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Developed Approach Based on Equilibrium Optimizer for Optimal Design of Hybrid PV/Wind/Diesel/Battery Microgrid in Dakhla, Morocco

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ABSTRACT In this paper, a new application of Equilibrium Optimizer (EO) is proposed for design hybrid microgrid to feed the electricity to Dakhla, Morocco, as an isolated area. EO is selected to design the microgrid system due to its high effectiveness in determining the optimal solution in very short time. EO is presented for selecting the optimal system design which can minimize the cost, improve the system stability, and cover the load at different climate conditions. Microgrid system consists of photovoltaic (PV), wind turbine (WT), battery, and diesel generator. The objective function treated in this paper is to minimize the net present cost (NPC), respecting several constraints such as the reliability, availability, and renewable fraction. The sensitivity analysis is conducted in two stages: Firstly, the impact of wind speed, solar radiation, interest rate, and diesel fuel on the NPC, and levelized cost of energy (LCOE) is analyzed. Secondly, the influence of size variation on loss of power supply probability (LPSP) is investigated. The results obtained by EO are compared with those obtained by recent metaheuristics optimization algorithms, namely, Harris Hawks Optimizer (HHO), Artificial Electric Field Algorithm (AEFA), Grey Wolf Optimizer (GWO), and Sooty Tern Optimization Algorithm (STOA). The results show that the optimal system design is achieved by the proposed EO, where renewable energy sources (PV and WT) represent 97% of the annual contribution and fast convergence characteristics are obtained by EO. The best NPC, LCOE, and LPSP are obtained via EO achieving 74327 $, 0.0917 $/kWh, and 0.0489, respectively.

INDEX TERMS Economic energy, optimal system design, optimization algorithms, net present cost, hybrid renewable energy system, microgrid, solar energy, PV panels, wind energy, energy storage.

I. INTRODUCTION

Due to the rapid consumption and environmental pollution of fossil fuel, the renewable energy sources (RESs) should be integrated into the power system in order to meet the future requirements. RESs (solar energy, wind energy, ocean energy, bioenergy, geothermal energy, etc.) have been installed in many places around the world especially in the rural places [1]–[5]. Wind energy and solar energy are the most prevalent renewable energy sources. In the remote places, small-scale off-grid (microgrid) system is installed rather than building the transmission line to bring the electricity from the generation stations to loads. A microgrid system is a small system that mainly contains solar and wind energy sources [1]. Because of the instability, intermittency, and high cost of the solar and wind system, the non-renewable energy

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sources and energy storage have been added to ensure the continuous and stable power supply [3], [4]. When RESs are integrated with other energy sources, the system is called hybrid renewable energy systems (HRESs). Based on the connectivity of HRESs to the power grid, HRESs can be classified into on-grid (HRESs are connected to grid) and off-grid (HRESs aren't connected to grid) [2]. HRESs have many advantages such as exploiting different energy sources for serving the community, increasing the penetration of RESs and reduction the use of fossils fuel, and reliability (covering the load demand under different wind speeds and solar irradiation) [6]. However, the cost, reliability, and electrical efficiency are still important problems which need more improvement. Thus, it is an important to exploit the optimization techniques for enhancing the performance of HRESs under different climate conditions. In [7], the modified nondominated sorting genetic algorithm NSGA-II and criteria importance though intercriteria correlation CRITIC for reducing the LPSP, the LCOE, and the power abandonment rate (PAR) have been presented. The optimal system of an off-grid wind/PV/hydrogen system was obtained. In [8], firefly algorithm (FA), shuffled frog leaping algorithm (SFLA), and the particle swarm optimization (PSO) were used to determine the optimal combination of RESs (PV/FC, PV/WT/FC, and WT/FC). The results showed that PV/WT/FC is the optimal configuration. In [9], NSGA II was used to detect the optimal rating of the distributed system for minimizing the power losses and expected energy. In [10], a heuristic optimization algorithm was developed for obtaining the optimal sizing of a PV/battery/diesel system. In [11], the multi-objective self-adaptive differential evolution (MOSaDE) algorithm was applied to identify the optimal capacity of a PV/wind/diesel/battery system. In [12], a metaheuristic optimization techniques was conducted to select the techno-economic optimal design of an off-grid PV/biogas generator/pumped hydro energy storage/ battery system. In [13], the dispatch control strategies and the optimal ratings of HRESs were presented. In [14], artificial intelligent (AI) controllers were employed to attain an efficient and optimized energy management operation for hybrid power system of (H2/WT/PV/GMT). In [15], an improved particle swarm optimization based on a fuzzy mechanism was proposed to minimize the cost and emission. In [16], an efficient metaheuristic technique based on artificial bee swarm was exploited for sizing optimization of wind/PV/hydrogen energy system. In [17], a metaheuristic optimization algorithm called grasshopper optimization algorithm (GOA) was applied to determine the optimal sizing of PV/wind/battery/ diesel generator. In [18], a new metaheuristic technique artificial shark optimization (ASO) was proposed for solving the economical operation problem of microgrid. In [19], an investigation on six meta-heuristic algorithms (Whale Optimization, Fire Fly, Particle Swarm Optimization, Differential Evaluation, Genetic Algorithm, and Teaching Learning-based Optimization) was conducted for selecting an appropriate optimization method which achieve the less cost. In [20], gradient-based optimizer (GBO) was applied in different applications to evaluate its performance. The results proved that GBO has a good performance. In [21], a new stochastic optimizer, which is called slime mould algorithm (SMA), has been proposed to solve engineering design problems. In [22], a new method for solving the optimization problems was presented, which is called heap-based optimizer (HPO). In [23], a new metaheuristic algorithm called Chimp Optimization Algorithm (ChOA) was proposed. The results showed that the ChOA has a superior performance. In [24], a hybrid optimization algorithm for energy storage management was proposed, which shifts its mode of operation between the deterministic and rule-based approaches depending on the electricity price band allocation. In [25], [26], multi-objective optimization was used to obtain the optimal design of photovoltaic/diesel generator/fuel cell energy system. In [6], [27]–[33], different optimization methods were introduced to minimize the cost and improve the reliability under different climate conditions. Table 1 summarizes the details of the reported studies with identifying their advantages and disadvantages. Most of reported studies have limitations of the need of design system factors, don't considering the reliability indices, requiring excess detailed data, need of comparison details.

EO includes high exploratory and exploitative search mechanisms to randomly change solutions, aiding in local minima avoidance throughout the whole optimization process which is the common disadvantage of many optimization algorithms, a high effectiveness in obtaining optimal solution, and less computational time or fewer iterations [34]. However, EO has been applied to solve several optimization problems in different fields. In [35], EO has been used to find the optimal threshold value for a grayscale image, while the EO prove a good ability to enhance the accuracy and research analysis of the segmented image. In [36], a recent population-based of Equilibrium Optimizer has been developed for solving the optimal power flow problem in the hybrid AC/DC power grids. In [37], the EO has been used to solve the OPF problem considering PV, wind and hybrid PV/wind integration. In [38], the EO has been applied to determine the critical characteristic parameters of the Au/GaN/GaAs Schottky barrier diodes.

In this paper, the recent EO is applied to obtain the optimal design of the microgrid system (PV/WT/battery/diesel generator). However, the main contributions of this work can be summarized in the following points:

- Developing approach based on EO for optimal design of PV/WT/diesel/battery microgrid system.
- The developed approach is compared with HHO, AEFA, GWO, and STOA as recent optimization algorithms in order to validate its effectiveness at different climate conditions.
- Energy management strategy (EMS) which is responsible for controlling the power flow between PV/WT/ battery/diesel generator is presented.

TABLE 1. Summary of reported methods in optimizing HRESs.

