



Journal of Renewable Energies

Revue des Energies Renouvelables

Journal home page: <https://revue.cder.dz/index.php/rer>

Research Paper

Cost optimization of a wind-solar-diesel system with battery storage

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ARTICLE INFO

Article history:

Received 24 March 2022

Accepted 04 September 2022

Keywords:

Hybrid energy system

Optimization

COE

HOMER

Metaheuristics algorithms

ABSTRACT

This work presents the optimization of a wind-solar-diesel system with battery storage for a continuous and reliable production of electrical energy. In this context, detailed mathematical modeling of the present system and its operation algorithm has been presented. The objective function of the system is to minimize its cost of energy (CoE) which estimates the average lifetime cost of power production per kWh. The cost elements comprising the CoE include investment costs, fuel costs, and operation and maintenance costs. The optimization is performed in the HOMER software in addition to three metaheuristic optimization techniques namely the Cuckoo Search algorithm (CS), the BAT algorithm (BA) and the Firefly algorithm (FA). The simulations conducted in this paper are based on meteorological data collected from an installation in Bouzareah. Simulation results show the excellent properties and superiority of the CS optimization method compared to HOMER, BA and FA algorithms and demonstrate the feasibility of the proposed hybrid PV-wind-diesel-battery system in Bouzareah.

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ISSN: 1112-2242 / EISSN: 2716-8247



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1. Introduction

In view of the consequences generated by the release into the atmosphere of greenhouse gases, the current trend is to promote the so-called green energy sources. Research and initiatives to develop more reliable and economical renewable energy systems are undertaken [1-4]. Thus wind, solar and / or thermal energy systems are booming. However, the generation of energy in these systems is highly dependent on the intermittent nature of meteorological resources. The solution adopted to overcome this problem is the coupling of at least two renewable sources (wind and photovoltaic for example) and the association of energy storage system thus constituting a multi-source system [5]. In general, a multi-source, multi-load system consists of a production unit which can result from the coupling of several production sources such as solar photovoltaic, wind power, the electrical distribution network (conventional source), etc. a storage unit which can also be the result of several storage elements (batteries, supercapacitors, hydrogen battery, etc.) and a consuming part which here represents the need to be satisfied [6, 7]. This requirement can be considered as a set of loads of a different nature among which a distinction is made between continuous loads and alternating loads. These parts are interconnected and are constantly interacting during the operation of the system. One of the major aspects of this configuration is the reliable generation of energy at low cost. Sizing is an important step in the process of managing energy flows because a poorly sized system can have degraded performance and poor coordination between production and demand [8, 9]. Determining the size of the components of the system is an important step to be taken in order to guarantee the satisfaction of the load, the correct operation of the system and avoid prohibitive costs [10-12].

In multi-source and multi-load systems, sizing is an important aspect at the development stage of the process. It allows determining the possible sizes of the various subsystems to be interconnected in order to meet the defined load requirements [12]. The approach generally developed is to determine the size of the system upstream and downstream to optimize its overall management. The purpose of sizing is to determine a configuration with the lowest possible cost to meet the energy demand while keeping the system operating within its safe limits. It is a study which allows the evaluation of the technical aspect of the system (capacity to satisfy the load for example), of the environmental impact of the installation (greenhouse gas emission) and of the economic aspect (overall cost) [3, 13, 14]. The objective is therefore to determine the configuration of the overall system, which depends on the weather conditions of the site, the loads to be supplied and the way in which the subsystems are interconnected and minimizes one or more well-defined performance criteria.

In recent years, wind, solar photovoltaic (PV) and biomass based systems have been drawing

more attention to provide electricity to isolated or energy deficient regions [1, 2, 6, 15-19]. On the other hand, several optimization algorithms, inspired by nature, which are metaheuristics imitating nature, seem promising to enrich the literature dedicated to hybrid energy system sizing. A wide variety of methods based on a population of solutions have been proposed in the literature, starting with evolutionary algorithms, going through genetic algorithms and arriving at algorithms based on swarm intelligence, namely, Particles Swarm Optimization (PSO) algorithm [20, 21], the Ant Colony Optimization (ACO) algorithm [22, 23], the Cuckoo Search (CS) algorithm [24, 25], the BAT algorithm (BA) [14, 26], Firefly algorithm (FA) [27, 28], etc., which have undergone remarkable investigations. In addition, the evolution of computer techniques has facilitated the use of optimization methods and tools. Indeed, several simulation tools such as HOMER [8, 29-31], Hybrid2 [32, 33], HOGA [33, 34], etc. have been implemented for the optimization and sizing of multi-source systems. However, these tools appearing in the form of a black box do not necessarily allow the user to modify their settings. This paper presents a hybrid PV-wind generation system along with storage to fulfill the electrical load demand of a small area in Bouzareah, Algiers, Algeria (Altitude: 314 meters, Latitude: 36 ° 8'N and Longitude: 03 ° 02'E). For optimal sizing of components, the Cuckoo Search algorithm (CS) [12, 13, 35, 36], the Firefly algorithm (FA) [12, 36] and the BAT algorithm (BAT) [14, 36] are used. To verify the strength of the proposed technique, the results are compared with the results obtained from the standard software tool, Hybrid Optimization Model for Electric Renewable (HOMER). The proposed objective function takes into account two optimization criteria: loss of power supply probability (LPSP) and system cost based on the unit electricity cost (CoE). For this aim, all the considered system components are modeled and detailed in section 2; in section 3, energy management system and objective function are discussed. Section 4, explains materials and methods used in the present study (CS, FA and BAT algorithms and HOMER Software). The obtained results and their corresponding discussions are presented in section 5.

2. Legal framework and funds of the renewable energies in Algeria

Algeria, like other countries that are members of the Organization of the Petroleum Exporting Countries (OPEC), wants to diversify its electricity production, and is looking to solar power for the bulk of its new generation capacity. About 98% of Algeria's electricity today comes from natural gas, but analysts have said the North Africa country's high sun radiation level makes it one of the largest markets for solar power on the continent. Algeria should attempt to reduce its dependence on natural gas for electricity, the development of renewable energies represents an essential vector for the sustainable economic and human development of the

country[37].

Algeria's Law on Renewable Energy Promotion establishes a general structure for the deployment of a Renewable Energy Policy and sets production targets. The law aims to promote sustainable development in Algeria, protect the environment and contribute to the international effort to curb climate change impacts. The legislation establishes a set of tools to promote the development and use of renewable energy[38]. Legislative framework to promote renewable energy (RE) in Algeria[38] are given in appendix A1 .

