Multi-Objective MPSO/GA Optimization of an Autonomous PV-Wind Hybrid Energy System

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Abstract-This article presents a study of the optimal sizing of an autonomous hybrid energy system (PV-wind-battery) as a power source for a typical household in an isolated village in Adrar, Algeria using the multi-objective Particle Swarm Optimization (MPSO) algorithm and Genetic Algorithm (GA). This study presents a new approach to obtain an optimal configuration and sizing of the main components integrated into the autonomous hybrid system (PV/wind) which meets the requirements of the desired system. In the first phase, the reliability criterion (LPSP) is met with the lowest Energy Cost (EC) value (min Total Net Present Cost (TNPC)). The required storage bank must have a low rate of aging in order to extend the battery life, which contributes to the reduction of the overall cost of the system.

Keywords-autonomous hybrid system; optimization and sizing (PV/wind); minimum energy cost; TRNSYS

I. INTRODUCTION

Many isolated sites are powered by autonomous electricity generation systems, using local renewable sources, such as photovoltaic (PV) panels, wind turbines, and micro turbines. Electricity from renewable sources is intermittent, dependent on weather conditions. These renewable generators are coupled to a storage system ensuring the continuous availability of energy. The renewable generators selected for our study is a hybrid system (PV/wind) with storage. Generally, the storage is ensured by batteries which currently consist one of the most used solutions. The batteries have very good yields, around 80-85%, and have a very competitive price, if we consider lead technology. The optimization of these systems is based on sizing criteria, maximizing the power generated to have a good yield and cost minimization. Knowing that the main research goal is the overall improvement of the performance of PV and wind conversion systems, the equivalence between the admissible efficiency and the average operating cost determines the degree of efficiency of use of these systems. Several criteria for optimizing the efficiency of hybrid systems (PV/wind) as well as techniques have been applied in order to have a good adaptation and a high efficiency.

Authors in [1] recommended an optimal design model for the design of hybrid solar-wind-battery systems for powering a telecommunication relay station. To assess the optimal system configuration and ensure that the annualized cost of the system is minimized while satisfying the probability of loss of required power. The five decision variables for Loss of Power Supply Probability (LPSP) included in the optimization process are the PV module number, PV module slope angle, wind turbine number, installation height of the wind turbine, and battery capacity. An iterative method to determine the optimal dimensioning of autonomous photovoltaic (PV-battery) is proposed in [2, 4], linear programming is used in [3] to design and optimize the components of a hybrid system (PV/wind/micro-hydro) which minimize the size and initial cost. A new approach to designing an autonomous hybrid wind PV/battery system is proposed in [5] taking into account both economic and ecological aspects. A technical-economic analysis of the complete study of the hybrid system (PV/diesel generator/battery) was done by the authors in [6] to minimize the cost and meet charging requirements and the optimal tilt angle of the PV panel in order to increase the energy generated by the use of a genetic algorithm. In [7], feasibility study and techno-economic evaluation of an autonomous hybrid system (PV/wind) with battery energy storage for a remote island were conducted using the HOMER software to obtain an optimal configuration of the autonomous system in terms of energy cost (COE) and system Net Present Cost (NPC). An iterative approach following the Total Energy Deficit (TED), the Total NPC (TNPC), and EC was developed in [8] to size the components of an autonomous hybrid system (PV/wind/diesel/battery) to satisfy the charge demand in a more cost-effective manner. An iterative optimization technique was used in [9] to determine the optimal configuration of an autonomous system (PV/wind/hydrogen) supplying a desalination unit which would guarantee a reliable energy supply with the lowest initial investment cost for any site. Optimal sizing and techno-economic evaluation of the pumped storage-based PV power generation system was presented in [10] to maximize power supply reliability and minimize lifecycle cost. The Pigeon Inspired Optimization (PIO) algorithm was used for optimization sizing of a PV-wind hybrid power system in [11]. Several thermal insulation solutions have been proposed [12-14] in order to ensure excellent thermal comfort of a home and to minimize energy needs while improving energy efficiency.

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This paper presents a comprehensive and integrated study divided into two phases.