Reference	Year	Hybrid RESs	Location	Algorithm	Objective function	Advantages	limitations
Maleki et al. [1]	2017	PV/battery	Birjand, Iran	ABSO	TLCC	Provide a GIS-based framework.	The study is missing the uncertainty of solar radiation, affecting significantly the results.
Fathy et al. [31]	2020	PV/wind/battery/diesel	Sakaka, KSA	HHO , GWO, MVO, ALO, WOA, SSO	COE	Detailed study with many results.	There is no information about the proposed SSO.
Xu et al. [7]	2020	wind/PV/hydrogen	Gansu, China	-RL-based NSGA-II -Traditional NSGA-II	-LCOE -LPSP -PAR	Proposes a data-driven two-stage multi-criteria decision-making (MCDM) framework.	No many configurations to confirm the best one in this location.
Samy et al. [8]	2019	-PV/WT/FC -PV/FC -WT/FC	Egypt	-FA -SFLA -PSO	NPC	Simple methodology.	FA is not a powerful algorithm to solve the microgrid system design.
Ghazvini et al. [10]	2019	PV/battery/diesel	NA	Algorithm based on V2G	cost	Applied a new heuristic optimization algorithm based on V2G.	Computational efficiency is not discussed.
Ramli et al. [11]	2018	PV/wind/diesel/battery	Yanbu, KSA	MOSaDE	-COE -LPSP	Exploit the capabilities of the proposed MOSaDE.	The proposed MOSaDE is not compared with other algorithms.
Das et al. [12]	2019	PV/biogas/PHES/battery	India	-WCA -MFO -GA	NPC	The application of the microgrid to powering the radio transmitter station.	The GA is not a powerful algorithm.
Ghenai et al. [13]	2020	PV/FC	Sharjah, UAE	NA	NPC	The use of design optimization and dispatch control together.	The optimization algorithm is not declared.
Diab et al. [33]	2019	PV/WT/diesel/battery	Abu-Monqar, Egypt	-WCA -MFO -PSOGSA -WOA	COE	Clear study.	Renewable fraction is not considered in the constraints.
Zeng et al. [15]	2020	CHP/FC/battery/heat buffer tank	NA	Improved PSO	-Cost -Emission	The work solves the heat/energy dispatch problem using an improved algorithm.	Computational efficiency is not proved for the improved algorithm.
Maleki et al. [16]	2016	WT/PV/hydrogen	Davarzan, Iran	ABSO	LCC	Proposition of a microgrid design for powered RO desalination system.	There is no comparison with other algorithms
Bukar et al. [17]	2019	PV/WT/battery/diesel	Yobe, Nigeria	-PSO -CSA -GOA	COE	Development of a robust rule-based energy management strategy.	The computation time is not declared.
Malheiro et al. [27]	2015	WT/PV/diesel/battery	Portugal	MILP	COE	Clear study.	The reliability is not considered in this work which can decrease the credibility of the designed system.
Chen et al. [28]	2017	WT/PV/FC	China	Multi-objective optimization method based on Hammersley Sequence Sampling	-Capital cost -Electricity efficiency -Reliability	Established of a new multi-objective optimization framework.	Pareto curve is unreadable.
Maleki el al. [29]	2014	-PV/wind/diesel/battery -PV/diesel/battery -Wind/diesel/battery -Diesel alone	Rafsanjan, Iran	-DHS -DSA	Total Annual Cost	Detailed study with many comparisons.	The reliability and renewable fraction factors are not considered, that can doubt the credibility of the system.
Ismail el al. [30]	2013	-PV/battery/diesel -Standalone PV -Diesel generator only	Malaysia	GA	Minimize cost	The use of the optimal tilt angle of the PV panels in order to increase the generated energy.	The optimization is not clear.
Kharrich et al. [39]	2019	-PV/WT/diesel/battery -PV/tidal/biomass/battery -PV/biomass	Morocco	PSO	NPC	Multiple scenarios and different locations.	No comparison with other algorithms.
Heydari et al. [40]	2016	PV/biomass	Kerman, Iran	HSA	NPC	A clear study.	The PV/biomass scenario is not compared.
Elkadeem et al. [41]	2019	-PV/diesel/Battery -WT/diesel/Battery -PV/WT/diesel/ Battery -Diesel only	Dongola, Sudan	HOMER Pro	NPC	Developed an approach to the agriculture and irrigation areas.	The results are not compared with other algorithms.

- Applying the sensitivity analysis to study the effect of irradiation, wind speed, fuel price and interest rate on the NPC.
- Studying the effect of the size variation on the LPSP, availability and renewable fraction.
- The system reliability is investigated by taking the loss of power supply probability (LPSP) as an objective function. Also, net present cost (NPC) and levelized cost of energy (LCOE) are used as an objective function to minimize the cost.

The reminder of this paper is structured as follows: Section 2 presents the system modeling (PV/WT/battery/ diesel generator). Section 3 introduces the optimization problem function (NPC, LPSP, and LCOE). Section 4 describes the latest three optimization algorithms (HHO, AEFA, and EO) and energy management strategy. Section 5 gives the location and specification of the studied system. Section 6 provides a comparative study among the different optimization algorithms. The conclusion is drawn in Section 7.

II. SYSTEM MODELING

In this section, the modeling of PV, WT, diesel generator, and battery is presented as follows

A. PV SYSTEM

The PV module consists of several series-connected photovoltaic cells. The output power (KW) of each pv panel (P_{pv}) can be written as [39], [40]

$$P_{pv} = I(t) \times \eta_{pv}(t) \times A_{pv} \tag{1}$$

where, I represents the solar irradiation (kW/m^2), η_{pv} represents the PV panel instantaneous efficiency, and A_{pv} is the area occupied by PV panels (m^2).

The efficiency of pv can be calculated using the following equation

$$\eta_{pv}(t) = \eta_r \times \eta_t \times [1 - \beta \times (T_a(t) - T_r) - \beta \times I(t) \times \left(\frac{NOCT - 20}{800}\right) \times (1 - \eta_r \times \eta_t)] \tag{2}$$

where, η_r and η_t represent the reference efficiency and the efficiency of the MPPT equipment, respectively; β is the temperature coefficient of the efficiency; T_a and T_r are the ambient and the PV cell reference temperatures (°C), respectively; and NOCT represents the nominal operating cell temperature (°C).

B. WIND SYSTEM

Based on the wind speed, the output power of the wind turbine has three cases as given in the following equation [39], [41]

$$P_{wind} = \begin{cases} 0, & V(t) \le V_{ci}, V(t) \ge V_{co} \\ a \times V(t)^3 - b \times P_r, & V_{ci} < V(t) < V_r \\ P_r, & V_r \le V(t) < V_{co} \end{cases} \tag{3}$$

where, V represents the velocity, P_r is the wind rated power, V_{ci}, V_{co} and V_r are the cut-in, cut-out, and rated wind speed, respectively. while the a and b are two constants expressed as

$$\begin{cases} a = P_r \Big/ \left(V_r^3 - V_{ci}^3\right) \\ b = V_{ci}^3 \Big/ \left(V_r^3 - V_{ci}^3\right) \end{cases} \tag{4}$$

The wind rated power can be obtained from

$$P_r = \frac{1}{2} \times \rho \times A_{wind} \times C_p \times V_r^3 \tag{5}$$

where, ρ is the air density (kg/m3), A_{wind} is the swept area of the wind turbine (m^2), and C_p is the maximum power coefficient ranging from 0.25 to 0.45%.

C. DIESEL SYSTEM

The diesel generator is used as a backup source in the microgrid systems in order to support the renewable energy sources and enhance their efficiency. the fuel consumption of the diesel generator F_{dg} is calculated as [11], [30]

$$P_{dg} = \frac{F_{dg}(t) - A_g \times P_{dg,out}}{B_g} \tag{6}$$

where, $P_{dg,out}$ represents the diesel output power (KW); A_g and B_g are the fuel consumption curve coefficients (L/KWH); and P_{dg} represents the diesel rated power (KW).

D. BESS SYSTEM

The battery system is an important component in the isolated microgrids, where it is considered as a power supply at absence of solar radiation or wind speed. based on the load energy during the day and the required period for supplying this load from the battery bank, the battery capacity is calculated as [30]:

$$C_{bat} = \frac{E_l \times AD}{DOD \times \eta_{inv} \times \eta_b} \tag{7}$$

where, $\boldsymbol{E_l}$ is the daily load (kWh); AD is the autonomy days number; DOD is discharge depth (80%); and $\boldsymbol{\eta_{inv}}$ and $\boldsymbol{\eta_b}$ are the inverter and battery efficiencies, respectively.

III. OPTIMIZATION PROBLEM

In this section, the main objective function, the energy management strategy, and the solution steps followed in the solution methodology are explained.