3. Rural Electrification

The electrification situation in Algeria is influenced by demographic and geographical factors. The densely populated coastal regions have grid electrification of effectively 100%. This is not economically feasible for the thinly populated regions in the interior, due to the relationship between the costs of grid extension and the number of consumers reached. In order to encourage the rural population to stay in their original areas and thus prevent migration into cities, the governmental programme entitled "Plan National d'Electrification" from 1970 aims to create comparable living conditions as in the cities, so that "harmonious development"[39] is guaranteed in the country. The annual electricity demand is increasing annually by 5 -7 %, an increase which has already led to the first serious supply shortages, as the app. 6 000 MW of installed power in the Algerian power station park proved to be insufficient. In particular, load peaks during cooling periods in summer create problems. A total power of 306 MW is installed in decentralised units. Of this power, 175 MW is generated by 183 diesel generators with power ratings between 0.35 MW and 8 MW [39], the origin of the remaining 131 MW is not specified. In order to accelerate grid extension, a network of public and private companies was established; the members include 35 local public enterprises, one national enterprise (KAHRIF) and numerous smaller private companies, which together have a total annual capacity for grid extension of 8000 km. Photon international, February 2006, reported that in 2005 the electrification rate was 98%; official detailed information concerning the exact number of not connected villages and houses are not available. CDER estimate about 700 villages with about 34 000 dwellings without grid connection[40]. According to the law, regenerative energy has the status of being specially recommended for financial support, but to date only 16 villages in southern Algeria have been electrified with photovoltaic energy within a demonstration project which ended in September 2000 and Cumulated capacities of 13115 KWp in 2019[40]. As the project was financed with State funds, it was possible to meet the requirement that the supply be of an equivalent standard to a conventional grid connection by installing a correspondingly high total power. The plan was to install purely photovoltaic systems for isolated houses and

small villages, and hybrid systems (PV/diesel) for population centres of the south. The aim was also to gain initial experience with this promising new technology, so that later, when prices become more favourable, the demand could be estimated and capacity could be planned on a realistic basis. It would also allow the rapid deterioration caused by the desert-like climatic conditions to be taken into account. The know-how on technical questions, installation and investment costs would be the responsibility of the energy utility, whereas local authorities would manage maintenance, and rate charging and collection. To date, there is great satisfaction with the systems and the supply, as they have proved to be robust and highly reliable [39].

4. Case studies

In this paper, Bouzareah site is considered that is a suburb of Algiers, in Algeria. It's a Mountainous Area at an altitude of over 300 meters. Bouzareah is a coastal Algerian site, and which, according to the Koppen Geiger climate classification, can be considered as a temperate climate with a hot and arid summer (CSA climate) [41] . Table 1 shows the geographical coordinates of this city.

Table 1: The geographical coordinates of Bouzareah

Longitude (°)	Latitude (°)	Elevation from sea (m)
3.02	36.79	304

5. Technical study

5.1 Modelling of renewable energy sources

The considered hybrid renewable energy system consists of photovoltaic panels (PV), wind turbine, battery banks and diesel generator as shown in Figure1 to maintain the supply and load demand. The energy storage system is based on the battery banks and is charged or discharged according to the satisfaction of the load demand compared to the energy produced by the wind and PV based on a dispatch strategy given in the following. In case of the load demand is not satisfied by the power of other units, the diesel generator is used as a back-up power supply. A modeling of each component of the hybrid system is presented, in order to predict and evaluate the performance of the system to meet the load demand.

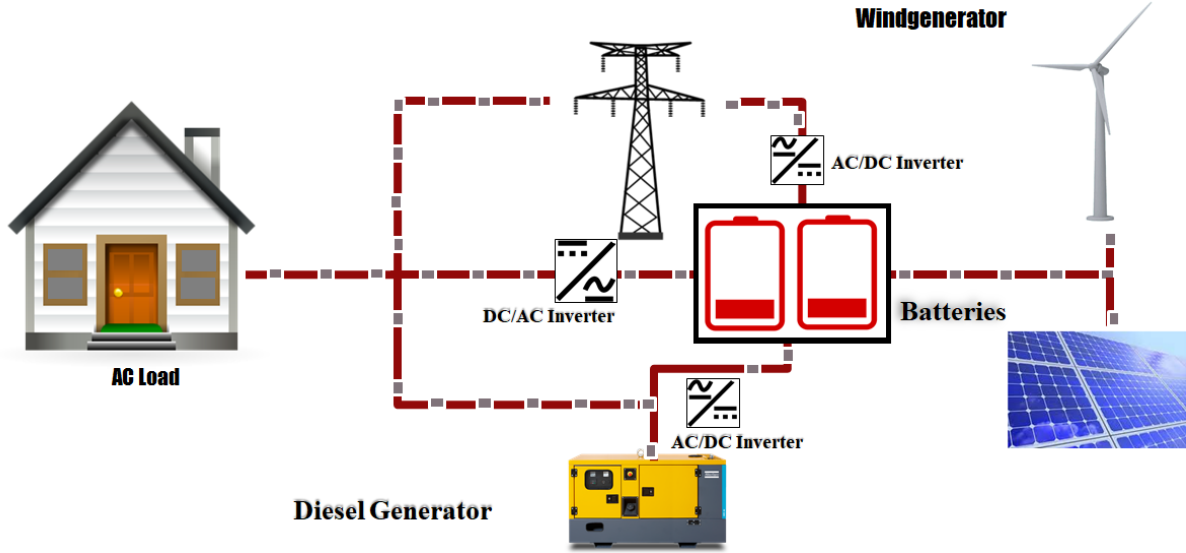


Fig 1. Schematic diagram of the proposed system

5.1.1 Modeling of photovoltaic system

The output power of the PV array is calculated as a function of the solar radiation and temperature as shown in the following [3, 14]:

$$P_{1pv}(t) = P_{mpv} \left(\frac{G_T(t)}{G_{T,STC}} \right) [1 + \alpha_p (T_c(t) - T_{c,STC})] \quad (1)$$

Where P_{mpv} is the rating of the PV module (%), $G_T(t)$ is the solar radiation incident at time t (kW/m^2), $G_{T,STC}$ is the incident radiation at standard conditions (1000 W/m^2), α_p is the temperature coefficient of power ($\%/^{\circ}\text{C}$), $T_{c,STC}$ is the ambient temperature at standard condition ($^{\circ}\text{C}$) and $T_c(t)$ is the PV cell temperature ($^{\circ}\text{C}$) at time t which can be calculated by the following approximate expression [42]:

$$T_c(t) = T_a(t) + \frac{NOCT-20}{800} G_T(t) \quad (2)$$

where $T_a(t)$ is the ambient temperature ($^{\circ}\text{C}$) at time t and $NOCT$ is the Nominal Operating Cell Temperature defined as the temperature reached by open circuited cells in a module under specific conditions, where the best module operated at a $NOCT$ of 33°C , the worst at 58°C and the typical module at 48°C respectively [43].

The rating of the PV module, P_{mpv} is related to the maximum output voltage V_{mpv} and to the maximum output current, I_{mpv} , as indicated in the following equation [10]:

$$P_{mpv} = V_{mpv} * I_{mpv} \quad (3)$$

Furthermore, the power generated from PV generator composed by N_{pv} panels is given by:

$$P_{pv}(t) = N_{pv} * P_{1pv}(t) \quad (4)$$

Where N_{pv} is the number of the PV module.