At first, a study of the optimal sizing of an autonomous hybrid energy system (PV/wind/battery) as a power source for a typical Algerian village household is conducted using MPSO and GA. This work relates to the development of a technical and economic analysis and evaluation methodology carried out for a hybrid system (PV/wind). The results are compared and discussed. Our study is based on two models: the reliability model developed according to the concept of LPSP and the economic model based on TNPC and the battery aging model. In order to achieve our objective, we proposed two essential contributions which are MPSO algorithm and GA. A case study is being investigated for the analysis of an autonomous hybrid system (PV/wind) intended to supply a village of habitats in Adrar Algeria. The simulation results relating to the different system configurations and their corresponding costs are presented. The type of storage used in our system is the lead acid battery.

In the next phase, in order to guarantee the state of health of the storage batteries, we have chosen a configuration which ensures longer battery lifetime and minimum aging rate from a study of its State of Charge (SOC). The application of the Rainflow algorithm allows extracting the number of cycles of the signal with its corresponding depth of discharge. The operating cycles used to study the aging of the battery were based on the battery life given by the manufacturer.

II. MODEL OF THE HYBRID SYSTEM COMPONENTS

The solar/ wind hybrid energy production system consists of a PV generator, a wind turbine, a storage battery bank, AC/DC converters, DC/DC converters, a controller, and cables. In order to predict the performance of the hybrid system, the individual components must first be modeled.

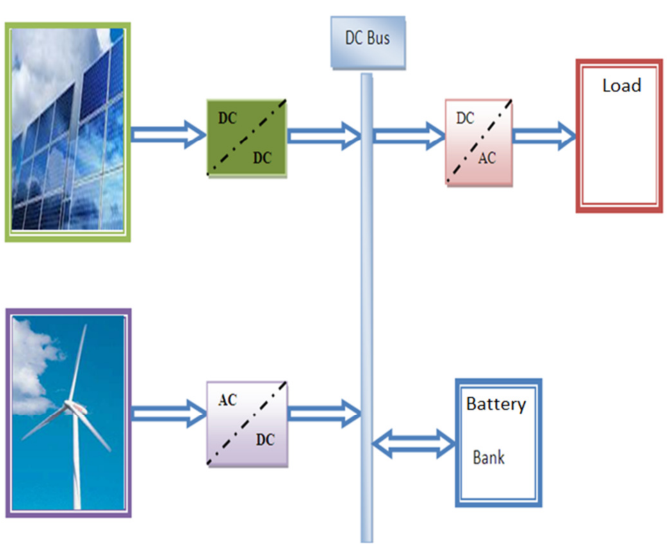

Fig. 1. Block diagram of the hybrid system.

The power delivered by the different energy sources depends on several parameters. For the solar generator, the parameters influencing the power supplied by the generator are: The metrological data of the site: ambient temperature *Ta* and irradiation *Ir* and the A_{pv} surface of the solar panel field.

For the wind generator, the supplied power is influenced by the metrological data of the site: Ambient temperature *Ta* and wind speed ws and the surface swept by the rotor of the wind turbine *Awt*.

A. Modeling of the PV System

The model of the solar generator is given by [5, 15, 17, 18]:

$$P_{pv}[w/m^2] = \eta_G A_{pv} I_r \quad (1)$$

where η_G is the overall efficiency of the generator given by:

$$\eta_G = \eta_r \eta_{pv}[1 - \beta_t(T_c - T_{NOCT})] \quad (2)$$

where η_r is the reference efficiency of the solar generator, η_{pv} is the degradation factor of the solar generator according to its lifetime, β_t is the coefficient of the influence of the temperature of the PV cells on the efficiency of the generator.

The temperature of the junction or the cell of the PV panel is given by:

$$T_C = 30 + 0.075(300 - I_r) + 1.14(T_a - 25) \quad (3)$$

where T_{NOCT} is the nominal operating cell temperature and I_r the irradiation or solar sunshine.