A. NET PRESENT COST

The net present cost is the sum of all component's costs (PV, wind, diesel, and battery) over the project lifetime N (20 year) including the capital (C), operation & maintenance (OM), replacement (R), and fuel costs. Also, the interest rate (i_r) that equal 13.25%, inflation rate (δ) which equal 13%, and the escalation rate (μ) with 2% are taken into the consideration. NPC modeling is expressed as follows [40]:

$$NPC = C + OM + R + FC_{dg} \tag{8}$$

1) PV AND WT COSTS

The costs modeling of pv and wt are similar, the capital cost of each one is expressed based on its initial cost ($\lambda_{PV,WT}$) and its area ($A_{PV,WT}$). The capital cost is calculated as follows [42]:

$$C_{PV,WT} = \lambda_{PV,WT} \times A_{PV,WT} \tag{9}$$

The operation & maintenance costs are expressed as

$$OM_{PV,WT} = \theta_{PV,WT} \times A_{PV,WT} \times \sum\nolimits_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{10}$$

where, $\theta_{PV,WT}$ is the annual operation & maintenance cost for any component. the replacement costs are considered null because the project lifetime and the pv or wt lifetime are the same.

2) DIESEL COSTS

The costs of the diesel generator are calculated as [43]

$$C_{dg} = \lambda_{dg} \times P_{dg} \tag{11}$$

$$OM_{dg} = \theta_{dg} \times N_{run} \times \sum\nolimits_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{12}$$

$$R_{diesel} = R_{dg} \times P_{dg} \times \sum\nolimits_{i=7,14\ldots} \left(\frac{1+\delta}{1+i_r}\right)^i \tag{13}$$

$$C_f(t) = p_f \times F_{dg}(t) \tag{14}$$

$$FC_{dg} = \sum\nolimits_{t=1}^{8760} C_f(t) \times \sum\nolimits_{i=1}^{N} \left(\frac{1+\delta}{1+i_r}\right)^i \tag{15}$$

where, C_{dg} is the diesel investement cost, λ_{dg} is the diesel initial cost, OM_{dg} represents the operation and replacement cost, θ_{dg} is the annual O&M cost of diese, 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) BESS COSTS

The initial and O&M costs of the bess are expressed as follows [42]

$$C_{BESS} = \lambda_{bat} \times C_{bat} \tag{16}$$

$$OM_{BESS} = \theta_{bat} \times C_{bat} \times \sum\nolimits_{i=1}^{T_B} \left(\frac{1+\mu}{1+\delta}\right)^{(i\_1)N_{bat}} \tag{17}$$

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

4) INVERTER COSTS

The inverter investment and O&M costs are presented as follows [43]

$$C_{inv} = \lambda_{inv} \times P_{inv} \tag{18}$$

$$OM_{Inv} = \theta_{Inv} \times \sum\nolimits_{i=1}^{N} \left(\frac{1+\mu}{1+i_r}\right)^i \tag{19}$$

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

B. LEVELIZED COST OF ENERGY

The LCOE is the cost of kilowatt per hour that is calculated as [17]

$$LCOE = \frac{NPC \times CRF}{\sum_{t=1}^{8760} P_{load}(t)} \tag{20}$$

where, CRF is the capital recovery factor which is used to convert the initial cost to an annual capital cost. It can be expressed as follows:

$$CRF(ir, R) = \frac{i_r \times (1+i_r)^R}{(1+i_r)^R - 1} \tag{21}$$

C. LOSS OF POWER SUPPLY PROBABILITY

The lpsp is a technical factor that expressed the reliability of system. the lpsp is expressed as follows [39]

$$LPSP = \frac{\sum_{t=1}^{8760} \left(P_{load}(t) - P_{pv}(t) - P_{wind}(t) + P_{dg,out}(t) + E_{bmin}\right)}{\sum_{t=1}^{8760} P_{load}(t)} \tag{22}$$

D. RENEWABLE ENERGY FRACTION

The transfer from the classical electricity production to the renewable energy was not easy, the majority introduced the renewable energies partially, while the objective is to use 100% of renewable energy. therefore, the renewable energy factor is dedicated to calculate the percent of the renewable energy used. the renewable energy fraction (RF) is expressed as follows [29]:

$$RF = \left(1 - \frac{\sum_{t=1}^{8760} P_{dg,out}(t)}{\sum_{t=1}^{8760} P_{re}(t)}\right) \times 100 \tag{23}$$

where, P_{re} represents the total renewable energy power.

E. AVAILABILITY INDEX

The availability index (A) is calculated to predict customer satisfaction. the availability index is calculated as [39]

$$A = 1 - \frac{DMN}{\sum_{t=1}^{8760} P_{load}(t)} \tag{24}$$

$$DMN = P_{bmin}(t) - P_b(t) - \left(P_{pv}(t) + P_{wind}(t)\right) + P_{dg,out}(t) - P_{load}(t) \times u(t) \tag{25}$$

where, u has 1 when the load is not satisfied and 0 on the contrary.

F. CONSTRAINTS

The constraints are presented to achieve the desired system design. in this microgrid system, the constraints are given as follows

$$0 \leq A_{pv} \leq A_{pv}^{max},$$
$$0 \leq A_{wind} \leq A_{wind}^{max},$$
$$0 \leq P_{dgn} \leq P_{dgn}^{max},$$
$$0 \leq P_{Cap\_bat} \leq P_{Cap\_bat}^{max}$$

Algorithm 1 Pseudo-Code of Harris Hawks Optimizer [44]

Initialize the population size and max iteration (K_{max})
Initialize a set of random rabbit location, within the limits $X^i_{min} \leq X^i_{rabbit} \leq X^i_{max}$.
Evaluate the objective function for all rabbits
While (k < K_{max})
  Calculate the fitness of hawks
  Set x_{rabbit} in the best location
  for each hawk **do**
  Update the initial energy E_0, energy E and jump strength J ▷ $E_0 = 2$ rand() -1, $E = 2E_0 \left(1 - \frac{t}{T}\right)$, $J = 2$(1- rand ())
    if ($|E| \geq 1$) **then**
    Exploration phase
    if ($|E| < 1$) **then**
    Exploitation phase
      if (r $\geq$0.5 and $|E| \geq 0.5$) **then**
      Soft besiege
      else if(r $\geq$0.5 and $|E| < 0.5$) **then**
      Hard besiege
      else if (r $<$ 0.5 and $|E| \geq 0.5$) **then**
      Soft besiege with progressive rapid dives
      else if (r $<$ 0.5 and $|E| < 0.5$) **then**
      Hard besiege with progressive rapid dives
Return x_{rabbit}

$$
\begin{aligned}
LPSP &\leq LPSP^{max}, \\
RF^{min} &\leq RF, \\
A^{min} &\leq A \\
AD^{min} &\leq AD
\end{aligned}
\tag{26}
$$

IV. OPTIMIZATION ALGORITHMS

A. HHO

In [44], a new nature-inspired optimization algorithm, called Harris Hawks Optimizer, has been proposed. This method depends on the cooperative behavior and chasing style of Harris' hawks. The pseudo-code of the HHO algorithm is presented below.

1) AEFA

In [45], the Coulomb's law of electrostatic force was used with the aim of creating a novel AEFA. AEFA is an outstanding optimization algorithm for non-linear optimization. The pseudo-code of the AEFA algorithm is presented in Algorithm 2.

2) GWO

GWO has been proposed by Mirjalili *et al.* [46]. GWO algorithm mimics the leadership hierarchy and hunting mechanism of grey wolves in nature. Four types of grey wolves; alpha, beta, delta, and omega are employed for simulating the leadership hierarchy. In addition, the three main steps of hunting, searching for prey, encircling prey, and attacking prey, are implemented. The GWO pseudo-code is presented in Algorithm 3.

