OPTIMIZATION AND CONTROL STRATEGY OF MULTI-SOURCE SYSTEM USING GENETIC ALGORITHM

Amina **GABOUR**, Samia **BENZAHIOUL**, Abbderrezak **METATLA**, Toufik **SEBBAGH**
LGMM Laboratory, Université 20 Aout 1955 - Skikda, Algeria
a.gabour@univ-skikda.dz, sbenzahioul@univ-skikda.dz, a.metatla@univ-skikda.dz, t.sebbagh@univ-skikda.dz

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Abstract*: The aim of this paper is to design the sizing and optimization of multi-source system PV/Diesel/Battery, whereat the power management algorithm is applied to feed load in Algeria where the GA method is used to find the best configuration of the system and for sizing purpose of the components, based on the minimum total cost of the system (STC) subject to renewable energy fraction (FR).Thus, the results show the impact of RF on the STC in addition to the choice of the best configuration and the most adequate one.*

1. INTRODUCTION

Renewable energy systems gained an outstanding significant interest. They are considered as a solution to face the reduction of fossil fuel resources which cause the CO emissions.

Besides, Algeria initiates a dynamics of green energy by launching an ambitious program for development purpose of Renewable energy and energy efficiency, for which purpose, the Government aims to developing solar energy. Likewise, Algeria is located in the centre of North Africa between the 358 and 388 of latitude north and 88 and 128 longitude east, whose surface is assessed to 2,381,741 km^2 whereat the Sahara occupies 80% of the total area [1], it is characterized by high solar radiation intensity. Subsequent to which, the photovoltaic systems have recently been used for various applications in Algeria, in respect such as: Electrification, pumping water, telecommunication, public lighting etc.

At the current time, solar systems are considered as one of the most popular sources, namely in research level. Further, there exist a lot of studies in the literature related to hybrid PV system size optimization, cost analysis, among which [2-9].

In the paper [2], genetic algorithms are applied for sizing remote PV systems and a comparison with two classical methods, worst month method and loss of power supply probability (LPSP) method are made. A year of synthetic hourly meteorological data of Adrar, Algeria, generated by PVSYST software, has been used in the simulation. The methods have been applied to a PV lighting systems with orientation due south and inclination angles between 0° and 90° to define the lowest cost of the system. Genetic algorithms and worst month methods give results close to each other between 0° and 60° but the system is largely oversized by the worst month method when the tilted angle is over 60°. Yahiaoui et al. [3], worked on optimization of PV/DG systems in Algeria using particle swarm optimization (PSO) algorithm. The constraint method has applied to minimize three objectives' functions, the total cost of the system, loss of load probability (LLP) and CO_2 emission of the hybrid power generation system. Results demonstrated that the combination of the two power sources (PV-Diesel) is required to be able to cover the energy deficit. Also in [4], PSO and the ε-constraint method have been applied to minimize optimal sizing of an autonomous hybrid PV/diesel system in a rural village of Ilamane, province of Tamanrasset, Algeria. Three objective functions are considered the total cost of the system (ACS), the loss of load probability (LPP) and the total CO_2 emissions produced by diesel generators. In the study, the ε-constraint method is used to handle constraints and multiple objectives of the system with simplicity and computational efficiency. In another study [5], PSO is used for an Optimal Sizing for PV systems in isolated island in East Nusa Tenggara, Indonesia. The objective function of the system is considered the Annual cost of system (ACS). The optimal sizing consists of 75,300 × 165W PV panels, 3×5MWh of battery banks (Batt) and 12MW of Diesel Generator (DG) units. A modeling and Cost Analysis of three different power generating configurations DG, PV/Batt and PV/DG/Batt in Tunisia, Jordan and Kingdom of Saudi Arabia (KSA), are presented in [6]. Further, two criteria are considered in this approach: initial investment and operational costs in addition to pollutant emission. Also, numerical simulations are applied to model these systems then characterize their performance. The best solution in Saudi Arabia was using diesel engine. However, using diesel engines leads to rise in pollutant emissions. Likewise, it was found that the best power supplying configuration in Tunisia and Jordan is the PV/DG/Batt. In [7] a developed simulation program using iterative approach is used to optimize the sizes of PV/Batt system, for electrification of small community in Palestine. Economic analysis is done based on life cycle cost to define the lowest Cost Of Energy (COE). The results showed that the lowest COE is found 0.326 \$/kWh and happens at 100% PV contribution and 0.7 autonomy days (AD). Artificial Bee Colony Algorithm (ABC) applied in [8] for optimal sizing of stand-alone PV system in Helwan city, Egypt. Two objective functions are used. The first is the maximization of the PV module output power, whilst the second represents the minimization the life cycle cost (LCC). Also, comparison between ABC algorithm and Genetic Algorithm (GA) optimal results is made. The results demonstrated that the ABC is more efficient than GA in obtaining the optimal cost of the PV system. In the paper from Bataineh [9], PV system design is presented to provide electricity for a single residential household in rural area in Jordan. A computer program is developed to finding the optimal combination of PV array and batteries for the design of stand-alone photovoltaic systems in terms of reliability and costs. Life cycle cost (LCC) and annualized unit electrical cost of system are calculated.

In addition, there exist several commercial software in literatures which were developed for optimization of standalone and hybrid PV systems, they can be found in [10] in full details.

Above and beyond, for evaluation purpose of the performances of PV-Battery-Diesel system to supply electricity to the remote site in Algeria, GA was used to find the best configuration considering different constraints.