B. Modeling of the Wind Generator

The power model of the wind generator is given by the following expressions [5, 15]:

$$P_{wg} = \tfrac{1}{2} C_p \eta_{gb}\ \eta_g\ \rho\ A_{wt} {w_s}^3 \quad (4)$$

$$P_{wg} = \tfrac{1}{2}\eta_G\ \ \rho\ A_{wt} {w_s}^3 \quad (5)$$

where C_p is the turbine efficiency, η_{gb} is the efficiency of the speed variator (drive controller), η_g the Generator efficiency, $A_{wt}[m^2]$, is the surface swept by the rotor of the turbine, $w_s[m/s]$ the wind speed, $Z[m]$ is the altitude , T_a is the ambient temperature, and ρ [kg/m^3] the air density:

$$\rho = (353.049/T_a).\exp(-0.034(Z/T_a) \quad (6)$$

C. Modeling of the Storage System

The charge-discharge expression of the lead-acid battery is given by the following expression:

$$Soc_{bat} = Soc_{bat}(t-1) +$$

$$\left(E_{pv}(t) * \eta_{dcdc} + E_{wt}(t) * \eta_{acdc} - \frac{E_{ld}}{\eta_{inv}}\right) * \eta_{cha} \quad (7)$$

where $E_{pv}(t)=P_{pv}(t)*\Delta t$, $E_{wt}(t)=P_{wt}(t)*\Delta t$, $E_{ld}(t)=P_{ld}(t)*\Delta t$, and $P_{pv}(t)$, $P_{wt}(t)$, $P_{ld}(t)$ are respectively the PV generator power, the wind generator power, and the load demand in an instant *t*. Δt is the step time of the simulation, η_{inv} is the inverter efficiency, η_{cha} is the battery charging efficiency, which generally depends on the charging current and is between [0.65 and 0.8].

When the load demand is greater than the available generated energy, the battery bank is in discharging state. Thus, the Soc_{bat} at instant *t* can be expressed as:

$$Soc_{bat} = Soc_{bat}(t-1) + \left(E_{pv}(t) * \eta_{dcdc} + E_{wt}(t) * \eta_{acdc} - \frac{E_{Ld}}{\eta_{inv}}\right) * \frac{1}{\eta_{disch}} \quad (8)$$

where η_{disch} is the battery discharging efficiency, it is supposed to be equal to 1. In all cases the state of batteries charging must satisfy the following condition:

$$Soc_{bat\_min} < Soc_{bat}(t) < Soc_{bat\_max}$$

where Soc_{bat_min} and Soc_{bat_max} are the limit states of battery charging. Soc_{bat_max} is considered as the nominal capacity of the storage system:

$$Soc_{bat\_max} = C_{bat\_n}.$$

The inferior limit is given by:

$$SOC_{bat\_min} = DOD * C_{bat\_n}$$

where DOD(%) is the battery Depth Of Discharge [17].

III. Sizing and Optimization Procedure

The developed process was used to calculate the optimum value of the PV module area, the wind turbine, and the optimal battery capacity for a standalone PV/wind hybrid system.

A. Enunciation of the Optimal Sizing Problem

The estimate of the hybrid PV/wind energy/battery size is formulated as an optimization problem where the express of the objective function is according to the constraints and the performances of the system. The objective function and the constraints are detailed in the following subsections.

B. Objective Function

The objective functions of the optimization problem must minimize the total economic cost of the TNPC and EC of the system and to satisfy the energy needs. We are focused on finding the best combination of multiple sources for a hybrid system, i.e. the PV panel surface (A_{pv}), the area swept by wind turbines (A_{wt}) and the nominal storage capacity of the battery bank (C_n).

1) Economic Evaluation

This assessment is based on the concept of the current global net cost: the cumulative cost of a product throughout its life cycle, from the start of its conception until its dismantling. It includes the initial cost (acquisition + installation) of all system components, the cost of all component replacements required during the lifetime of the system, and the cost of maintenance. The lifetime of the system is usually considered to be the lifetime of the element with the longest lifetime. In this article, the economic approach used based on the TNPC and the EC taking into account the lifetime and replacement costs of each element of the system.