Algorithm 2 Pseudo-Code of AEFA [45]

Initialize a set of random population $X^i_B = (X^1_B, X^2_B, \ldots, X^N_B)$ of N size, within the limits $X^i_{min} \leq X^i_B \leq X^i_{max}$.
Initialize the velocity to a random value
Evaluate the fitness of all population
Set iteration to zero
 Reproduction and Updating
 While criteria not satisfied **do**
  Calculate K(t), *best*(t) and *worst*(t)
   for i = 1: N **do**
    Evaluate the fitness values
    Calculate the total force in each direction
    Calculate the acceleration
    $V_i(t+1) = \text{rand}() \times V_i(t) + a_i(t)$
    $X_i(t+1) = X_i(t) + V_i(t+1)$
   end for
end while

Algorithm 3 Pseudo-Code of GWO [46]

Initialize the grey wolf population $X^i_p = (X^1_p, X^2_p, \ldots, X^N_p)$ within the limits $X^i_{min} \leq X^i_p \leq X^i_{max}$.
Initialize parameters *a*, *A*, *and C*
Calculate the fitness of whole population
X_α = *the best search agent*
X_β = *the second best search agent*
X_δ = *the third best search agent*
While (*iter* < *iter*$_{max}$)
  for $i = 1$: N **do**
    Update the position of the current search agent
  end for
 Update *a*, *A*, and *C*
 Calculate the fitness of whole population
 Update X_α, X_β, and X_δ
 iter = *iter* +1
end while
return X_α

3) STOA

The STOA has been proposed by Dhiman and Kaur [47], it's a bio-inspired algorithm created to solve the constrained industrial problems. The main inspiration of this algorithm is the migration and attacking behaviors of sea bird sooty tern in nature. These two steps are implemented and mathematically modeled to emphasize exploitation and exploration phases in a given search space. The STOA pseudo-code is presented in Algorithm 4.

B. EQUILIBRIUM OPTIMIZER

In [34], a recent algorithm called EO has been proposed. EO is inspired by the control of volume mass balance model

Algorithm 4 Pseudo-Code of STOA [47]

Initialize the population $X_p^i = (X_p^1, X_p^2, \ldots, X_p^N)$ within the limits $X_{min}^i \leq X_p^i \leq X_{max}^i$.
Initialize parameters S_A, C_B
Calculate the fitness of whole population
$P_{best} \leftarrow$ best search agent
While $(iter < iter_{max})$
  for i = 1: N **do**
    Update the position of the current search agent
  end for
  Initialize parameters S_A, C_B
  Calculate the fitness of whole population
  Update P_{best}
  $iter = iter + 1$
end while
return X_α

which is used to estimate both dynamic and equilibrium states. The EO pseudo-code is presented in Algorithm 5. The various parameters utilized in these optimization techniques are given in Appendix.

V. ENERGY MANAGEMENT STRATEGY

The sizing process of HRES is proposed by energy management strategy (EMS) which used in this study and given in Fig.1. The main goal of EMS is extracting the energy as much as possible from RESs which in turn minimize the fuel consumption, battery deprivation, losses, and cost.

In the proposed EMS, there are four modes and they are as follows:

1) Battery Charging ($SOC\ (t) > SOC\ (t)^{max}$): The RESs generated power is greater than the load and the battery isn't fully charged. Thus, the extra power is used for charging the battery.
2) Dissipated Power ($\boldsymbol{SOC\ (t) = SOC\ (t)^{max}}$): The generated power from RESs exceeds the load and the battery is fully charged. Thus, the extra power will be dissipated in a dump load.
3) Battery Discharging ($\boldsymbol{SOC\ (t) < SOC\ (t)^{min}}$): The RESs generated power doesn't cover the load and the battery SOC is less than min SOC. Thus, the battery is used to supply the power.
4) Diesel Operating ($\boldsymbol{SOC\ (t) > SOC\ (t)^{min}}$): The power extracted from PV and WT is insufficient and the battery SOC is greater than min SOC. Thus, diesel generator is exploited for covering the load and charging the battery.

VI. LOCATION AND SPECIFICATION OF THE STUDIED SYSTEM

The microgrid system is installed to supply a small industrial area by the electricity in the Dakhla location, Morocco as shown in Fig. 2. Microgrid system comprises PV, WT, diesel, and battery. The hourly load power, solar radiation, air density, and wind speed in this project are shown in Figs.3-6, respectively. The technical and economic specifications of the studied system are listed in Table 2. The project lifetime is 20 year. The annual O&M cost of PV, wind turbine, diesel, and battery are listed in Table 2.

Algorithm 5 Pseudo-Code of Equilibrium Optimizer [34]

Initialize the particle's populations $X_p^i = (X_p^1, X_p^2, \ldots, X_p^N)$ within the limits $X_{min}^i \leq X_p^i \leq X_{max}^i$.
Initialize parameters $a_1 = 2$; $a_2 = 1$; $GP = 0.5$;
While $(iter < iter_{max})$
  for i = 1: N **do**
    Evaluate the fitness of al particle's
    if $fit(\vec{C}_i) < fit(\vec{C}_{eq1})$
      replace $\vec{C}_{eq1}$ with $\vec{C}_i$ and $fit(\vec{C}_{eq1})$ with $fit(\vec{C}_i)$
    else if $fit(\vec{C}_i) > fit(\vec{C}_{eq1})$ & $fit(\vec{C}_i) < fit(\vec{C}_{eq2})$
      replace $\vec{C}_{eq2}$ with $\vec{C}_i$ and $fit(\vec{C}_{eq2})$ with $fit(\vec{C}_i)$
    else if $fit(\vec{C}_i) > fit(\vec{C}_{eq1})$ & $fit(\vec{C}_i) > fit(\vec{C}_{eq2})$ & $fit(\vec{C}_i) < fit(\vec{C}_{eq3})$
      replace $\vec{C}_{eq3}$ with $\vec{C}_i$ and $fit(\vec{C}_{eq3})$ with $fit(\vec{C}_i)$
    else if $fit(\vec{C}_i) > fit(\vec{C}_{eq1})$ & $fit(\vec{C}_i) > fit(\vec{C}_{eq2})$ & $fit(\vec{C}_i) > fit(\vec{C}_{eq3})$ & $fit(\vec{C}_i) < fit(\vec{C}_{eq4})$
      replace $\vec{C}_{eq4}$ with $\vec{C}_i$ and $fit(\vec{C}_{eq4})$ with $fit(\vec{C}_i)$
    end if
  end for
  $\vec{C}_{ave} = (\vec{C}_{eq1} + \vec{C}_{eq2} + \vec{C}_{eq3} + \vec{C}_{eq4})/4$
  Construct the equilibrium pool
  $\vec{C}_{eqpool} = \{\vec{C}_{eq(1)}, \vec{C}_{eq(2)}, \vec{C}_{eq(3)}, \vec{C}_{eq(4)}, \vec{C}_{eq(ave)}\}$
  Accomplish memory saving (if iter > 1)
  Assign t
  for i = 1: N do
  Randomly choose one candidate from the equilibrium pool (vector)
  Construct $\vec{F}$, $\vec{GCP}$, $\vec{G_0}$, $\vec{G}$ and update concentrations $\vec{C}$
end for
$iter = iter + 1$
end while

VII. RESULTS AND DISCUSSION

In this work, the latest EO is proposed to design the optimal sizing of PV, WT, diesel, and battery. The results obtained by the proposed algorithm are compared with other recent approaches, HHO, AEFA, GWO, and STOA, to validate the effectiveness of the proposed EO in achieving the best reliability and minimum cost. The convergence characteristics of HHO, AEFA, GWO, STOA, and EO are shown in Fig.7. Based on convergence process, EO has the best performance where it is faster than HHO, AEFA, GWO, and STOA. Thus, EO consumes less computation time to reach the optimal solution which in turn reduces computer resource usage as well as achieving the less cost. On the other hand, the HHO, AEFA, GWO, and STOA algorithms need more time to reach the solution as well as high cost of NPC. The best value of the algorithms is founded in iterations 24 (AEFA), 33 (EO), 39 (HHO), 45 (GWO), and 66 (STOA). Normally, in the microgrid design problem, 100 iteration is largely sufficient.