This paper explores the importance of the renewable factor (RF) in minimizing the total investment cost (STC) of the multi-source system.

2. CONFIGURATION AND MODELING OF THE MULTI-SOURCE SYSTEM

The multi-source system proposed in this study is shown in *figure 1.* Thus, the power system consists of photovoltaic generator, Diesel generator and a battery bank.

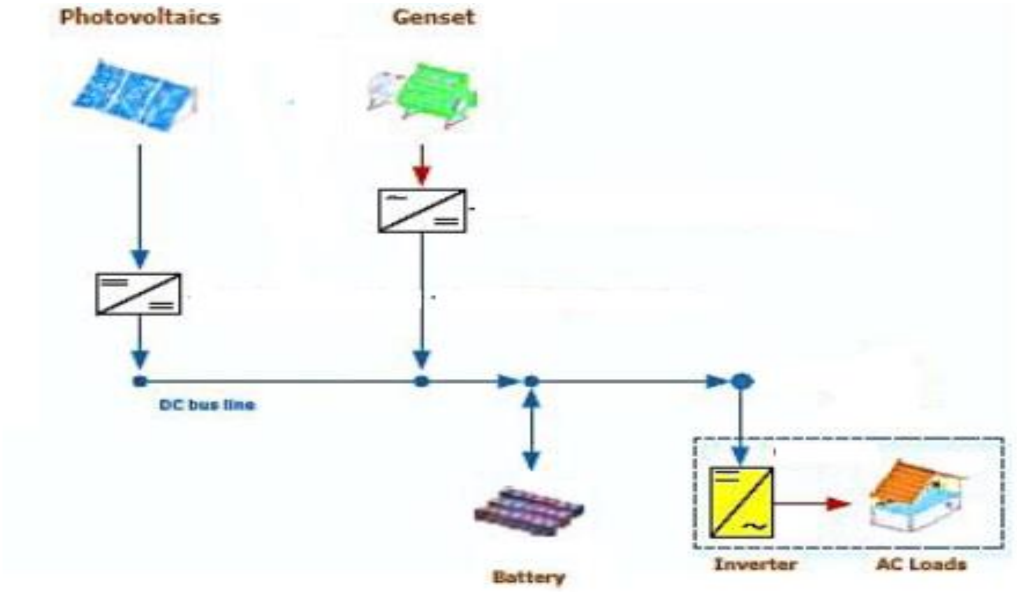


Fig.1. Configuration of a multi-source system

2.1. PV system

The hourly output power of a PV panel can be written as follows [11]:

$$P_{PV}(t) = V_{CO}(t).I_{sc}(t).FF \tag{1}$$

$$I_{sc}(t) = [I_{sct} + K_i.(T_c(t) - 25)].\frac{G(t)}{1000} \tag{2}$$

$$V_{CO}(t) = V_{cost} - K_v.T_c(t) \tag{3}$$

$$T_c(t) = T_a(t) + \frac{NOCT-20}{800}.G(t) \tag{4}$$

where: I_{sct} (A) is the standard short circuit current, K_i (A /°C) is the short circuit current temperature coefficient, $G(t)$ (W/m²) is the global irradiance incident on the PV module, V_{cost} (V) is the standard open circuit voltage, K_v(V/°C) is the open circuit voltage temperature coefficient, T_c (°C) is the temperature which can be estimated from the ambient temperature, T_a (°C) and the solar radiation and FF is the fill factor.

The total hourly output power of the PV modules ($P_{PV}(t)$) can be calculated by:

$$P_{PV}(t) = N_{PV,p}.N_{PV,s}.P_{PV}(t) \tag{5}$$

where $N_{PV,p}$ is the number of panels connected in parallel, variable of optimisation, $N_{PV,s}$ is the number of panels connected in series, it is calculated as:

$$N_{PV,s} = \frac{V_{bus}}{V_{PV,nom}} \tag{6}$$

V_{bus} is the DC bus voltage, it is chosen to be equal to 48 V and $V_{PV,nom}$ is the nominal voltage of the PV module.

2.2. Battery bank

For charging process and discharging process of the battery bank, the storage battery capacity is subject to the following constraints [12]:

$$\mathrm{C}_{\mathrm{bat}min} \leq \mathrm{C}_{\mathrm{bat}}(t) \leq \mathrm{C}_{\mathrm{bat}max} \tag{7}$$

C_{batmin} and $\mathrm{C}_{\mathrm{batmax}}$ are calculated as discussed in [13], they are the maximum and minimum allowable storage capacity.

C_{batmin}, is determined by:

$$\mathrm{C}_{\mathrm{bat}min} = (1 - \mathrm{DOD})\mathrm{C}_{\mathrm{bat}max} \tag{8}$$

The total number of the batteries is defined by:

$$N_{BAT} = N_{BAT,p}.N_{BAT,s} \tag{9}$$

where: $N_{BAT,p}$ is the number of panels connected in parallel, variable of optimization; $N_{BAT,s}$ is the number of batteries connected in series, is calculated as:

$$N_{BAT,s} = \frac{V_{bus}}{V_{BAT,nom}} \tag{10}$$

The storage battery capacity is computed during the charging state as follows:

$$\mathrm{C}_{\mathrm{bat}}(t) = \mathrm{C}_{\mathrm{bat}}(t-1) + (P_{RE}(t) - (P_{load}(t)/\eta_{\mathrm{inv}}))\eta_{cha}\Delta t \tag{11}$$

And for the discharging state, the storage battery capacity is computed as follows:

$$\mathrm{C}_{\mathrm{bat}}(t) = \mathrm{C}_{\mathrm{bat}}(t-1) + (P_{RE}(t) - (P_{load}(t)/\eta_{\mathrm{inv}}))\,/\eta_{dech})\Delta t \tag{12}$$

η_{cha}, η_{dech} are the charging and discharging efficiency of the battery, η_{inv} is the inverter efficiency. (In this article, $\eta_{cha} = 90\%, \eta_{dech} = 85\%$ and $\eta_{\mathrm{inv}} = 95\%$ [14]).