2) Total Net Present Cost

The current TNPC in $, can be expressed as follows according to [8]:

$$TNPC(\$) = IC + PW_{crec} + PW_{cnonrec} \quad (9)$$

where *IC* is the initial cost of the system components.

$$IC = C_{ipv} * P_{pv} + C_{iw} * P_w + C_{ibat} + C_{iinv} \quad (10)$$

where C_{ipv} is the initial cost of the photovoltaic system, C_{iw} the initial cost of the wind system, C_{ibat} the initial cost of the storage system, C_{iinv} the initial cost of the inverter. P_{wcrec} and $P_{wcnonrec}$ are factors for the conversion of the recurring and non-recurring costs to their present value, defined by [8]. The component cost assumptions on which we based our calculations are given in Table I [6, 8].

TABLE I. COST OF THE SYSTEM COMPONENTS

Component	Unit price (US$/W)	Maintenance cost during the first year (%)	Life time (years)	Interest rate d (%)
PV array [a]	2.29	1% of price	25	8
Wind turbine [b]	3.00	3% of price	20	
Battery [a]	0.213	1%of price	4	
Inverter [a]	0.711	0%of price	10	

a http://www.solarbuzz.com.

b Mean value of the literature data.

3) Energy Cost ($/kwh)

The cost per kWh of the EC produced in $/KWH can be determined by the ratio of the annualized total cost (TAC) to the annual energy produced by the system [7-9, 15,16]. EC can be calculated according to (11), (12).

$$EC\left(\$/_{kwh}\right) = \frac{TAC}{\sum_{t=1}^{8760} E_{pr}(t)} = \frac{TNPC*CRF}{\sum_{t=1}^{8760} E_{pr}(t)} \quad (11)$$

CRF is the recovery factor, expressed as:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

where *i* is the interest rate and *n* the lifetime of the system in years. For this study, we have assumed an interest rate of 8% and *n* = 20 years.

C. The Constraints

To find solutions for the optimization problem, a set of constraints must be satisfied with any feasible solution throughout the system operations as follows:

The SOC of the battery bank must satisfy the following constraints at any times:

$$Soc_{min} < Soc < Soc_{max}$$

The system's LPSP must be less than the allowed LPSP reliability index:

$$LPSP < LPSP_{index}$$

1) Reliability Estimation According to LPSP

LPSP is defined as the fraction of all energy losses and energy demand in a defined period of operation (in our study we used t = 1year) [16]:

$$LPSP = P_r\{E_{bat} \le E_{bat_{min}}\} = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_l(t)*\Delta t} \quad (13)$$

LPS (Loss of Power Supply) can be calculated with the following relation:

$$LPS(t) = \left(P_l(t) - P_w(t)\right) * \Delta t$$
$$-\left(P_{pv}(t) * \Delta t + C_{bat}(t-1) - SOC_{bat\_min}\right) * \eta_{inv} \quad (14)$$

IV. IMPLEMENTATION OF THE PSO ALGORITHM

PSO is a new evolutionary algorithm, which was originally inspired by the regularity of the cluster activities of birds. Thus, a simplified model using group intelligence was established. PSO is initialized as a set of random particles, each particle having its own position and velocity vectors. The optimal solution is searched for iteratively. In each iteration, the particles update themselves by tracking two "extremes". The first extreme, called *pbest*, is the best solution found by the particle itself. The other extreme, called *gbest*, is the best solution currently found by the entire swarm [21-25]. The position and velocity vectors of each particle can be calculated as:

$$V_i(t+1) = mV_i(t) + (C_1 r_1(pbest_i(t) - X_i(t)) +$$
$$C_2 r_2\left(gbest_i(t) - X_i(t)\right) \quad (15)$$
$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (16)$$
$$m = \frac{2}{2-\varphi-\sqrt{\varphi^2-4\varphi}} \quad (17)$$
$$\varphi = C_1 - C_2 \quad (18)$$
$$\varphi > 4 \quad (19)$$

C_1 and C_2 are the cognitive and social parameters respectively in this study C_1=C_2=1. r_1 and r_2 are random numbers between 0 and 1. In this article, the objective functions are defined as minimum {*EC*, *TNPC*}, under the constraint of inequality, the main program is developed in Matlab.