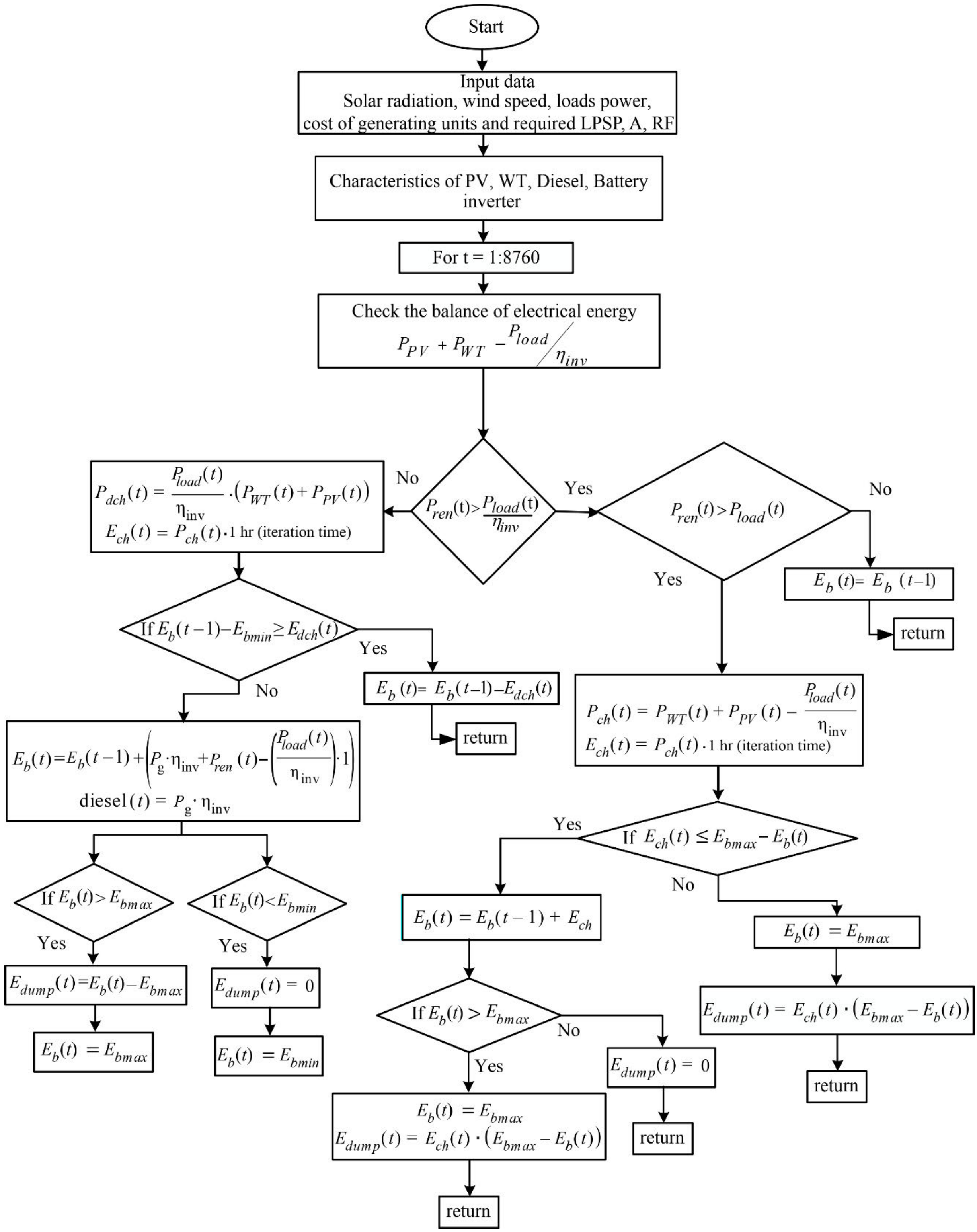

FIGURE 1. Power management of the hybrid PV/WT/Diesel/battery system.

From Table 3, it can be noted that the EO achieves the optimal sizing compared with AEFA, HHO, GWO, and STOA results, where the PV area is 231.090 m^2, the wind-swept area is 76.0147 m^2, the diesel generator rated is 1.357 kW, and the battery nominal capacity is 20.403 kWh. On the other hand, Table 4 presents the NPC, LCOE, LPSP, Av, and RF for HHO, AEFA, GWO, STOA and EO. The results prove that the EO has the least cost, where NPC equals

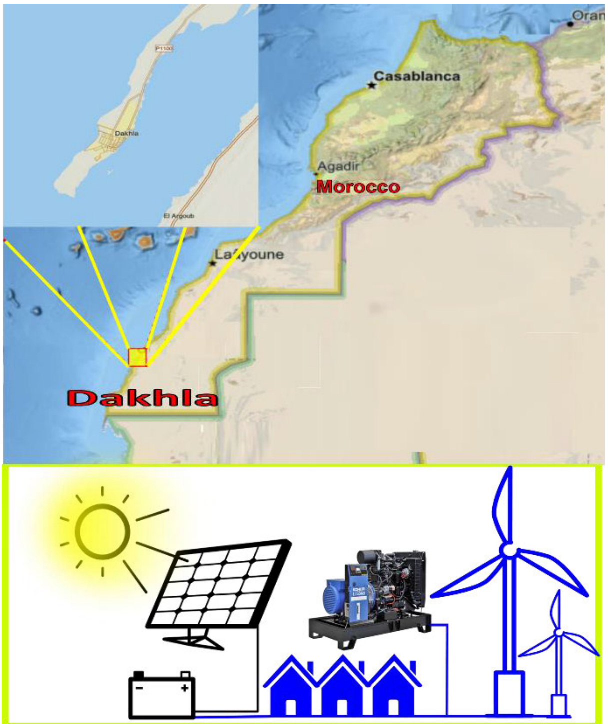

FIGURE 2. Location and components of the microgrid.

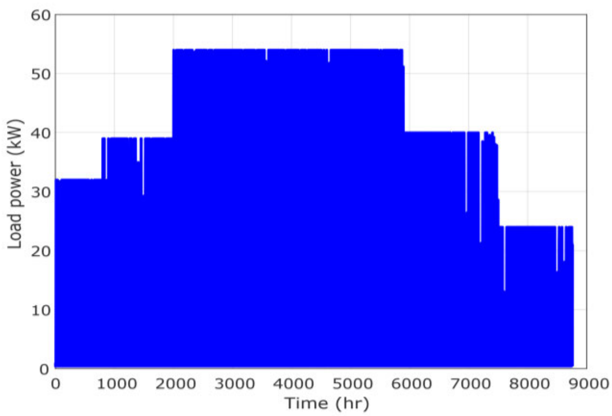

FIGURE 3. Hourly load power over one year of the studied system.

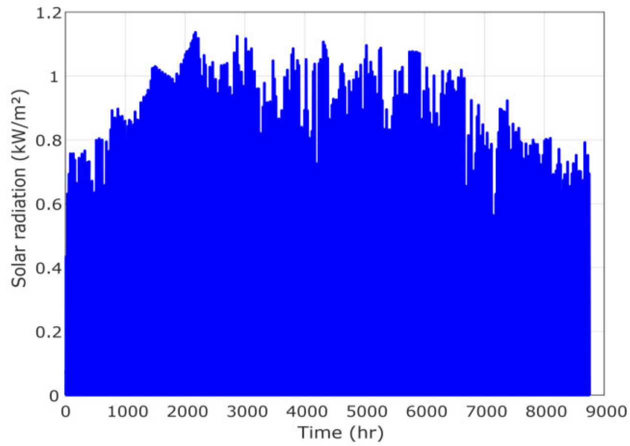

FIGURE 4. Hourly solar radiation over one year of the studied system.

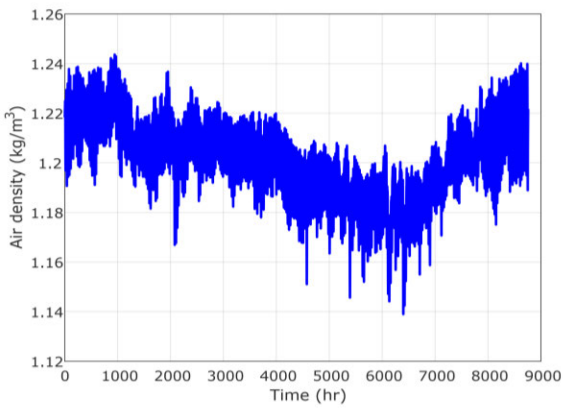

FIGURE 5. Hourly air density over one year of the studied system.

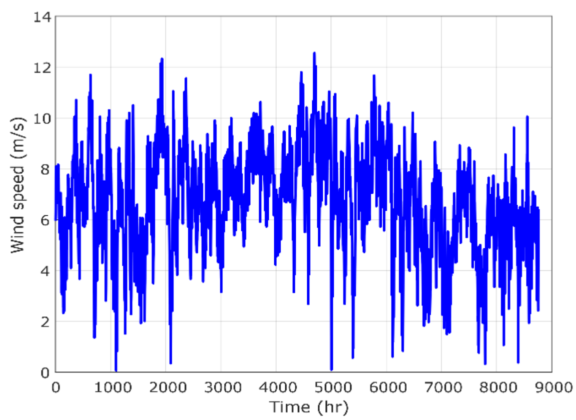

FIGURE 6. Hourly wind speed over one year of the studied system.