2.3. Diesel generator

The diesel fuel consumption $F(t)$ during a period of time t, and the fuel cost is calculated for a year, as per discussed in [15], as follows:

$$F(t) = 0.246\, P_{DG}\,(t) + 0.08415\, P_R \tag{13}$$

$$C_f = P_f.\sum_{t=1}^{8760} F(t) \tag{14}$$

where: $P_{DG}(t)$ is the DG generated power, kW, P_R is the DG rated power, kW, and P_f is the fuel cost per liter.

The operational of DG has to be in range between the rated capacity and specified minimum value:

$$P_{DGmin}\,(t) \le P_{DG}\,(t) \le P_{DGmax}\,(t) \tag{15}$$

2.4. Control strategies

This strategy can be explained by the following steps:

$$\Delta \mathrm{P} = \mathrm{P_{PV}(t)} - \mathrm{P_L(t)} \tag{16}$$

$$\mathrm{P_L(t)} = \frac{\mathrm{P_{load}}}{\eta_{\mathrm{inv}}} \tag{17}$$

where: $P_{PV}(t)$: the renewable power of the system which is in our case the Photovoltaic's power, P_{load}: the demanded load power.

1- If $\Delta P=0$, the battery banks is either charged or discharged and the $C_{bat}(t)$ of the battery banks depends on the previous value at the time t. The diesel generator is turned off.

2- If $\Delta P>0$, the remaining power will be used to charge the battery bank. The diesel generator is turned off. When the $C_{bat}(t)$ of battery banks reaches its maximum value C_{batmax}, the excess power is dumped.

3- If $\Delta P<0$, the deficient power will be supplied by the battery bank or by the diesel generator. If the demand load is less than the minimum power of diesel generator, these later run at their rated power P_R, the batteries will be charged with the remaining power.

A flowchart of the proposed operational strategy for the multi source system is shown in *figure 2.*

3. PROBLEM DESCRIPTION AND THE PROPOSED APPROACH

3.1. Cost analysis

The System Total Cost (STC) is one of the indicators in economic analysis, it can be determined from the following equation [16]:

$$F_c(x) = \sum N_{PV,P} \times N_{PV,s} \times \left(C_{A,PV} + 20 \times C_{M,PV} + C_{I,PV}\right) + \sum N_{BAT,P} \times N_{BAT,S} \times \left(C_{A,BAT} + C_{I,BAT} + (r_{BAT} \times (C_{A,BAT} + C_{I,BAT})\right) + (20 - r_{BAT} - 1) \times C_{M,BAT}) + C_{T,D} \tag{18}$$

where $C_{A,PV}$ is the acquisition cost of PV panel *(€)*, $C_{M,PV}$ is the maintenance cost per year of the PV panel *(€ /year)*, $C_{I,PVb}$ is the installation cost of the PV panel *(€)*, $C_{A,BAT}$ is the acquisition cost of battery *(€)*, $C_{M,BAT}$ is the maintenance cost per year of the battery *(€/year)*,

$C_{I,BAT}$ is the installation cost of the battery *(€)*, r_{BAT} is the expected number of battery replacements during the lifetime of the system operation, $C_{T,D}$ is the operation cost of the diesel generator, is calculated as follows:

$$C_{T,D} = C_{I,D} + M_D + \frac{C_D}{Life_D} + C_f \tag{19}$$

where $C_{I,D}$ is the installation cost of the diesel generator *(€)*, C_D is the diesel generator acquisition cost *(€)*, M_D is the diesel generator's hourly maintenance cost *(€/h)* ,$Life_D$ is the diesel generator lifetime *(h)*,C_f is the fuel cost *(€)*.