V. SITE DESCRIPTION

The meteorological data used in this study have been recorded at the New Energy Algeria (NEAL) station installed at the roof top of the Research Unit in Renewable Energies in the Saharan Medium (URERMS) located in Adrar (Figure 2).

Fig. 2. NEAL station.

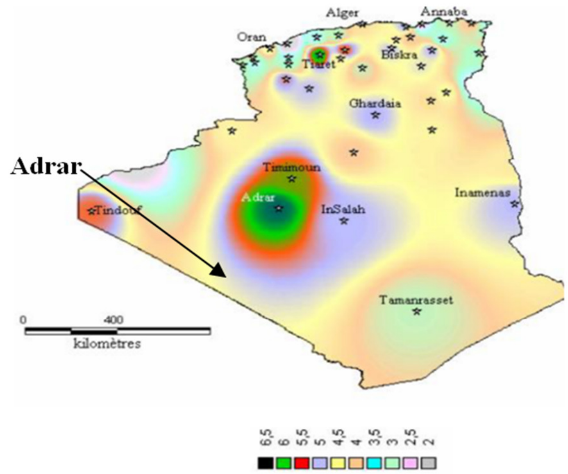

Fig. 3. Algeria wind map.

Adrar is the administrative capital of Adrar Province, the second largest province in Algeria. The commune is sited around an oasis in the Tuat region of Sahara Desert. According to the 2008 census, it has a population of 64,781, with an annual growth rate of 4.0%. Adrar lies at an elevation of 258m above sea level. Its geographical coordinates are 27°52′N, 0°17′W. Adrar has a hot desert climate, with long, hot summers and short, warm winters, and averages just 15mm of rainfall per year. Summer temperatures are consistently high as they commonly approach 40°C. The temperatures at night are still hot at around 27°C. Even in early May or in late September, daytime temperatures can rise up to 45°C. Figure 3 shows the annual wind map.

A. Wind Potential

To evaluate the wind potential of the site, measurements of wind speeds were taken on site during the year 2015, with half hour intervals. Figure 4 shows the wind profile during January.

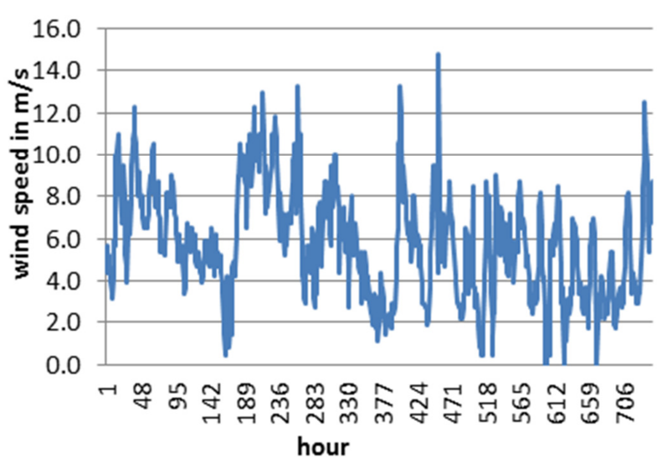

Fig. 4. Wind profile during January, 2015.

B. Solar Potential

Measurements of the solar irradiation were also taken on site, by using the orientation and inclination of the PV modules, the latitude of the place, and the values of the global radiation were calculated. The quantity of the global irradiation received per day for 1m of horizontal surface is indicated, the mean value of the radiation measured every hour of January and July is given in Figure 5.