74327 $ whereas NPC of HHO, AEFA, GWO, and STOA equal 80877 $, 83557 $, 79482 $, and 86144 $, respectively. The computational time of HHO, AEFA, GWO, STOA, and EO equals 65253 s, 34859 s, 48642 s, 67516 s, and 35110 s, respectively. Thus, the proposed EO algorithm consumes less time, 35110 s, to achieve the optimal sizing compared with other algorithms. Table 5 presents the sizing of the hybrid PV/wind/diesel/battery system by units. It can be observed that the EO presents the best configuration by using 145 PV panels, 7 WTs, 10 diesel generators, and 11 batteries.

The power management of the hybrid PV/wind/diesel/battery system based on HHO, AEFA, GWO, STOA, and EO algorithms is shown in Fig.8. The results based on HHO and EO algorithms show that the hybrid system mainly depends on the PV system while the wind, diesel, and battery are not considered as a primordial source. On the other hand, when AEFA, GWO, or STOA algorithm are used, PV and wind systems should be taking as the same level, which increase the net present cost for these algorithms. The results prove that the EO can achieve less cost compared with other algorithms.

TABLE 2. The economic and technical data of the microgrid [48], [49].

Symbol	Quantity	Conversion
N	Project lifetime	20 year
i_r	Interest rate	13.25 %
μ	Escalation rate	2 %
δ	Inflation rate	12.27 %
P	Rated power of one panel	415 W
λ_{pv}	PV initial cost	300 $ /m²
θ_{pv}	Annual O&M cost of PV	$0.01 * \lambda_{pv}$ $ /m²/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
P	Rated Power of one turbine	3.6 kW
λ_{wind}	Wind initial cost	125 $ /m²
θ_{wind}	Annual O&M cost of wind	$0.01 * \lambda_{wind}$ $ /m²/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	0.43 $ /L
N_{diesel}	Diesel system lifetime	7 year
λ_{bat}	Battery initial cost	100 $ /kWh
θ_{bat}	Annual operation & maintenance cost of Battery	$0.03 * \lambda_{bat}$ $ /m²/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 $ /m²
θ_{inv}	Annual O&M cost of inverter	20 $ /year
η_{inv}	Inverter efficiency	97 %

TABLE 3. The optimal sizing of the hybrid system.

	HHO	AEFA	GWO	STOA	**EO**
PV (m²)	345.673	245.337	264.602	210.906	**231.090**
Wind (m²)	144.972	393.159	298.826	171.099	**76.0147**
Diesel (kW)	0.24	0.079	0.178	1.813	**1.357**
Battery (kWh)	23.811	27.677	22.671	26.951	**20.403**

This means that less wind turbine units and PV panels will meet the load requirements.

Fig. 9 shows the load demand and the power extracted from PV, WT, diesel, and battery during specific hours based on EO. It can be seen that the PV power is greater than the load during the zoomed period. The generated power by WTs is a small and contribute to supplying the load all time. Diesel

TABLE 4. NPC, LCOE, LPSP, Av, and RF of the microgrid.

Algorithm	NPC ($)	LCOE ($/kWh)	LPSP (%)	Av (%)	RF (%)	**Time (s)**
HHO	80877	0.0999	2.18	99.18	99.97	65253
AEFA	83557	0.1032	1.83	99.29	99.99	34859
GWO	79482	0.0982	0.0173	99.2643	99.9906	48642
STOA	86144	0.1064	0.0376	98.4821	99.6517	67516
EO	**74327**	**0.0918**	**4.89**	**97.63**	**99.50**	**35110**

TABLE 5. Optimal sizing of the microgrid system based on EO.

Component	Number of units	Nominal power (kW)
PV panel	145	60.17
Wind turbine	7	25.2
Diesel generator	10	1.4
Battery system	11	20.35

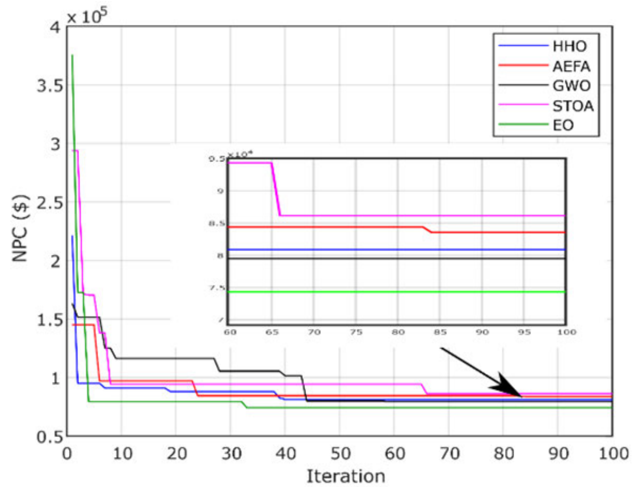

FIGURE 7. NPC convergence using HHO, AEFA, GWO, STOA, and EO algorithms.

generator is employed to supply the load when the power extracted form PV, WT, and battery is less than the load. During the certain period, diesel generator shares in covering the load for short periods. When the power extracted from PV, and WT exceeds the load and the battery isn't fully charged, the battery will be charged. On the other hand, the battery contributes (discharge) to supplying the load when the power extracted from PV, and WT is less than the load. In order to validate the correct design, the battery SOC obtained by EO within specified period is plotted in Fig.10 and Fig.11. It can be observed that battery SOC is within the specified limits which demonstrates the correct design. These values (SOC_{max} and SOC_{min} given in Table 2) are selected to avoid any problem for the battery material, i.e. the limit is presented as a security condition of the battery material.

On the basis of the studied algorithms (HHO, EO, AEFA, GWO, and STOA), the percentage contribution of PV, WT,

