IJCTA, 9(38), 2016, pp. 99-110

Optimal Sizing of Stand-Alone Hybrid PV-Diesel-Battery System Using PSO and the ε-Constraint Method

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ABSTRACT

The present paper presents a methodology to perform optimal sizing of a small autonomous hybrid PV/diesel system in rural village in Algeria. A particle swarm optimization (PSO) and the ε-constraint method have been used to minimize simultaneously the total cost of the system, unmet load, and fuel emission. The case study is the rural village of Ilamane, province of Tamanrasset, the south of Algeria (latitude 23.12°N and longitude 5.27°E), the system is an autonomous hybrid PV/diesel system that includes photovoltaic (PV) panels, diesel generator, and battery bank.

Keywords: Hybrid, PV, PSO, ε-constraint, optimization.

1. INTRODUCTION

Algeria's economy depends on hydrocarbons resources, but this does not preclude the fact that Algeria has a high potential of renewable energy, the development of this potential must guarantee durability on a human scale by exploring the advantages of these free renewable energy resources and studying the ways to increase the efficiency on how this energy can be used mostly in small and remote villages where they need energy to improve the standards of their life. Several papers have reviewed the power generation and reliability of small standalone power systems [1-2]. The lack of technology, at affordable prices, is one of the causes that hinder the investment in such underdeveloped countries[3]. Developing new technologies and improving the ones that already exist are requiring. Hybrid energy systems are one of the possible solutions to these problems[4]. In hybrid systems, the generation predictability with combining the several resourcesis increased and the resources cover each other's deficits[5].Optimally sized design of hybrid RES is an important issue in hybrid systems[6]. In recent research works for optimization of a RE unit, there is an increase in usage of evolutionary computations, due to they are suitable for multi-objective issues by implementing a heuristic algorithm.

In recent years, researchers applied multiobjective evolutionary algorithms (MOEA) to solve one of these problems. O. Erdinc & Uzunoglu [7] reviewed the state-of-art of hybrid system sizing approaches also M. Fadaee et Radzi [8] presented a review of multi-objective optimization methods applied to different HRES (like genetic algorithm (GA), particle swarm optimization (PSO)) from the point of view of placement, sizing, operation, design, planning and control.

MOEA, which classified in population-based methods[9] are suitable for this problem because they have the ability to attain the global optimum[10]. PSO an original stochastic optimizer with fast speed and

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simple way of realization than genetic algorithm and ant colony optimization has been effectively applied to solve large range of problems of RES[11] like planning, designing and control by finding optima of complex search processes through iteration of each particle of population [12-13]. The comparative analysis shows that the PSO technique performs better than GA, when applied for a sizing problem in terms of number of iterations and CPU utilization time [14]. According to Mezura-Montes et al [15].

Multi-objective algorithms are typically divided into 3 classes:

(1) Pareto-based techniques deal with multiple objectives using ranking and selection in the population.

(2) Non-Pareto-Based techniques deal with combination of objective functions and problem transformation.

(3) Mixed techniques which use both approaches.

In this paper, PSO and ε-constraint method which is a non Pareto-based search technique have been used to minimize simultaneously the total cost of the system, unmet load, and fuel emission. The idea of this approach is proposed by Sharafi and. ELMekkawy [16] to minimize the total cost while CO_2 emission and unmet load are considered as constraint bound by permissible levels. This approach is used to optimally size a small stand-alone hybrid PV-Diesel-battery system to electrify a remotely located village in the southern Algerian Sahara called Ilamene (province of Tamanrasset). The peak load of the autonomous hybrid system is small, of the order of 5 kW. Some recent control methods are discussed in [32-36].

The rest of the paper is structured as follows.Section 2 describes the problem to be solved, Section 3 presents the proposed approach, followed by Section 4 which discusses the modelling of hybrid PV/diesel system components andSection 5 deals with optimization module of system.Section 6 gives brief idea about PSO, and Section 7 gives results & discussion followed by the conclusion.