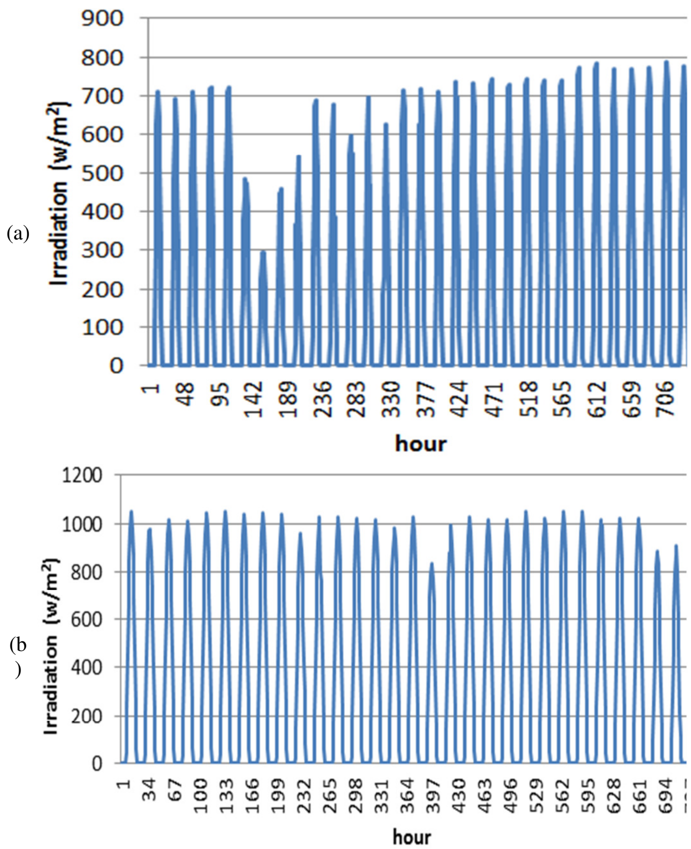

Fig. 5. Global irradiation in (a) January and (b) July.

C. Potential Analysis

The annual solar irradiation profile for the proposed site shows that there is a marked seasonal variation in solar irradiation (greater in summer). The Adrar region has an acceptable wind potential. This feature has led the region to favor initiatives in wind energy generation.

D. Load Profile

The exact identification of the consumer's charge profile will facilitate the determination of the size of our generators. The system under study is supposed to supply a load for domestic use. The power demanded by a particular kind of household is not fixed throughout the year. The time of maximum loading of the energy system by the load varies according to the season as a consequence of the variation of the duration of the day. For our part, we consider that the total load demand for usable electrical energy for lighting, refrigeration, air conditioner, TV, radio, hair dryer, and iron is 6.126kWh/d. The load profile taken into account in our study is for a typical Adrar village household. Figure 6 illustrates the monthly electrical energy demand.

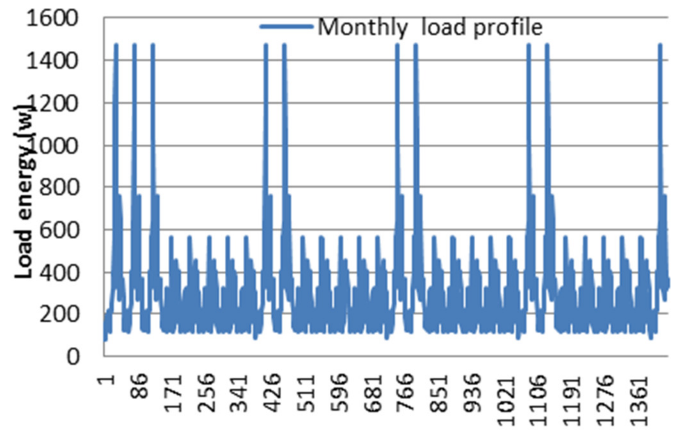

Fig. 6. Monthly load profile.

VI. RESULTS AND DISCUSSION

In order to find the optimum design of the hybrid system (PV/wind/battery), the proposed algorithm is implemented using Matlab/Simulink. The optimal sizing results for the desired loss of LPSP of 5% in both cases of optimization are presented in the following paragraphs. The fitness function is defined as the minimum cost of electricity produced by the hybrid system. In the case of a single-objective optimization using the PSO and GA optimization algorithms, we have considered the following parameters:

- Lower and upper limits of decision variables:

$$S_{pvmin} < S_{pv} < S_{pvmax} \quad (20)$$

$$S_{wmin} < S_w < S_{wmax} \quad (21)$$

$$C_{bmin} < C_b < C_{bmax} \quad (22)$$

where S_{pvmin}=1m^2, S_{pvmax}=12m^2, S_{wmin}=1m^2, S_{wmax}=12m^2, C_{bmin}=150Ah, C_{bmax}=200Ah

- Maximum probability of dissatisfaction of the tolerated demand LPSP <5.