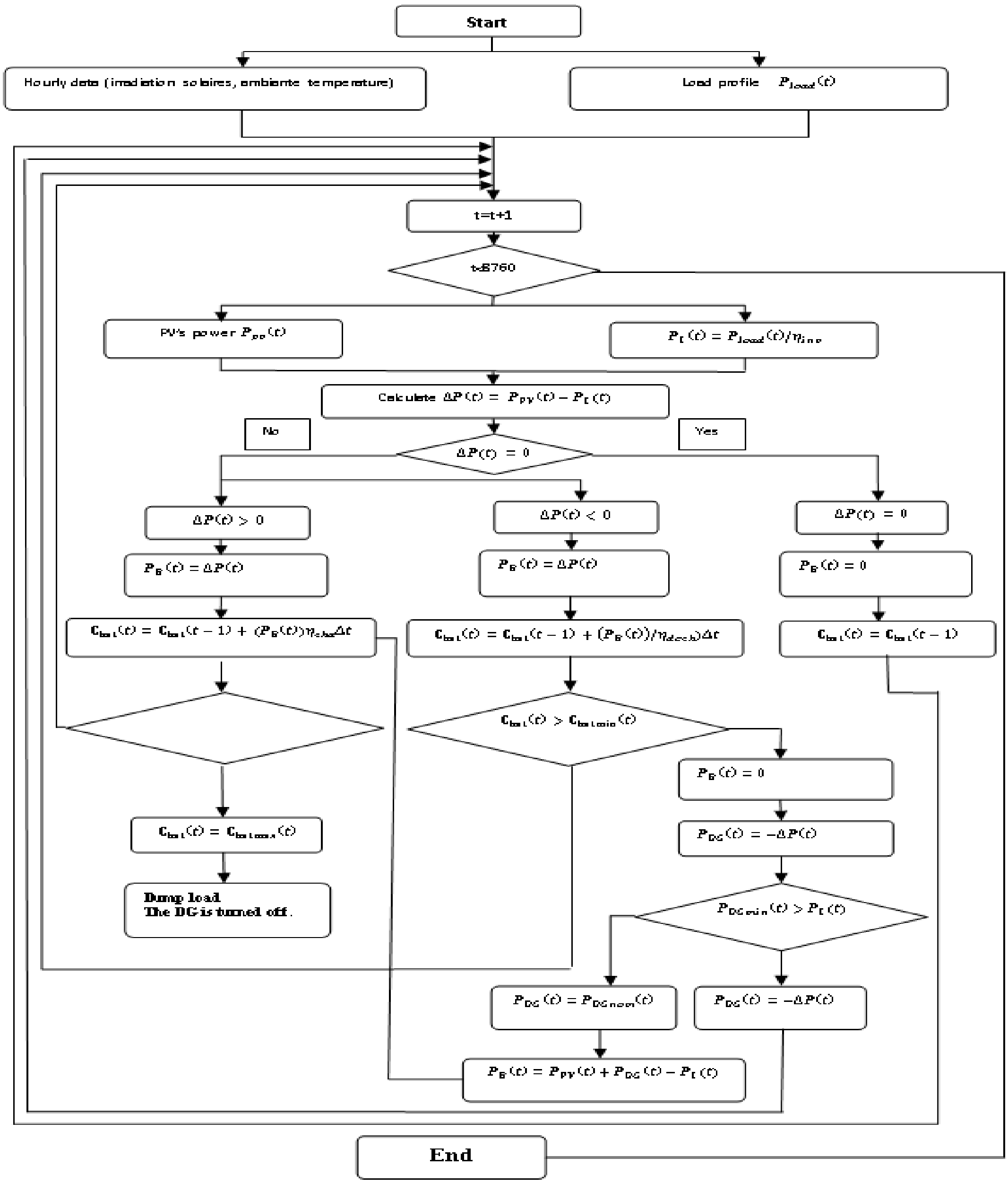


Fig. 2. Flow chart of the proposed operational strategy for the multi source ystem

The electrical energy supplied to the required load demand through the renewable energy sources is known as a renewable factor (RF) [17] or renewable energy fraction (FR) [18], FR is a number between 1 and 0, if FR equal to 1 means total generated power supply to the load from renewable energy source, in other side, if the value of FR is zero, the load is supplied by DG sources. The renewable fraction calculated is shown as [18]:

$$FR = \frac{E_{RE}}{E_{RE}+P_{DG}} \tag{20}$$

where: E_{RE} represents the produced renewable energy which is consider the Photovoltaic's power (P_{PV}) in our case, P_{DG} represents the diesel generator power, E_{RE} + P_{DG} represents the total energy production of the multi-source system.

3.2. Genetic algorithm

GA is a stochastic optimization proposed for the first time by Holland [19], GAs are adaptive heuristic search algorithms based on the evolutionary ideas of natural selection and genetics. GAs are utilized to solve NP-Hard optimization problems which cannot be solved with classical methods due various complexities such as non-linearity, non-convexity, multimodality, discontinuity, and mixed-types variables among others [20]. Design of energy systems is among such complex problems.

The most important three operators of GAs are: selection, crossover and mutation.

The first step of a GA is the random generation of the initial population. Then a GA follows an iterated procedure that consists of the following steps [21]:

1. Evaluation of objective(s) function(s).
2. Reproduction of population, which makes duplicates of good solutions and eliminates bad solutions.
3. Crossover, in which existing population members (parents) are mated in order to produce new population members (offspring).
4. Mutation, which randomly changes the values at a portion of population members.

In a single objective optimisation, there is one goal: the search for an optimum solution. However, in multi objective optimisation there are two goals or more than two.

3.3. Case study

3.3.1. Components characteristics

PV panels and batteries constitute the inputs of the optimal sizing procedure. The technical specification and the costs of each component are described below:

Table1.Specification of PVpanels [22]

$V_{OC}(V)$	45.50
$I_{sc}(A)$	8.90
K_v(%/°c)	- 0.335
$K_i(\%/°c)$	0.047
$NCOT$ (°C)	46.00
$C_{A,PV}$ (€)	228.65
$C_{I,BAT}$ (€)	33.50
$C_{M,BAT}$ (€/year)	6.85

Table 2. Specification of batteries [22]

C_B (Ah)	180.00
$C_{BAT,nom}$(Ah)	12.00
$V_{BAT,nom}$ (V)	80.00
DOD (%)	85.00
$C_{A,BAT}$ (€)	147.90
$C_{I,BAT}$ (€)	20.88
$C_{M,BAT}$ (€/year)	5.68

The life of the system is assumed equal to 20 years, the service life of the battery is 4 years.