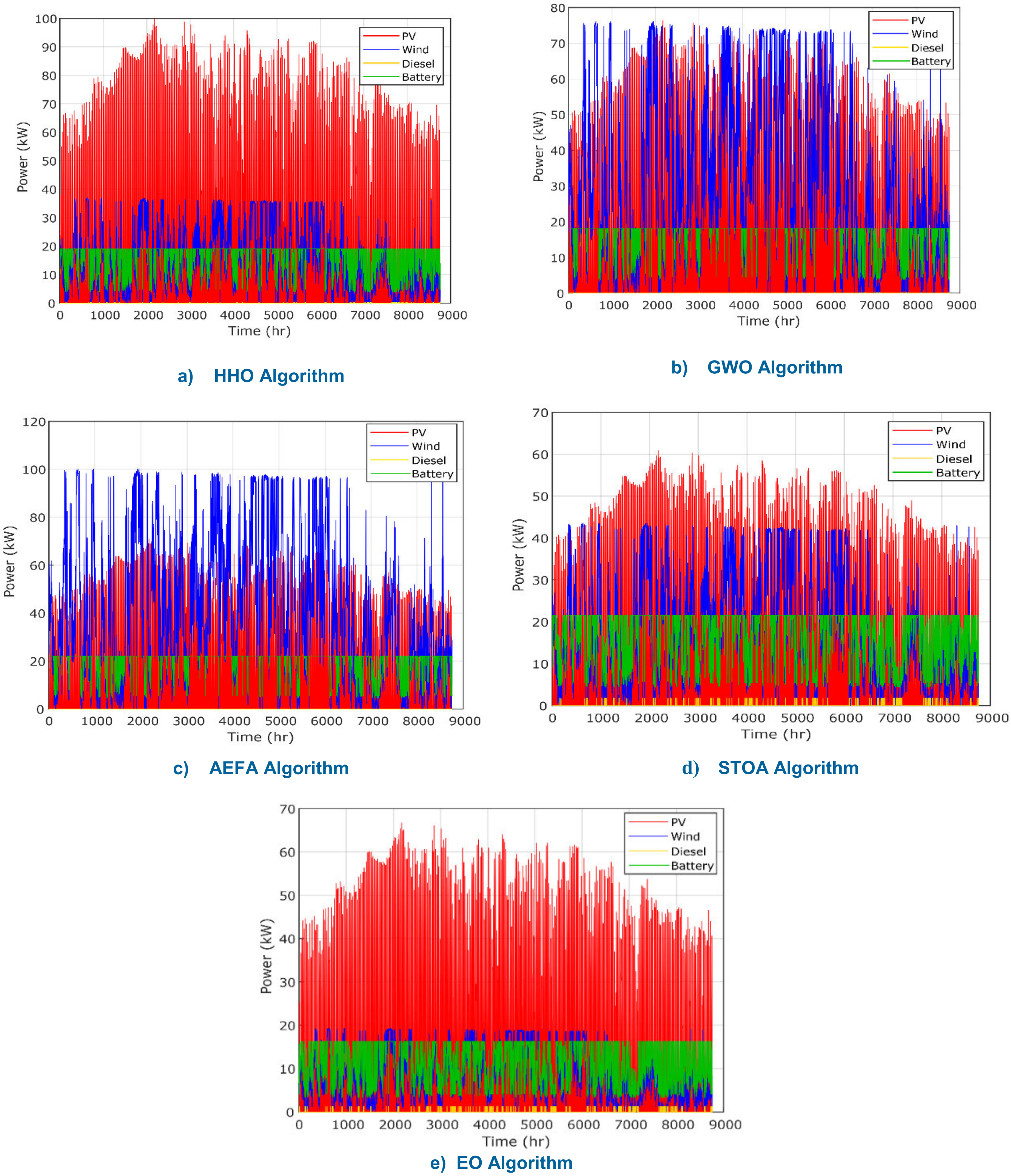

FIGURE 8. **Energy management over one year in the hybrid system using a) HHO, b) AEFA, c) GWO, d) STOA and e) EO.**

battery, and diesel in covering the annual load is illustrated in Fig.12. Based on EO, it is clear that PV, WT, battery, and diesel system shares in covering 65%, 33%, 2%,1% of load, respectively. The results prove that the EO is an effective and appropriate solution algorithm in microgrid systems.

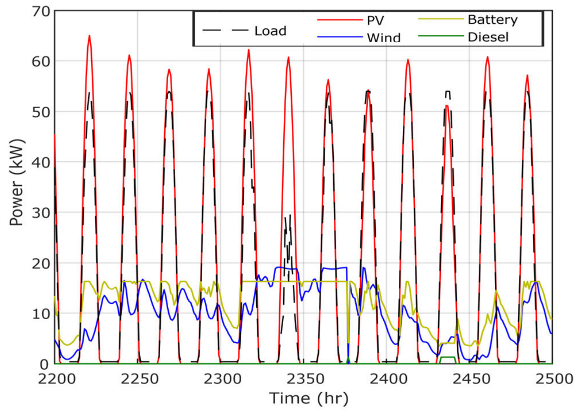

FIGURE 9. Time-response of PV, WT, battery, diesel generator, load powers obtained via EO during some hours.

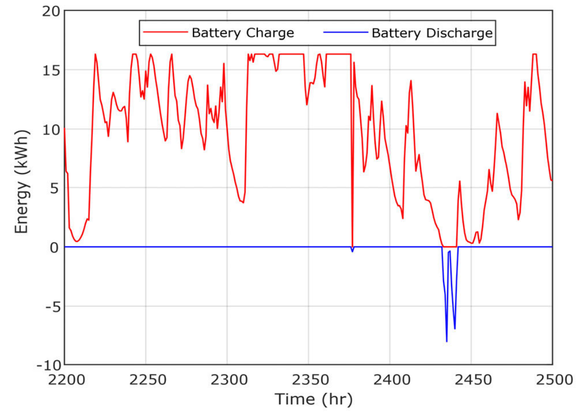

FIGURE 11. Battery charge and discharge curve during some hours.

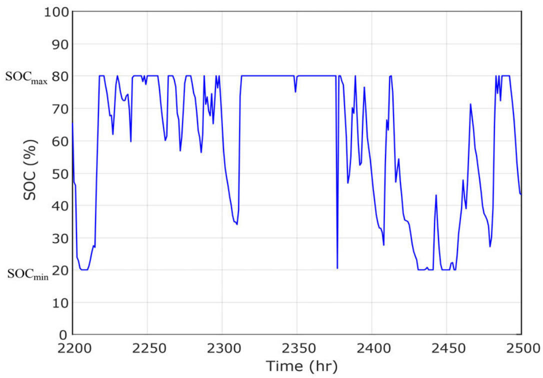

FIGURE 10. Battery SOC during some hours obtained via the EO.

VIII. SENSITIVITY ANALYSIS

Given that wind speed and solar radiation are changed with time whereas the fuel price is high, it is important to analyze and assess the economic performance under changing these parameters. A sensitivity analysis is conducted to determine the influence of solar radiation, wind speed, interest rate and fuel price on the NPC, LCOE, and LPSP factors. The sensitivity adjustment is conducted on 4% decrement/ increment. Fig.13 shows the impact of varying the parameters on NPC, where "0" on the x-axis refers to the nominal values. At lower values of chosen parameters, it can be observed that the NPC increases with decreasing the values of wind speed, solar radiation, or interest rate whereas NPC decreases with decreasing the diesel fuel. At larger values of chosen parameters: 1) it can be noted that the higher interest rate or wind speed, the lower NPC. 2) with more diesel fuel or solar radiation, NPC will increase.

The influence of varying the parameters on LCOE is illustrated in Fig.14. The sensitivity parameters nominal values

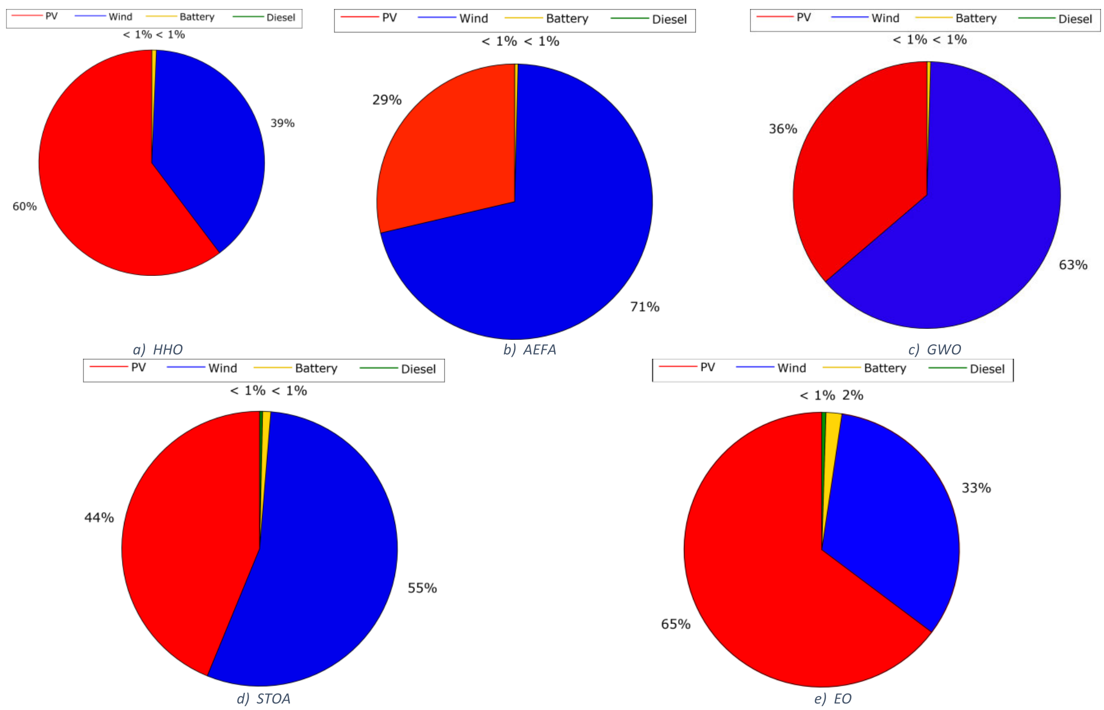

FIGURE 12. Annual contribution of PV, WT, Battery, and DG obtained by *a*) HHO, *b*) AEFA, *c*) GWO, *d*) STOA and *e*) EO.