The sizing results using PSO algorithm for different value of tolerated LPSP are given on Table II.

TABLE II. PSO RESULTS

LPSP	Spv	Swt	Cb	LPSP	Cost $\$$/kwh*10^{-1}
<2	7.45	8.91	155.2	1.99	2.70
<3	6.50	8.47	154	2.99	2.47
<4	6.04	7.76	150	3.97	2.44
<5	6.03	6.63	150	4.95	2.74

To validate the optimization method and ensure the good convergence of the algorithm, we applied another optimization algorithm, the GA. The results are shown in Figure 6. They show that the obtained solution is indeed in the optimal zone. The solution was obtained at the 40th iteration starting from the initial conditions after 80 evaluations of the objective function. The simulation results given by the GA algorithm are summarized in the Table III for LPSP <5.

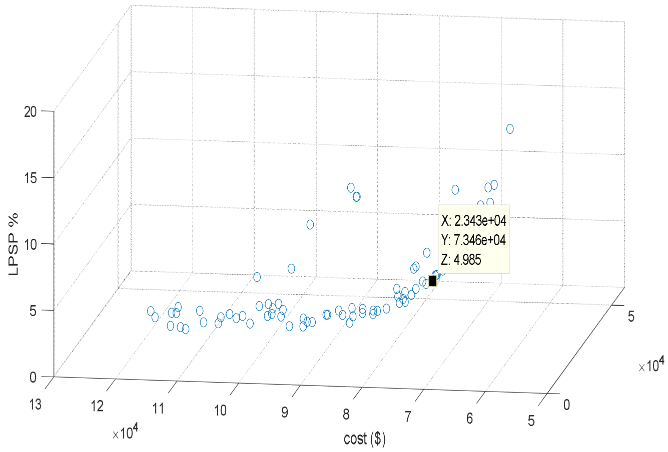

Fig. 7. GA convergence.

TABLE III. GA RESULTS

LPSP	Spv	Swt	Cb	LPSP	Cost $/kwh *10^{-1}
<2	8.88	6.11	166	1.96	2.62
<3	8.68	5.59	156.74	2.63	2.42
<4	6.9	6.4	154	3.86	2.66
<5	6.7	5.57	153.15	4.98	2.34

The simulation results show that the cost, the size of the generators (PV, wind), and the battery capacity depend on the desired LPSP. They are important for low LPSP values. In view of establishing optimal system dimensioning, another parameter was proposed, which allows the estimation of the rate of aging of the battery for each configuration.

VII. Calculation of the Number of Cycles According to the Depth of Discharge

The study is based on the mathematical model of a GEL VRLA SOLAR type plate battery given by [26, 27]:

$$N_{c(DOD)} = 12850e^{-(9.738*DOD)} + 3210e^{-(1.429*DOD)} \quad (23)$$

To extract the number of cycles (NC) and the corresponding DOD, the Rain flow algorithm has been applied to the SOC of our system .

A. *Calculation of Aging*

The aging rate per cycle ($A_{r/c(DOD)}$) is calculated based on the life cycle of the battery and the DOD. The expression is written in the following form [26, 27]:

$$A_{r/c(DOD)} = \frac{1}{N_{c(DOD)}} \quad (24)$$

B. *Simulation Results*

TABLE IV. PSO/GA RESULTS

LPSP	PSO		GA	
	AR %	AR (year)	AR %	AR (year)
<2	6.11	16.36	8.07	12.39
<3	7.47	13.38	8.80	11.36
<4	7.39	13.53	7.73	12.92
<5	8.08	12.38	9.12	10.96

In our case and for a LPSP ≅5 we choose the results given by the PSO algorithm which gives a lifetime of 12.38 years and an aging rate of 8.08%. The surface of PV panels installed was A_{pv}=6.03m^2, the surface swept by the rotor of the wind turbine was A_{wt}=6.63 m^2, and the storage capacity was C_b=150Ah. To see the effectiveness of the optimal result found, we present the SOC of the batteries during the year in Figure 8.