One diesel generator of a rated power of 16 kW is used; its lifetime is 7000 h. The fuel price is 0.17 €/l according to [23]. The capital cost and the maintenance cost of the diesel generator are respectively 6830 € and 0.2 €/h [16].

3.3.2. Meteorological Data and Load Profile

The system is assumed to be installed in the site of Ghardaia, Algeria, latitude: 32°24’N, longitude: 3°48’E and altitude: 450 m above sea level and it is proposed in order to meet the power demand of remote consumers. A community consisted of around 100 individual residential buildings.

The hourly solar radiation and hourly temperature are presented in *figure 3* and the hourly load profile is presented in *figure 4.*

3.4. The Objective Function and the Constraints

In order to examine the relation between the cost and RF, the objective function is the *STC* and the constraint is the *RF*.

The objective function:

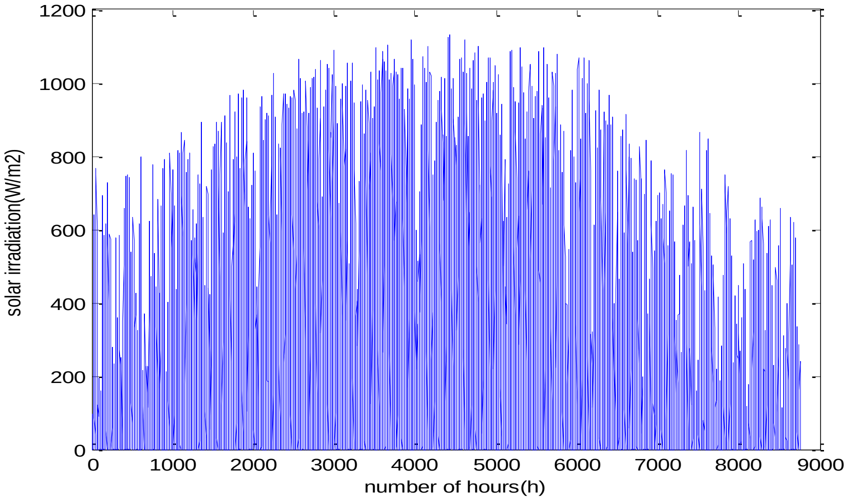
$$Min\ (STC) \tag{21}$$

is subject to:

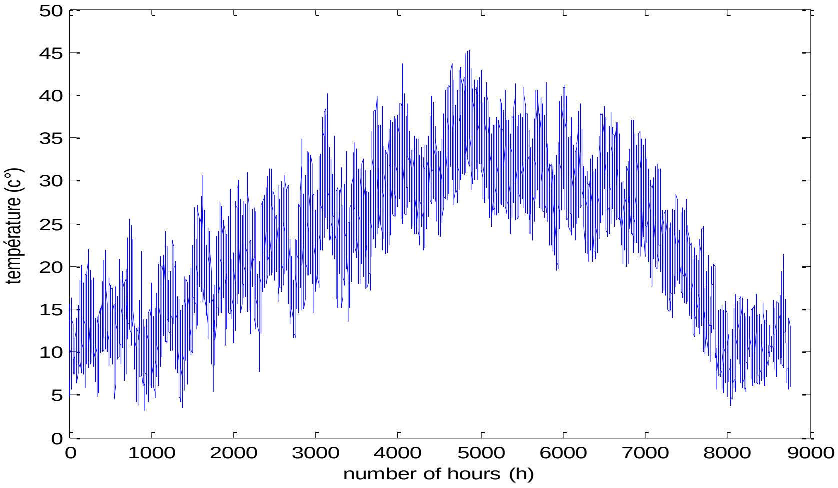
$$RF_{désired} \leq RF \tag{22}$$

We consider two scenarios:

- ✓ **Senario 1:** $RF_{désired} = 0.5$
- ✓ **Senario 2:** $RF_{désired} = 0.8$



(a) Solar irradiation



(b) Ambient temperature

Fig. 3. Hourly means values of meteorological conditions

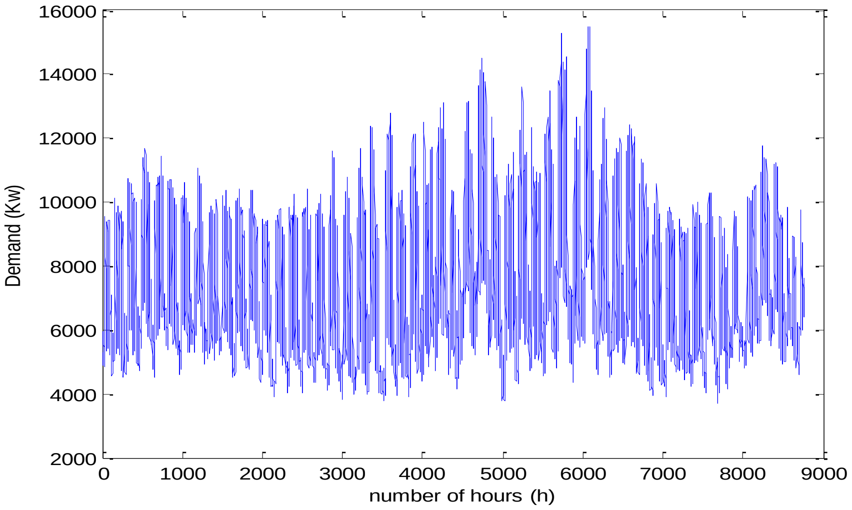


Fig. 4. Load profile during one year

The upper limit is defined by the constraint on number of components:

$$\begin{cases} 1 \le N_{PV,p} \le N_{PV,pmax} \\ 1 \le N_{BAT,p} \le N_{BAT,pmax} \end{cases} \tag{23}$$

and additional constraints:

$$\mathrm{C}_{\mathrm{bat}_{min}} \le \mathrm{C}_{\mathrm{bat}}(t) \le \mathrm{C}_{\mathrm{bat}_{max}} \tag{24}$$

$$P_{DGmin}\ (t) \le P_{DG}\ (t) \le P_{DGmax}\ (t) \tag{25}$$

A genetic algorithm implemented in Matlab as “ga” command [24], is used for optimization to find out the optimal sizing of the multi-source system consisting of PV, Diesel generator and Batteries as a storage system, to supply the studied area. In this simulation, GA parameters consist of:

- ✓ 40 populations size according to the following equation:

$$\text{number of populations} = \max(\min(10.\text{number Of Vars}, 100), 40) \tag{26}$$

Number Of Vars represents variables’ number.

- ✓ 100 maximum generations.

For the other parameters, we used the default settings like stopping criterion:

- ✓ The average change in the fitness function value below the function tolerance, which is considered 10^{-6} ,
- ✓ The stall generation, which is considered 50.

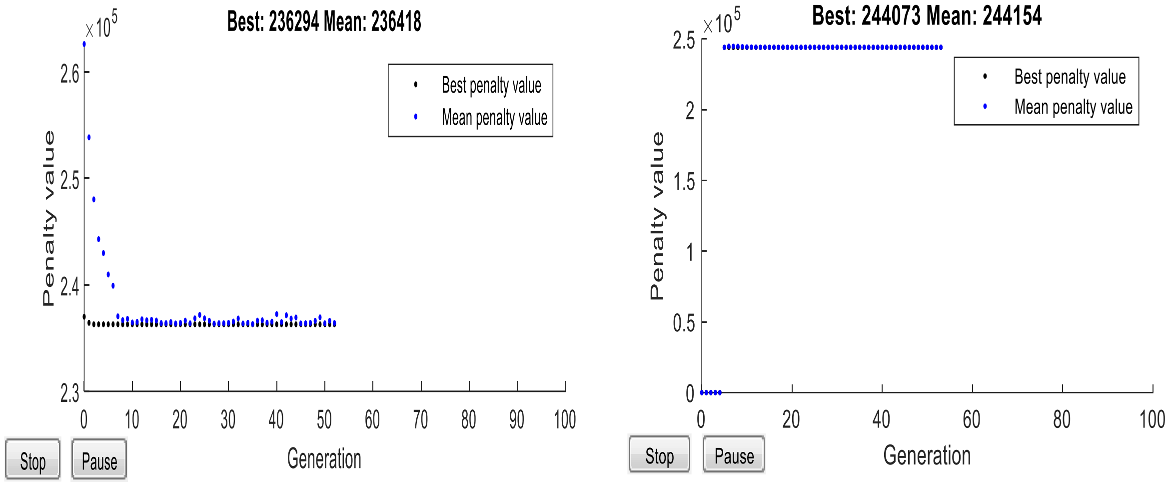
Each chromosome consists of two genes (PV’s number and battery’s number). Optimization routine takes a long time to compute solution.

4. RESULTS AND DISCUSSSION

According to the control strategy adopted in this study, the demand is always satisfied. The application of the chosen approach leads to obtain the results presented in Table 3 and *figures 5, 6, 7* and *8*.

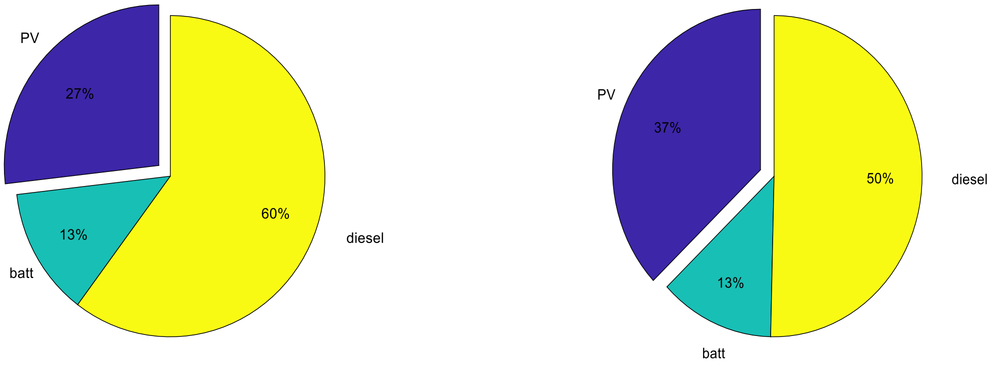
Table3. Optimal results

	$N_{PV,P}$	$N_{BAT,P}$	STC (€)	Operating hours of diesel (h/year)	Energy delivered by PV (Wh/year)	Energy delivered by diesel generators (Wh/year)
Senario 1	35	7	236294	4007	$6.37\text{x}10^7$	$2.65\text{x}10^7$
Senario 2	50	7	244073	3451	$9.11\text{x}10^7$	$2.28\text{x}10^7$



a)FR=0.5 *b)FR=0.8*

Fig. 5. Performance of genetic algorithm



a)FR=0.5 *b)FR=0.8*

Fig. 6. Details of STC

According to the result analysis presented and shown in Table 3 and *figures* 5-8, respectively:

- It can be depicted from results that the *STC* is dependent on *RF*, the increase of the renewable factor *RF* results in theincrease of *STC*.
- It also shows the highest renewable penetration of 80% with the value of *STC* = 244073(€). The combination includes 50 PV Panels and 07 batteries. Here, the diesel generators are operated for 3451 h in a year, the utilization of PV system with high penetration can minimize the operational cost of Diesel generator as shown *figure* 6, and reduces the fuel consumption accordingly.