5.1.2 Modeling of wind energy system

The output of the wind generator is calculated in a two-step process. In the first step, the wind speed at the hub height of the wind generator is the ratio of the wind speed at hub height to the wind speed at anemometer height and is given by the following equation [3]:

$$\frac{V(H_m)}{V(H)} = \frac{\ln\left(\frac{H_m}{A}\right)}{\ln\left(\frac{H}{A}\right)} \quad (5)$$

in which H is the hub height of the wind turbine (m), H_m is the anemometer height (m), $V(H)$ is the wind speed at the hub height of the wind turbine (m/s), $V(H_m)$ is the wind speed at anemometer height (m/s) and A is the surface roughness length, which is a parameter that characterizes the roughness of the surrounding terrain, where the representative surface roughness lengths (m) as given in [44].

In the second step, the whisper 200 windgenerator, that is a three-blade horizontal axis wind turbine with three-phase permanent magnet synchronous generator (PMSG), is used. Its mathematical model from the wind generator power curve produced by the manufacturer equation was approximated by polynomial regression as follows [45]:.

$$P_{1w}(t) = \begin{cases} 0, & v < v_{in} \\ a_1 v^7 + a_2 v^6 + a_3 v^5 + a_4 v^4 + a_5 v^3 + a_6 v^2 + a_7 v + a_8, & v_{in} \leq v \leq v_{out} \\ 0, & v > v_{out} \end{cases} \quad (6)$$

where, v , v_{in} and v_{out} are the wind speed, the cut in speed and the cut out speed (m/s) respectively, while the coefficient, a_i for $i = 1, \dots, 8$ of the characteristic equation are given in [45]. Therefore, the energy generated by the wind generator system, $P_w(t)$ is represented by Equation (7):

$$P_w(t) = N_w P_{1w}(t) \Delta t \quad (7)$$

where N_w is the number of wind turbines.

5.1.3 Modeling of Battery storage

The principal function of a battery in a renewable energy system is to provide power when other generating sources are unavailable.

In charging state, the generated power exceeds the load demand. Subsequently availability of power in the battery bank at time t , $P_{Bat}(t)$ is expressed by the equation given below:

$$P_{Bat}(t) = P_{Bat}(t-1) + \left[(P_{PV}(t) + P_w(t)) - \frac{P_L(t)}{\eta_{inv}} \right] \eta_B \quad (8)$$

where, P_L is the load demand, η_{inv} the efficiency of the inverter and η_B is the battery bank efficiency. While in discharging state, the generated power fails to meet the load demand. Subsequently availability of power in the battery bank at time t , $P_{pBat}(t)$ is expressed as

follows:

$$P_{pBat}(t) = P_{pBat}(t - 1) + \left[(P_{PV}(t) + P_w(t)) - \frac{P_L(t)}{\eta_{inv}} \right] \quad (9)$$

5.1.4 Modeling of Bi-directional converter

Power converter converts the DC electricity from sources such as batteries or fuel cells to AC electricity and vice versa. The output power of PV panels, wind generator and batteries are DC thus to meet the AC load demand, inverters are required. The size of an inverter is chosen according to peak AC load demand, P_{pl} . Therefore, the rated power of the inverter, P_{inv} , can be calculated as follows:

$$P_{inv} = \frac{P_{pl}}{\eta_{inv}} \quad (10)$$

A rectifier converts AC electricity to DC electricity.

5.1.5 Modeling of Diesel generator

The expressions for determining the diesel generator fuel consumption, is presented by the following expression [46]:

$$P_{GD} = 0.04155 Q_{fuel}^2 + 4.2 Q_{fuel} \quad (11)$$

Where

P_{GD} : is the power supplied by the diesel generator (kW)

Q_{fuel} is the hourly fuel consumption (l)

5.2 Energy management and objective function

5.2.1. Energy management system

In standalone hybrid system, an efficient energy management system is required to achieve reliability and cost effectiveness of the electricity generated.

In this study, the type of load demands is AC, to be satisfied by the hybrid system. The difference between power generation and load demand at any time can be calculated as:

$$\Delta P(t) = \left[(P_{PV}(t) + P_w(t)) - \frac{P_L(t)}{\eta_{inv}} \right] \eta_B \quad (12)$$

Case 1: if $\Delta P(t) > 0$, then the remaining power $\Delta P(t)$ is fed to the batteries as shown in Eq.(13):

$$P_{Bat}(t) = P_{Bat}(t - 1) + \Delta P(t) \quad (13)$$

If the power fed to the batteries is greater than the rating of batteries ($P_{max} = 80\% P_n$), where P_n is the nominal power, then, $P_{Bat}(t) = P_{max}$ and the remaining power is treated as excess electricity which is calculated as follows:

$$P_{ex}(t) = \Delta P(t) - P_{max} \quad (14)$$

This energy can be given to some dump load or no auxiliary load and other energy storage

devices.

Case 2: if $\Delta P(t) = 0$, then there is no power exchange and the total demand is met by the solar and wind generation.

Case 3: if $\Delta P(t) < 0$, then the required power $P_{pBat}(t)$ is provided by the batteries, as given by equation (9) above.

Thus,

$$P_{Bat}(t) = P_{Bat}(t-1) - P_{pBat}(t) \quad (15)$$

If power fed to the batteries is less than the rating of these latter ($P_{min} = 30\% P_n$) then, the unmated load will be equal to: $P_{def}(t) = P_{pBat}(t)$.

The unmated load must be zero to ensure that the total load is served reliably. So, a given level of unmet demand is the Loss of Power Supply Probability $LPSP$. Mathematically, $LPSP$ is calculated as follows:

$$LPSP = \frac{\sum_{t=1}^{8760} P_{def}(t)}{\sum_{t=1}^{8760} P_L(t)} \quad (16)$$

In order to solve the optimal sizing problem, the $LPSP$ can be maintained in specific tolerance band: $0\% \leq LPSP \leq 1\%$.

5.2.2 Objective function and constraints

The power exchange between different components and batteries storage management, while minimizing CoE of the overall proposed system and satisfying the load demand completely and at the same time satisfying the system constraints, is the main objective function of this work. For analyzing the studied system, cost optimization is performed on the basis of CoE, which is defined as the ratio of the Total Annualized Costs (TAC) and the annual energy produced by the system ($P_{gen}(t)$). The CoE is calculated as follow:

$$CoE(\$/kWh) = \frac{TAC(\$)}{\sum_{t=1}^{8760} P_{gen}(t)} \quad (17)$$

where, $P_{gen}(t) = P_{pv}(t) + P_w(t)$. The Total Annualized Costs (TAC) of the hybrid system contains, the annualized capital cost (C_{CAP}), the annualized maintenance cost (C_{MAN}) and the annualized replacement cost (C_{REP}) of each system component over the project lifetime, as follows:

$$TAC = C_{CAP} * CRF + C_{MAN} + C_{REP} \quad (18)$$

In which, CRF is the capital recovery cost which depends on annual interest rate i and lifetime of the project lf , it can be expressed by:

$$CRF = \frac{i(1+i)^{lf}}{i(1+i)^{lf}-1} \quad (19)$$

and

$$C_{CAP} = N_{pv} * C_{Cpv} + N_w * C_{Cw} + N_{bat} * C_{Cbat} + P_{inv} * C_{Cinv} \quad (20)$$

Where, C_{Cpv} , C_{Cw} , C_{Cbat} and C_{Cinv} are the capital cost of, PV panels (per kW), wind turbines (per kW), batteries (per Ah) and inverter (per kW), respectively, N_{bat} the number of batteries and P_{inv} the rating of the inverter.