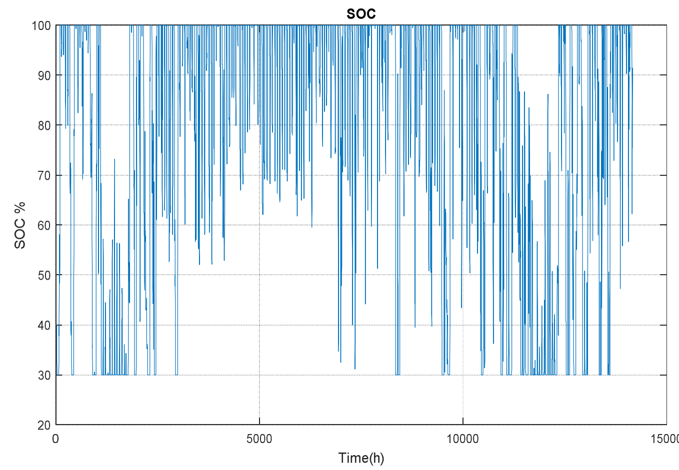

Fig. 8. SOC vs time.

This curve shows the complete exploitation of the batteries in the unfavorable period. The wind energy produced is equal to 2471.9KW per year, i.e. 8.58W per hour on average, which represents 56% of the energy demanded by the consumer. The PV energy produced by the panels is equal to 1760.4kW. Comparing to the energy demanded (4386.6kW per year), we find that there is an excess energy at an annual level. The latter is explained by the random nature of the renewable energy sources.

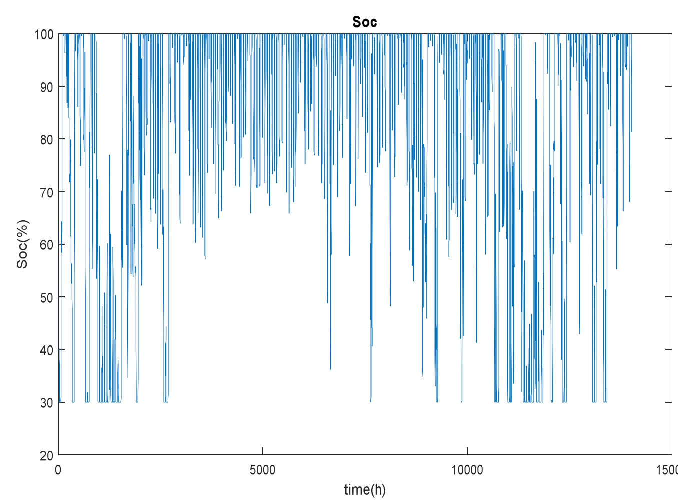

Fig. 9. The new SOC.

VIII. Conclusion

Given the geographical location, the nature of the terrain and the duration of the sunshine, Algeria is a most suitable country for the production of renewable energy. The work presented in this article concerns the production of electricity from a hybrid system (PV/wind) with a completely autonomous storage system to supply the households of an isolated village in the Adrar region of southern Algeria. The objective was to maintain a high level of reliability with a minimum cost thanks to the optimal dimensioning of the hybrid system for a load and a given probability of energy loss under the criteria of a minimum ecological and economic cost of the system and low battery aging rate. Optimal dimensions of the PV module and the wind turbine as well as the capacity of the battery were calculated after the modeling of the different components of the system and calculating the hourly power produced by the aerogenerator and by the PV generator for an analysis period of one year at the Adrar under Matlab/Simulink.

To validate the simulation results, a comparative study was made between the two optimization algorithms, PSO and GA. The obtained simulation and optimization results show that the chosen methods give good estimates of the desired reliability criterion (LPSP), low EC and TNPC, and low battery aging rate.

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