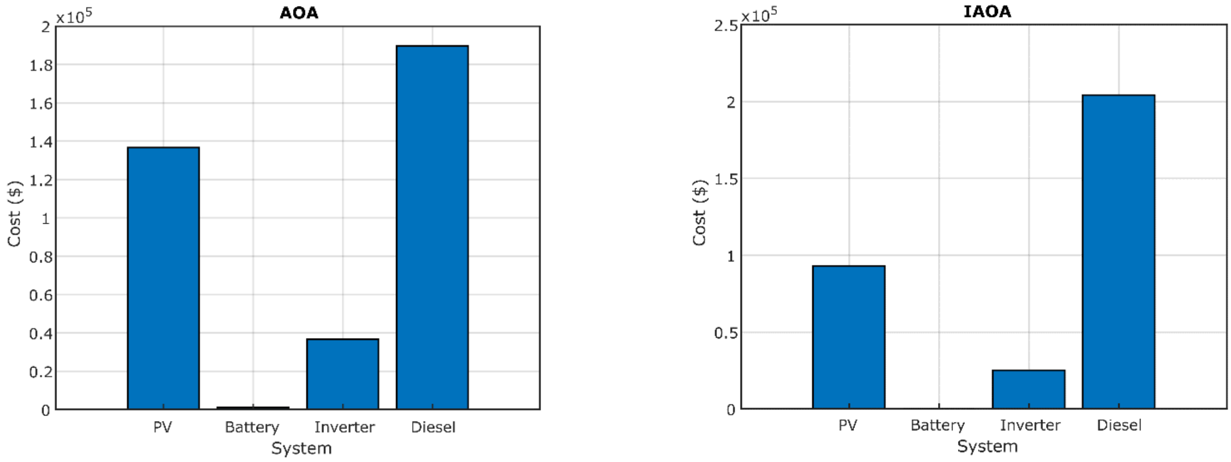


Figure 15. Costs results of PV/ diesel/battery HRES design using; 1) EO, 2) GWO, 3) AEFA, 4) HHO, 5) AOA, 6) IAOA.

7. Conclusions

The hybrid renewable energy systems (HRES) are recognized as attractive stand-alone power operations for producing electricity, which have several parameters that need to be optimized carefully by robust search methods to reach the main objectives. This paper has presented an improved algorithm called IAOA showing its efficacy in solving the HRES. The proposed IAOA uses the Arithmetic Optimization Algorithm (AOA) and Aquila Optimizer (AO) by producing a new hybrid method. This hybrid method tackles the weaknesses of the single search method; by avoiding premature convergence and coverage smoothly to the targeted region. The HRES has been investigated in design a microgrid for El Kharga region in Egypt. Two configurations have been suggested to feed electricity to the consumer. To validate the effectiveness of the proposed IAOA, five well-known optimization algorithms are used for the comparisons, which are EO, GWO, AEFA, HHO, and the original algorithm of AOA. As a result, the PV/wind/diesel/battery HRES shows its cost-effectiveness with a cost of energy of 0.2309 $/kWh, using the algorithm of IAOA. The results clearly showed that the proposed method got better results compared with other state-of-the-art methods. The main advantages of the proposed method are that it can find new best solutions for the tested problems by determining other expanded search areas. In addition, the proposed method avoided the main weaknesses raised in the conventional methods like the trapped in the local search area and no equilibrium between the search processes.

The proposed method can be further enhanced by studying its performance intensely and finding other alternatives to modify it for future work. It can also be tested for other cases to validate its ability to solve different problems. Moreover, the proposed method can solve other problems like high-dimensional feature selection problems, industrial engineering problems, scheduling cloud computing resources, parameter estimation problems.

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Appendix A

Table A1. Summary of the HRES parameters.

Symbol	Quantity	Conversion
N	Project lifetime	20 year
i_r	Interest rate	8.82%
μ	Escalation rate	5%
δ	Inflation rate	2%
λ_{pv}	PV initial cost	400 \$/m^2
θ_{pv}	Annual O&M cost of PV	$0.01 * \lambda_{pv}$ \$/m^2/year
η_r	Reference efficiency of the PV	25%
η_t	Efficiency of MPPT	100%
T_r	PV cell reference temperature	25 °C
β	Temperature coefficient	0.005 °C
$NOCT$	Nominal operating cell temperature	47 °C
N_{pv}	PV system lifetime	20 year
λ_{wind}	Wind initial cost	125 \$/m^2
θ_{wind}	Annual O&M cost of wind	$0.01 * \lambda_{wind}$ \$/m^2/year
C_{p_wind}	Maximum power coefficient	48%
V_{ci}	Cut-in wind speed	2.6 m/s
V_{co}	Cut-out wind speed	25 m/s
V_r	Rated wind speed	9.5 m/s
N_{wind}	Wind system lifetime	20 year
λ_{dg}	Diesel initial cost	250 \$/kW
θ_{dg}	Annual O&M cost of diesel	0.05 \$/h
R_{dg}	Replacement cost	210 \$/kW
p_f	Fuel price in Egypt	0.41 \$/L
N_{diesel}	Diesel system lifetime	7 year
λ_{bat}	Battery initial cost	100 \$/kWh
θ_{bat}	Annual operation & maintenance cost of Battery	$0.03 * \lambda_{bat}$ \$/m^2/year
DOD	Depth of discharge	80%
η_b	Battery efficiency	97%
SOC_{min}	Minimum state of charge	20%
SOC_{max}	Maximum state of charge	80%
N_{bat}	Battery system lifetime	5 year
λ_{inv}	Inverter initial cost	400 \$/m^2
θ_{inv}	Annual O&M cost of inverter	20 \$/year
η_{inv}	Inverter efficiency	97%