It should be noted that the lifespan of the wind turbines and PV panels are close to the project life, in our case it is about 20 years, therefore they have a replacement cost of zeros. Whereas, the batteries and converter must be replaced several times during the project, hence a non-zeros maintenance cost. Therefore, the maintenance cost is given by:

$$C_{MAN} = N_{pv} * C_{Mpv} + N_w * C_{Mw} \quad (21)$$

with, C_{Mpv} and C_{Mw} the maintenance cost of the PV panels (per kW) and wind turbines (per kW), respectively. While the replacement cost is given by:

$$C_{REP} = N_{bat} * C_{Rbat} + P_{inv} * C_{Rinv} \quad (22)$$

In which, C_{Rbat} and C_{Rinv} are respectively, the maintenance cost of batteries (per Ah) and inverter (per kW).

The objective function CoE_r is subjected to two operational constraints, namely, Loss of Power Supply Probability $LPSP$ and energy storage capacity. As mentioned before, the $LPSP$ can be maintained in specific tolerance band between 0 and 1%, $LPSP$ is equal to 0, when the load is permanently fulfilled, while when the load is never fulfilled, the $LPSP$ is equal to 1. In this paper, the $LPSP$ is assumed to be 0. The energy power flow through the storage system must meet the second operational constraint given by the following equation,

$$P_{min} \leq P_B \leq P_{max} \quad (23)$$

P_{max} denotes the highest power amount of storage system, it takes the value of the total nominal capacity of the battery (C_{bat}), while P_{min} refers to the lowest power amount of the storage system which can be assumed as, using Eq. (24)

$$P_{min} = (1 - DOD) * C_{bat} \quad (24)$$

in which the DOD is the maximum Depth Of Discharge. In our study, the DOD is such as to have maximum battery lifespan, which is guaranteed for a DOD between 30 and 50%.

In addition, some other feasible constraints related to the number of each component of the hybrid system are considered as follows:

$$\begin{aligned} 0 &\leq N_{pv} \leq N_{pv}^{max} \\ 0 &\leq N_w \leq N_w^{max} \\ 0 &\leq N_B \leq N_B^{max} \end{aligned}$$

Where, N_{pv}^{max} , N_w^{max} and N_B^{max} are the maximum, number of PV panels, wind generator and batteries respectively.

5.3 Materials and methods

This paper focus on the optimal design of a hybrid PV / wind /Diesel/ batteries system to ensure generating energy with minimum cost, maximum reliability and high efficiency. Since the optimal design problem of the cited system is presented as a nonlinear optimization problem, for this reason, we used three metaheuristic optimizations, namely, Cuckoo Search algorithm, BAT algorithm and Firefly algorithm, they are iterative stochastic algorithms inspired by nature, which aim to determine a global optimum. In addition, we present the considered HOMER software.

5.3.1 Cuckoo Search algorithm (CS)

The first considered meta-heuristic optimization algorithm in this study is the Cuckoo Search algorithm, inspired by the parasitism of cuckoo birds by laying their eggs in the nests of other birds, other species, it was developed by Yang and Deb [25]. The Cuckoo Search CS method relies on the aggressive cuckoo breeding strategy supplemented by a behavior called Levy's flights. In the Levy flight distribution, birds search for food in a random or quasi-random fashion, and essentially follow a random walk because the next step is based on the current position and the probability of transitioning to the next state. The Cuckoo Search algorithm aims at breeding high quality solutions for the near optimization problem. The steps of the Cuckoo Search algorithm are summarized in the flowchart below:

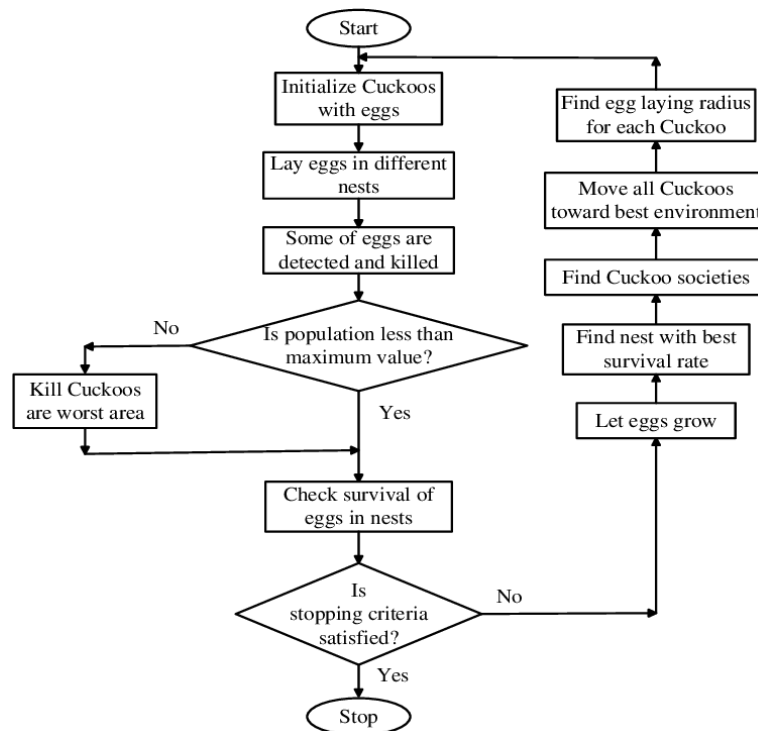


Fig 2: Flowchart of Cuckoo Search algorithm [25] & [47]

5.3.2 BAT algorithm (BAT)

The BAT algorithm is one of the promising meta-heuristics optimization algorithm proposed

by Yang [26]. It is based on the simulation of the echolocation behavior of bats. The ability of echolocation is fascinating as these bats can find their prey and discriminate between different types of insects, even in complete darkness. They achieve this by emitting sound signals to the environment and listening to the echoes that return to them. They can identify the location of other objects and instinctively measure how far they are away by delaying the return of sound. The standard BAT algorithm has many advantages; one of them is that it can achieve rapid convergence in the initial stages by moving from exploration to exploitation. This makes it an efficient algorithm when a quick fix is needed. The steps of the Bat algorithm [14] are summarized in the flowchart below:

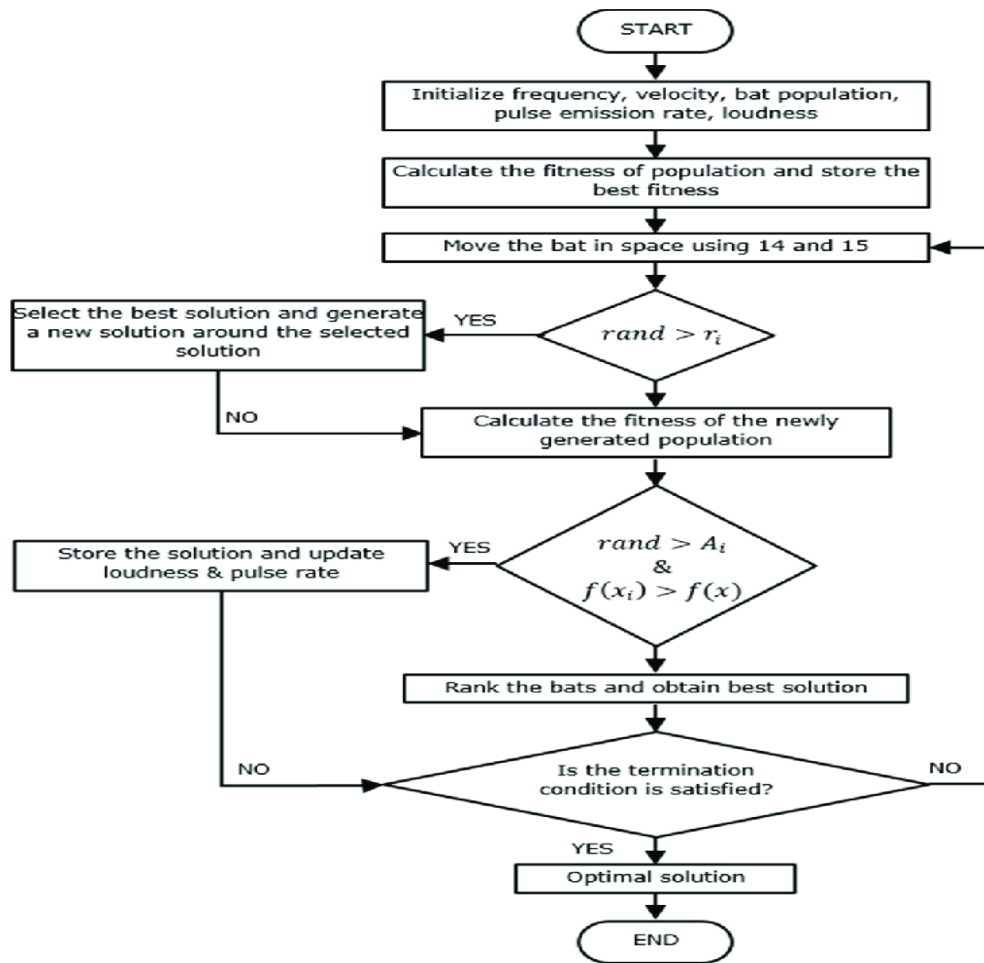


Fig 3: Flowchart of the Bat algorithm [14]

5.3.3 Firefly algorithm (FA)

The last meta-heuristic optimization algorithm considered is the Firefly algorithm, introduced by Yang [24]. The method is based on the principle of attraction between fireflies and simulates the behavior of a swarm of fireflies in nature, which gives it many similarities with other meta-heuristics based on the collective intelligence of the group. In this algorithm, fireflies move through the solution space. Each firefly emits a blink, the intensity of which is directly related to the quality of the solution it represents (objective function). At each iteration, the fireflies

perceive the other fireflies and the amount of light they emit. Each firefly compares its light intensity to that of the others. When it finds another firefly with a stronger light intensity, it moves in its direction. This displacement depends on the attractiveness of the target, which is calculated according to the intensity of the target position and the distance to it. The process is repeated for all the fireflies as many times as necessary. The Firefly algorithm [28] takes into consideration the following important points as shown in the Figure 4 below:

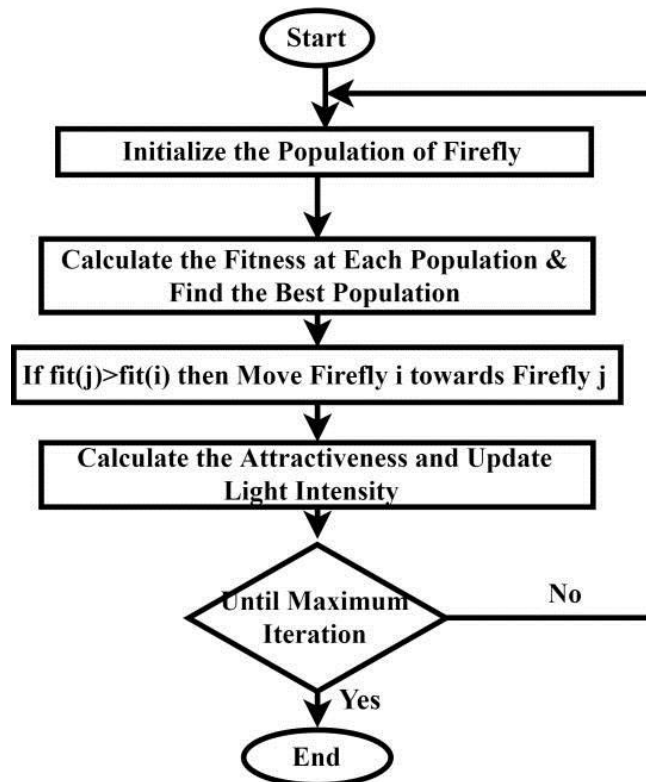


Fig 4: Flowchart of the Firefly algorithm [28]

5.3.4 HOMER software

HOMER (Hybrid Optimization Model of Electric Renewable) is one of the most widely used tool for designing hybrid systems. It was developed by the National Renewable Energy Laboratory (NREL) in 1993. HOMER calculates and ranks the possible hybrid system combinations in descending order of their Net Present Cost (NPC). However, the solutions obtained are not necessarily really optimal, but in fact correspond to the best solutions found among a set of combinations of parameters initially entered by the user. The disadvantages of the HOMER software are that the precision of the solutions is low because of the linear mathematical modeling of the components and without a correction factor, moreover the dimensioning of the components of the hybrid system supposes many simplifications during the optimization procedure, which impacts the accuracy of the results. The HOMER software uses the genetic algorithm to evaluate different scenarios and to determine the configuration of the system with acceptable reliability and the lowest life cycle cost. Therefore, when creating a

power system, it is necessary to make many decisions about system configuration such as:

- The most judicious components to be included in the design of the system;
- The size and number of each component.

After inputting the solar/wind resources for a year as well as the equipment cost, HOMER uses the data to give us the optimal sizing of the hybrid system based on economics and availability of resources [30] in three stages, which are simulation, optimization and sensitivity analysis.

5.3 Simulation results and discussion

Knowledge of energy consumption is an essential element in the study of hybrid energy system sizing (PV / wind /Diesel/ batteries). This can be obtained by estimating housing needs or by actually acquiring data. The energy consumption of a house depends on two essential parameters, the lifestyle of the inhabitants and the weather conditions of the considered site. Lights are usually, turned on at night and when the interior is dark. It is therefore linked to sunset and sunrise, to the activities of the inhabitants and to their possible presence during the day. In the present study, a typical charging system for a residential site in Bouzaréah with a typical single residential charge is considered for the present analysis case, in which the charge profile is the same for all days of the year.