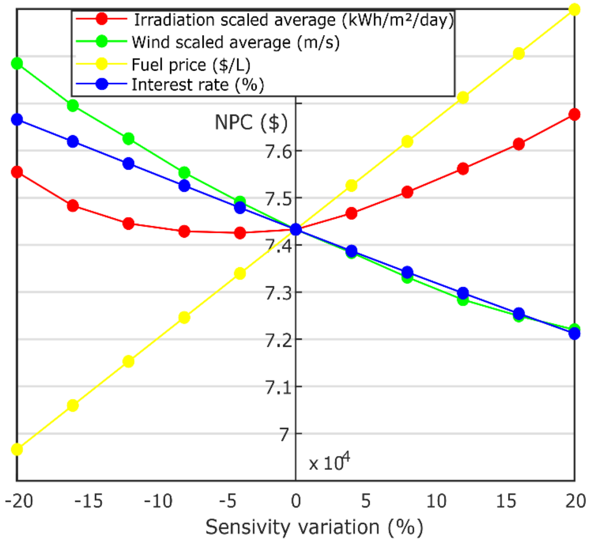

FIGURE 13. **Sensitivity analysis: the impact of changing the parameters on NP.**

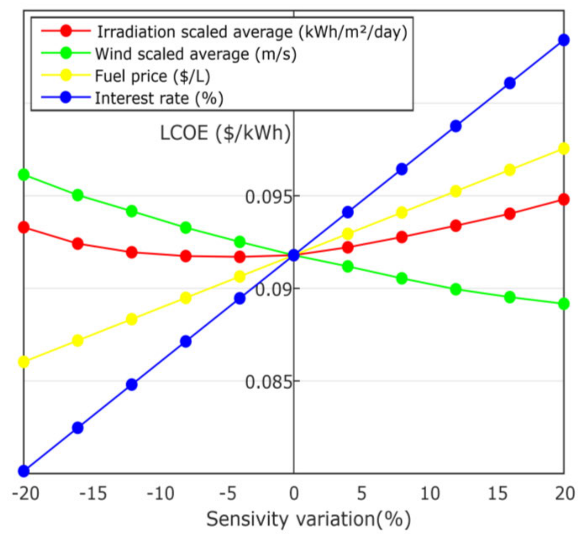

FIGURE 14. **Sensitivity analysis: the impact of changing parameters on LCOE.**

are located on "0". The following notes can be extracted from Fig.14: 1) LCOE increases when the wind speed or solar radiation decreases. 2) LCOE is proportional with interest rate or diesel fuel. 3) LCOE decreases with increased wind speed.

The effect of varying the sizing variable decision on the parameters; LPSP, availability and RF is studied.

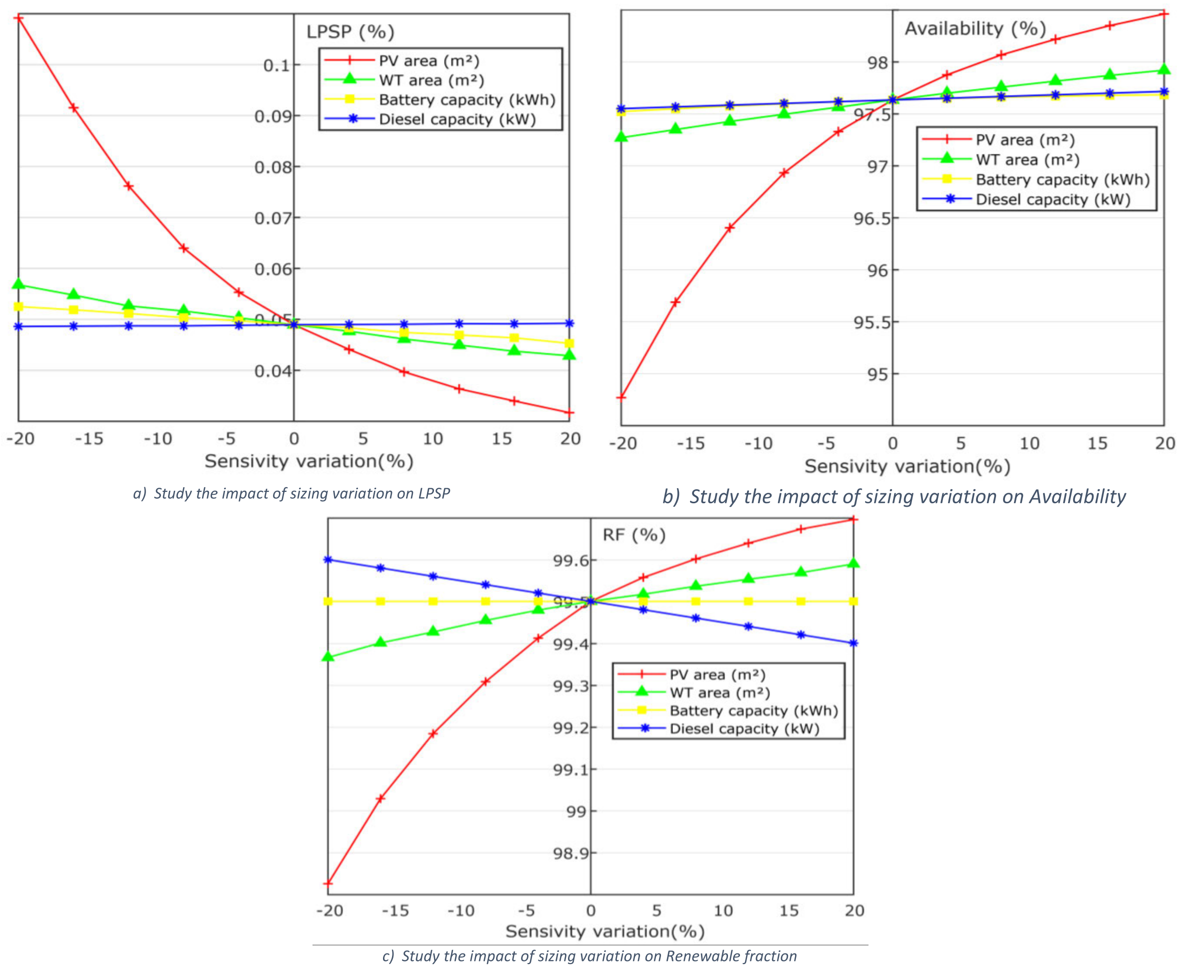

FIGURE 15. **Sensitivity analysis: the impact of sizing variables on the microgrid system factors, *a*) LPSP, *b*) Availability, *c*) Renewable fraction.**

Fig.15 shows that the chosen parameters has an effect on the system factors, mainly the variation of PV area.

IX. CONCLUSION

In this paper, a new application for EO has been proposed for design a microgrid based on PV/WT/diesel/battery system. The objective function is minimizing the net present cost, levelized cost of energy, increasing the reliability LPSP and the renewable fraction. The energy management strategy has been designed to cover the load at different climate conditions by controlling the power flow between system components. The proposed EO has been compared with HHO, AEFA, GWO, and STOA algorithms with the aim of evaluating its performance. The simulation results showed that the proposed method has the ability for designing the microgrid system. However, EO has the best optimal sizing with NPC of 74327 $, LCOE of 0.0918 $/kWh, and LPSP of 0.0489. The convergence characteristics showed that the EO takes very short time to reach the optimal solution compared with HHO, AEFA, GWO, and STOA which in turn reduces computer memory and the cost. Thus, the EO is considered as effective solution method in designing the microgrid systems. The partial shading of PV model is left as a future work.

APPENDIX

Algorithms	Parameters
HHO	β=2; Population size=10; Maximum iteration= 100
AEFA	K_0 =500; α= 30; Population size=10; Maximum iteration= 100
GWO	a=Linear reduction from 2 to 0; Search agents =10; Maximum iteration= 100
STOA	C_f = 2; Search agents=10; Maximum iteration= 100
EO	a_1= 3; a_2= 0.5; Generation probability (GP)=2.5; Population number=10; Maximum iteration= 100

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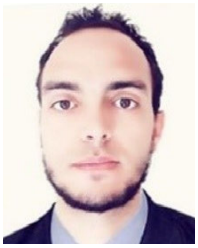

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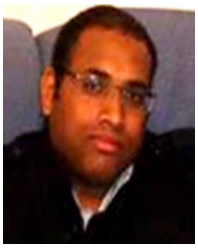

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