- ✓ The case study shows that the use of the system with a renewable factor $RF_{desired}$ = 0.5 is the most cost-effective system with a *STC* of 236294 €. The minimum value for the system's *STC* is obtained at the 52th iteration of the algorithm as shown in *figure* 5.
- ✓ The optimum PV selection is not affected only by the metrological condition (solar irradiation and temperature) or by the PV characteristics, but also by the desired *RF*.

A simulation of the produced powers by the optimal configuration over a period of one year is presented in *figure 7:*

- ✓ Regarding the state of charge of the batteries, we can verify that throughout the year, it can never exceed the permissible maximum value SOC_{max} (100% of *SOC*) and it can never be below the permissible minimum value, SOC_{min} (20% of *SOC*).
- ✓ It can be seen that the number of start / stop of the diesel generator depends on the state of charge of the battery.

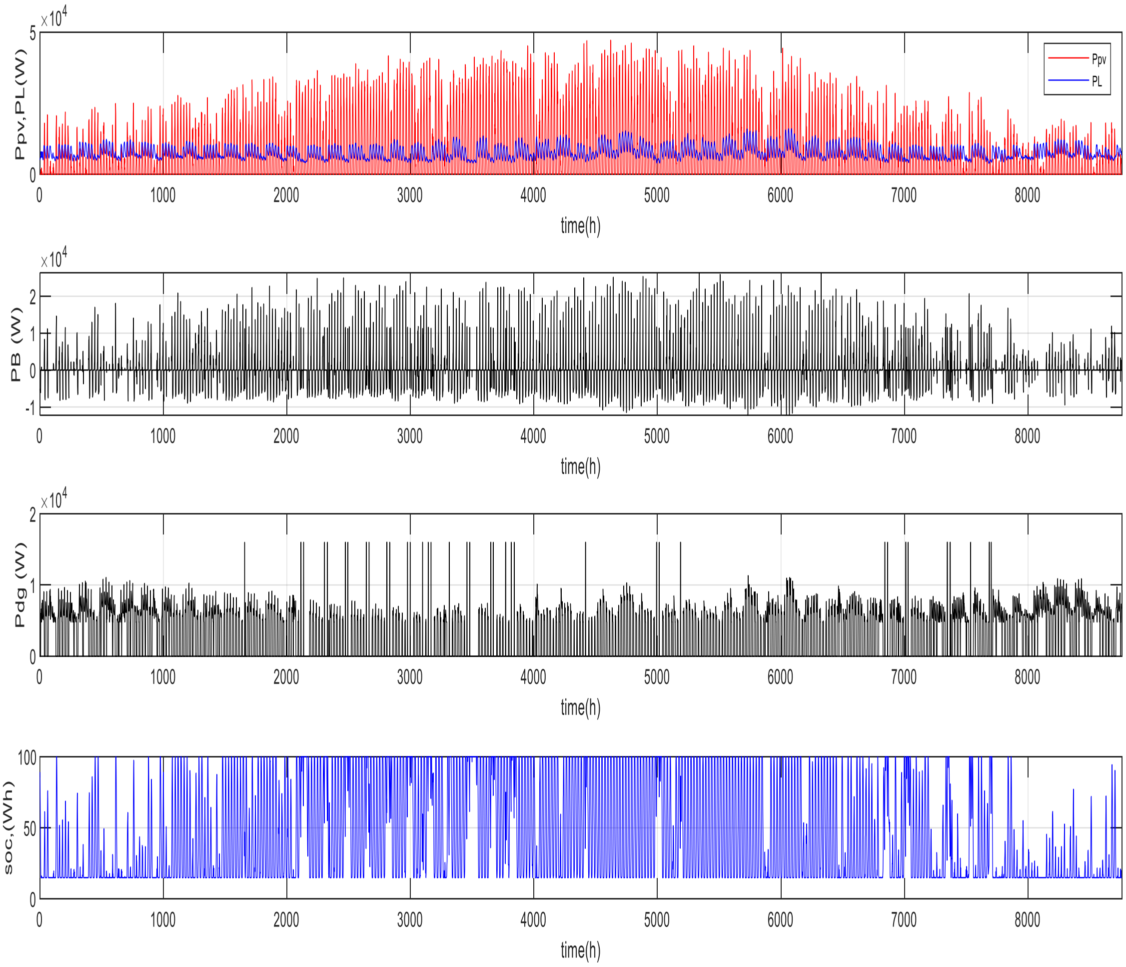


Fig. 7. Evolution of the powers $P_{PV}(t)$, $P_L(t)$, $P_B(t)$, $P_{DG}(t)$ and the state of charge of batteries in percent (SOC) during one year.

A simulation of the different powers produced by the optimal configuration of multi-source system over a period of 15 days is presented in *figure 8*.