Figures 5a and 5b show, respectively, the daily load profile and the yearly load profile considered in the present study with the day type weekdays. From Figure 5(a), the load demand has a peak of 0.7 kW at 19 pm and 20 pm and Figure 5(b) shows the electric AC load demand throughout the year with the average of 1105 kWh/year with also an average peak of 0.7 kW

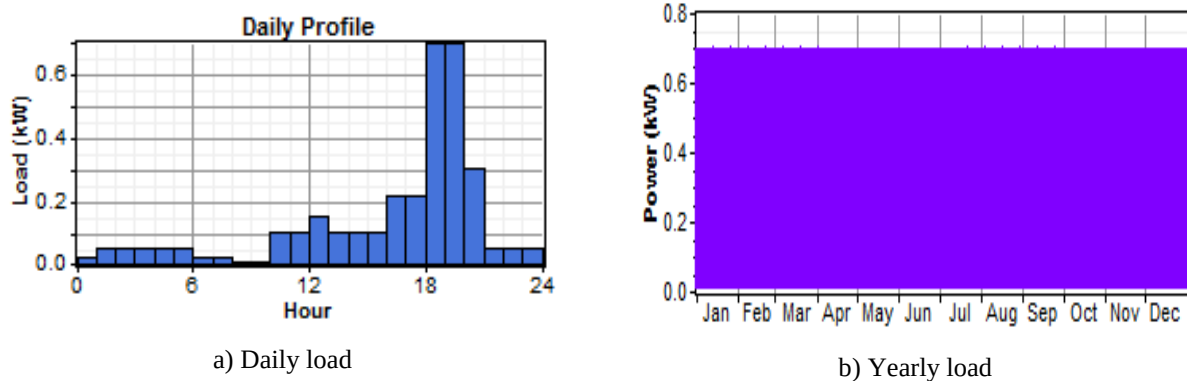


Fig 5. Daily load profile and Yearly load profile

Figure 6 represents the global and incident solar radiation, ambient temperature and wind speed at 36.8° N data recorder for every hour during 1 year, respectively. It is clear from Figure 6 that the hourly profiles of the hybrid system component appear to be good, with an average annual solar irradiation of 0.2966 kWh/m²/day and temperature of 16.9005 C°, while the average annual wind speed is about 4.7520 m/s.

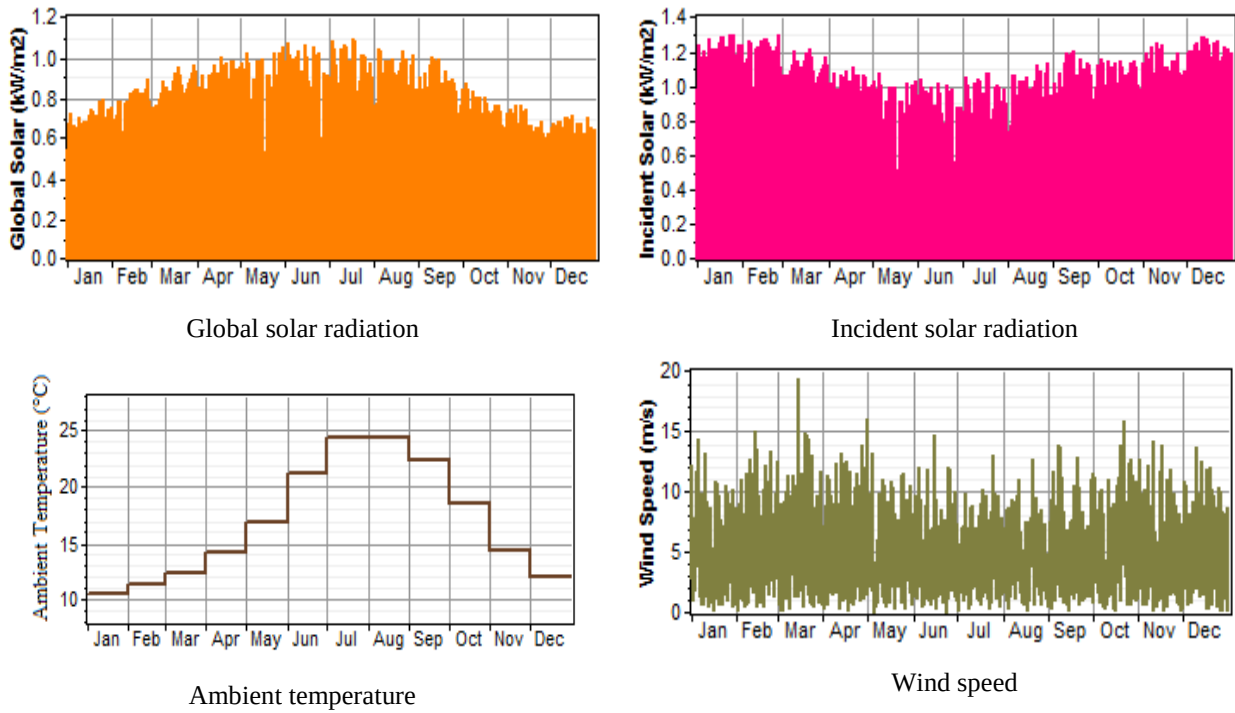


Fig 6. Yearly data of Global Solar Radiation, Incident Solar Radiation, Ambient Temperature and Wind Speed.

The technical and economical specifications of the components used in the system are listed in Table 2. The lifetime of the project was taken as 20 years with a rate of 6%.

Table 2. System component specifications

Parameter	Value/Unit	Parameter	Value/Unit
PV panel Isoltech STH -215-P		Inverter	
Maximum power (P_{max})	213.15 W	Rated Power	1000 W
Maximum power voltage (V_{mp})	29 V	Life time	20 Years
Maximum power current (I_{mp})	7.35 A	Efficiency	90 %
Open circuit voltage (V_{oc})	36.3 V	Capital and replacement cost	1293 \$ per kW
Short circuit current (I_{sc})	7.84 A	O&M cost	10 \$ per kW
Number of cells	60		
Nominal operating cell temperature	313.399°C		
Parallel resistance (R_{sh})	0.39383 Ω		
Series resistance (R_s)	2000 Ω		
Capital and replacement cost	\$ per kW		
O&M cost	10 \$ per kW		
Life time	20 Years		

Table 2. System component specifications (continued)

Wind generator		Whisper 200	Diesel Generator	
Rated Power		1 kW	Rated power	1 kVA
Rated wind speed		11.6 m/s	Life time Operating hours)	15000 hours
kWh/month		200 kWh/month	Minimum load ratio	10
Voltage		24,36 & 48 V	Capital and replacement cost	3700 \$ per kW
Cut-in wind speed		3.5 m/s	O&M cost	0.3 \$ per kW
Cut-out wind speed		24 m/s		
Rotor diameter		1.7 m		
Hub Height		25 m		
Lifetime		20 Years		
Capital and replacement cost		3000 \$ per kW		
O&M cost		1 \$ per kW		
Batteries			Others	
Voltage per string		2 V	Annual real interest rate	6 %
Lifetime throughput		680 kWh	Project lifetime	20 Years
Nominal capacity		200 Ah		
Capital and replacement cost		227 \$ per kW		
O&M cost		2.2 \$ per kW		

The algorithms are run for a maximum number of iterations of 100. Table 3 summarizes the comparison of optimization results of the proposed hybrid system by the CS, BA, FA and HOMER software. It is observed from the obtained results that the proposed hybrid system has CoE of 0.4276 \$/kWh by CS, BAT and FA and 0.773 \$/kWh by HOMER.