According to the simulation results related to the case studied:

- ✓ The storage battery bank capacity never exceeds the allowable maximum value and can never be below the allowable minimum value, which respects the constraint fixed by us at the level of the management of the battery.
- ✓ When the power $P_{PV}(t)$ is greater than $P_L(t)$, the bank of batteries is charged $(P_B(t)> 0)$ and discharged $(P_B(t) <0)$ in the opposite case,
- ✓ The diesel generator starts when the power $P_{PV}(t)$ is lower than $P_L(t)$ and the batteries are discharged, the diesel generator is used to cover the energy deficit,
- ✓ Moreover, the DG never operates below the allowable minimum value, 30% of its rated power.

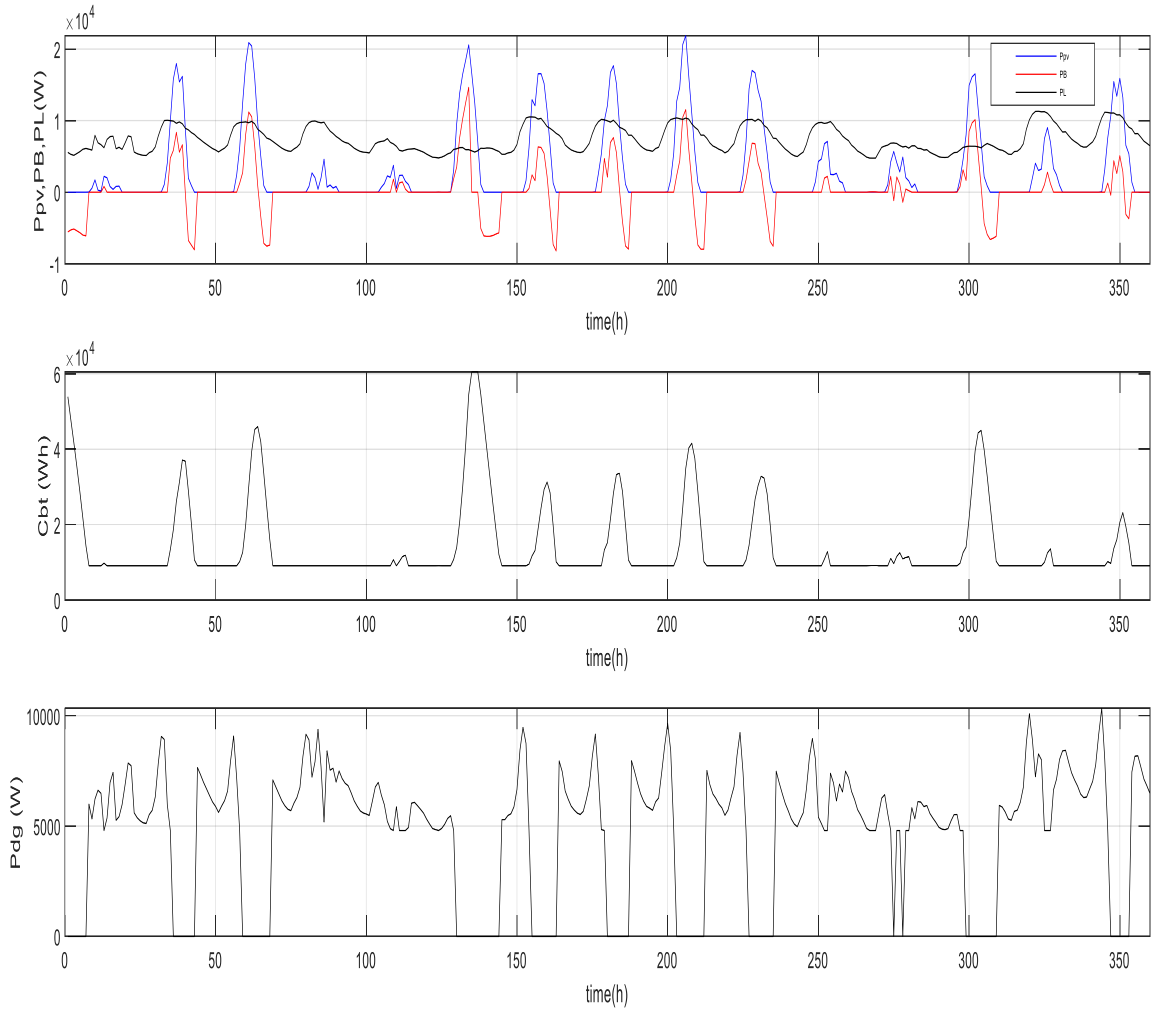


Fig. 8. Produced powers by the renewable resource $P_{PV}(t)$, demanded by the consumer $P_L(t)$, input / output of the bank of batteries $P_B(t)$, storage battery bank capacity $C_{bat}(t)$ and the power produced by the diesel generator $P_{DG}(t)$

5. CONCLUSION AND PERSPECTIVE

The performed work represents the sizing optimization of PV- diesel-battery system. Then, GA is used to find the optimal configuration of the number of PV panels and batteries. Also, the results obtained from the simulation show that the design and sizing optimization of the hybrid system can be achieved by using the proposed methods to find the best solution for the system.

The possibility of using this method is a great interest, it can be implemented in different cases for the optimal sizing and management of multi-source renewable energy system, for different load profile and meteorological conditions.

Further works will take into consideration other criteria like CO_2 emission, loss of probability of charge LPSP…etc and be focused on the study of the multi-objectives' optimization in order to examine the relation between the STC and RF or STC and other factors.

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