Table 3. Optimal sizing result for the proposed system obtained by the different algorithms and HOMER

Methods	Optimization results	N _{pv}	N _w	N _{batt}	Inv	COE(\$/kWh)
CS/BAT/FA		1	1	12	1	0.4276
HOMER		1	1	12	1	0.773

Table 4 illustrates the energy production and the consumption during a complete year. The produced energy from wind generator is around 95 % and 92 % of the total energy produced for CS, BAT, FA algorithms and HOMER, respectively, while the energy produced by photovoltaic panels is 8%. It is also indicated from Table 4 that the total load demand is 1141 kWh/year and 1193 kWh/year, where the excess electricity is 47% and 50% respectively, for CS, BAT, FA and HOMER.

Table 4. Energy production and consumption during a complete year

Energy Production		HOMER	%	CS/BAT/FA	%
Wind (kWh/year)		2366,77	92	2439.81	95
PV (kWh/year)		197.88	8	212.19	8
Total (kWh/year)		2564.06	100	2652	100

Energy Consumption		Excess Electricity			
HOMER	CS/BAT/FA	HOMER	%	CS/BAT/FA	%
(kWh/year)	(kWh/year)	(kWh/year)		(kWh/year)	
1141	1193	1217	47.5	1458	50

Figure 7 (a, b and c) presents the variation of iteration number versus PV/WT/Bat system cost of energy for each algorithm and the convergence history of the best (min), worst (max) and mean solution values. As can be seen from figure 7.a, the best solution of CS algorithm (CoE = 0.4276\$/kWh) is obtained after 3, 70 and 25 iterations for min, max and mean values respectively. So, for Firefly algorithm the best solution is obtained after 2, 100 and more than 100 iterations (Figure 7.b) respectively for min, max and mean values. Thus, the same best solutions of this system and for the BAT algorithm (Figure 7.c) are obtained respectively after 5, 30 and 22 iterations for min, max and mean values. Hence, the BAT algorithm is better than the other optimization algorithms, in terms of convergence speed.

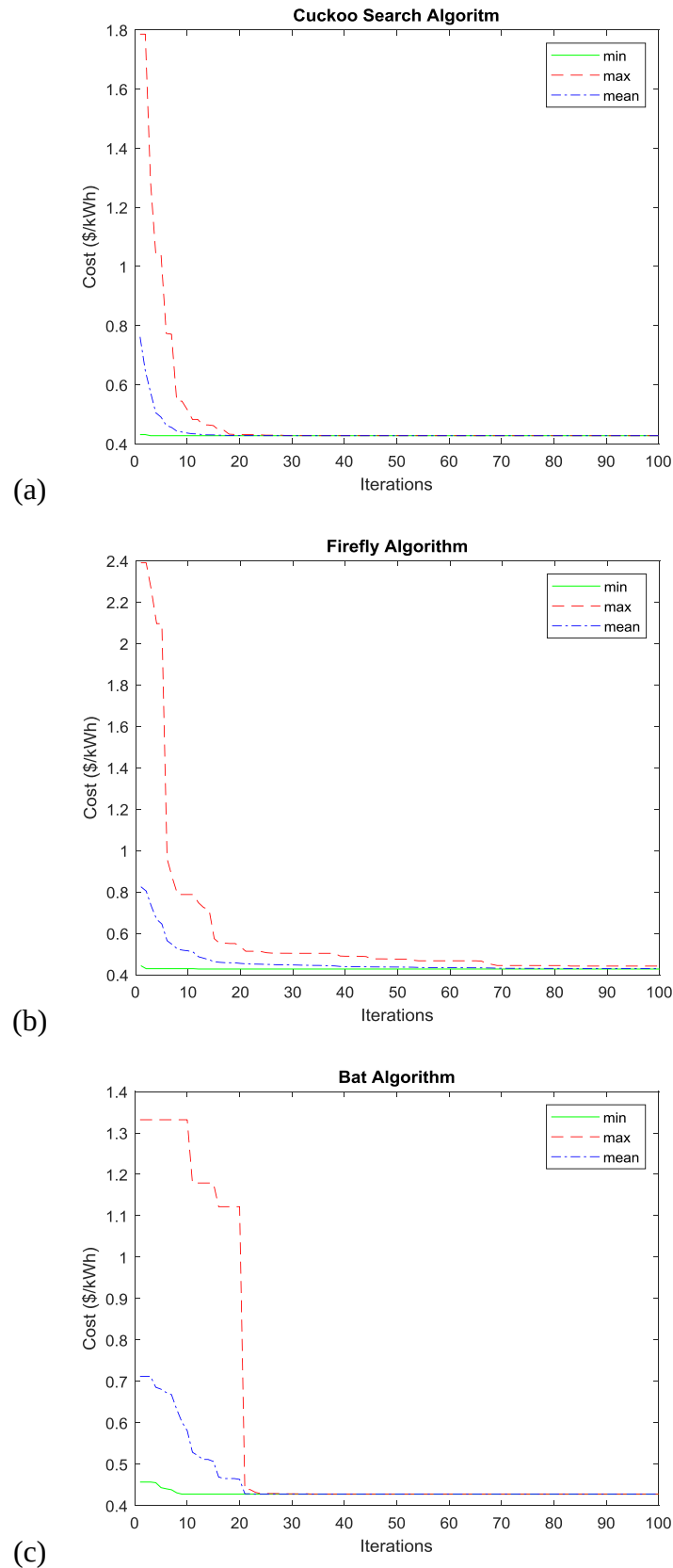


Fig 7. The variation of iteration number versus PV/WT/Bat system

Figure 8.a presents the convergence process of the PV/W/Batt system using the three optimization algorithms. As can be seen, the CS method achieves less cost than FA and BAT algorithms and, in other words, converges to a smaller amount of CoE. In addition, the

convergence speed of the CS algorithm is desirable compared to the other optimization algorithms. Thus, the best solutions of the PV/Batt system and W/Batt system are respectively, 0.4354 \$/kWh after 20, 20 and 100 iterations and 0.4564 \$/kWh after 47, 18 and more than 100 iterations (Figure 8(b and c)) for the CS, FA and BAT algorithm, respectively. However, for the PV/Batt system, the convergence process represented by Figure 8(b), the CS algorithm achieves less cost followed by the BAT and the FA algorithm, which always takes longer time. As can be seen from Figure 8c, representing the process of convergence of the W / Batt system, while still using the three optimizations algorithms, it is rather the BAT algorithm, which achieves a lower cost compared to the algorithms CS and FA, with a small difference between the first two, namely the BAT and CS (18 and 23, respectively). Furthermore, in all cases, the execution time is faster for the BAT algorithm compared to the other two considered optimization algorithms.

6. Conclusion

This paper presents a wind-solar-diesel system with battery storage element to fulfill the electrical load demand of a small area. For optimal sizing of components, this study uses: The Cuckoo Search algorithm (CS), the Firefly algorithm (FA) and the BAT algorithm (BAT) to verify the strength of the proposed technique, the results are compared with those obtained from the standard software tool, hybrid optimization model for electric renewable (HOMER), unlike the previous works on intelligent optimal sizing methods which all consider only one to two optimization algorithms. The proposed objective function takes into account two optimization criteria: loss of power supply probability (LPSP) and system cost based on the unit electricity cost (CoE). For this aim, all the considered system components are modeled and an objective function based on the CoE is defined. This study is applied to a household situated in Bouzareah, Algiers, Algeria (Altitude: 314 meters, Latitude: 36° 8' N and Longitude: 03° 02' E). It has been verified from the results that for:

- The obtained CoE of the proposed hybrid system (PV/WT/Bat system) is 0.4276 \$/kWh by CS, BAT and FA algorithms and 0.773 \$/kWh by HOMER.
- The variation of iteration number versus PV/WT/Bat system cost of energy for each algorithm and the convergence history of the best (min), worst (max) and mean solution values indicated that the BAT algorithm is better than the other optimization algorithms, in terms of convergence speed.
- The convergence process of the PV/W/Bat and the PV/ Batt system using the three optimization algorithms indicated that the CS method achieves less cost (smaller amount of CoE) than FA and BAT algorithms. Therefore, for the W / Batt system, while

still using the three optimization algorithms, it is rather the BAT algorithm, which achieves a lower cost compared to the CS and FA algorithms.

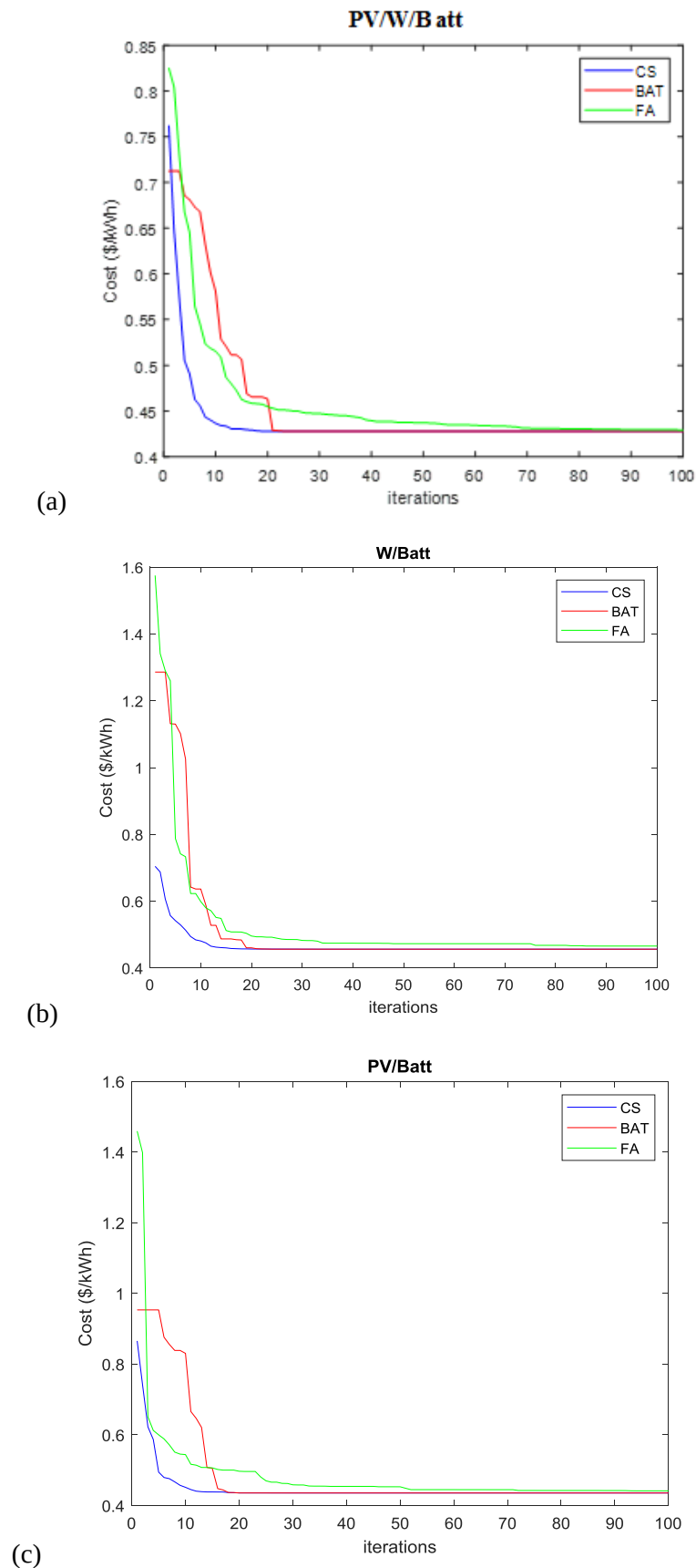


Fig 8. The convergence characteristics of the CS, BAT and FA algorithms

Furthermore, in all cases, the execution time is faster for the BAT algorithm compared to the other two considered optimization algorithms.

Also, it can be concluded that the PV/W/Batt system has the less CoE after the PV/Batt system, rather than W/Batt system. This is due to the fact that this system depends on the climate conditions of the studied region (Bouzareah) characterized by a high potential of solar radiation and suitable wind potential. Consequently, this work will contribute to enriching the PV/W/Batt system feasibility for the Mediterranean climatic region and especially for northern Algeria.

7. References

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APPENDIX

Table A1: Legislative framework to promote renewable energy (RE) in Algeria

Law No. 99-09 (28-6-1999) 	Define the contours of energy management policy
Law No. 99-11 (2000 Finance Bill) 	Creating the National Fund for Energy Management (NFEM) and determining its Functions
Law No. 09-09 on the Finance Bill 2010 	Provides the regulatory basis to create the National Fund for Renewable Energy and its functions. Determines financial resources (0.5% of oil royalties).
Executive Decree No. 	Provides the regulatory basis to create the National 11-423 (8–12) Fund for Renewable Energies and Cogeneration and December 2011 its functions.

Executive Decree No. 13-218 (18-6-2013) & Decree No 17-166 (22-5-2017)	➡	Closing the National Fund for Energy Management and transferring of its operations to the National Fund Executive. for Renewable Energies and Cogeneration.
Law No. 14-10 2015	➡	Closing the National Fund for Energy Management and transferring of its operations to the National Fund for Renewable Energies and Cogeneration Finance Bill
Ministerial decision (2-2-2014)	➡	Determines the guaranteed purchase rates related to electricity generation from solar photovoltaic
Executive Decree No. 17-98 (26-2-2017) & Executive Decree No. 17-204 (22-6-2017)	➡	Define the legal procedures for tendering to produce RE and cogeneration, and their integration into the national