2. PROBLEM DESCRIPTION

In this paper, the hybrid renewable energy system includes PV panels, storage system (Battery bank) and diesel generator. The energy flow of the system configuration is shown in Figure 1. The PV panels produce electricity from solar energy to satisfy the load demand of the system. When the energy produced is more than the needed load, the excess energy is supplied to feed the battery bank until it is full charged. When the energy produced by PV panels cannot meet the load, the batteries release energy to assist the PV panels to cover the load based on the state of charge of batteries. When the batteries are not able to meet the load requirements, the diesel generator is used as a backup unit.

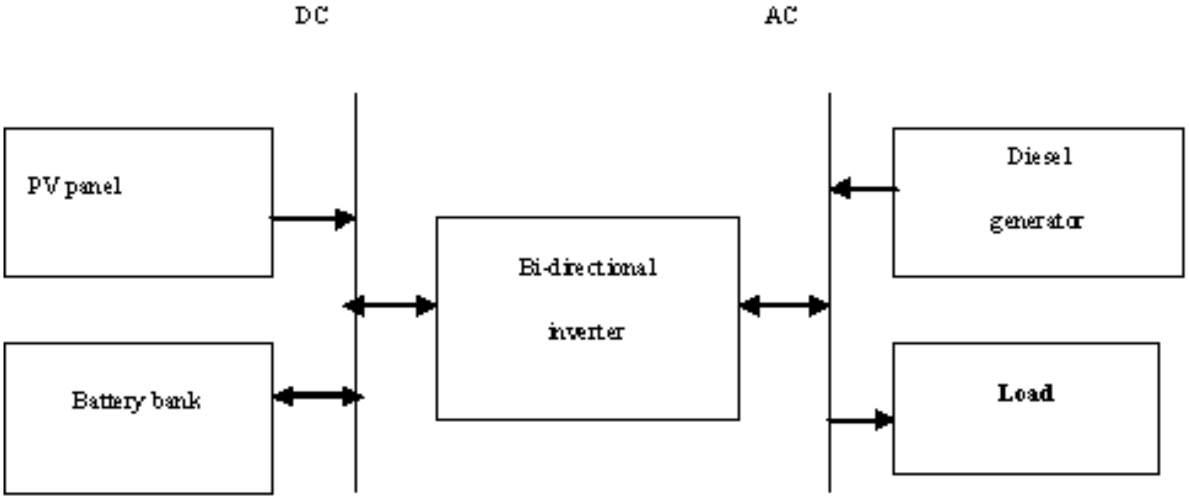

Figure 1: Energy flow of the hybrid system

3. PROPOSED APPROACH

The aim of this study is to find the optimal sizing model for a standalone hybrid PV/Diesel system with battery bank by using a PSO and ε-constraint method.

Three objectives functions are considered (the total cost of the system, the total CO_2 emissions produced by diesel generator, and the loss of load probability LPP). Design variables included in the optimization process are the size of the PV panels N_{pv}, the size of the battery bank N_{bat}, and the rated capacity of DG unit P_{dg}, these variables are defined in a vector named particle. Each particle represents a different configuration of the system. Total cost which is a function of design variables is considered as the fitness of particles for particles evaluation while CO_2 emission and unmet load are considered as constraints bound. The scheme of optimization using PSO and ε-constraint method is shown in figure 2. After entering the techno-economic parameters of the system such as the hourly load demand, hourly meteorological data, lifetime of the project, cost of the components ...etc, the next step is the initializing of the first population of particles, First each particle is generated randomly then in each iteration and for each particle, the objective function is calculated and it is sent to the simulation model for checking its feasibility (if it meets the constraints of the model)

The simulation model is run for one year to evaluate the performance of each particle. And it is carried out based on real weather data (insolation, temperature, etc.). The simulation model calculates the annual

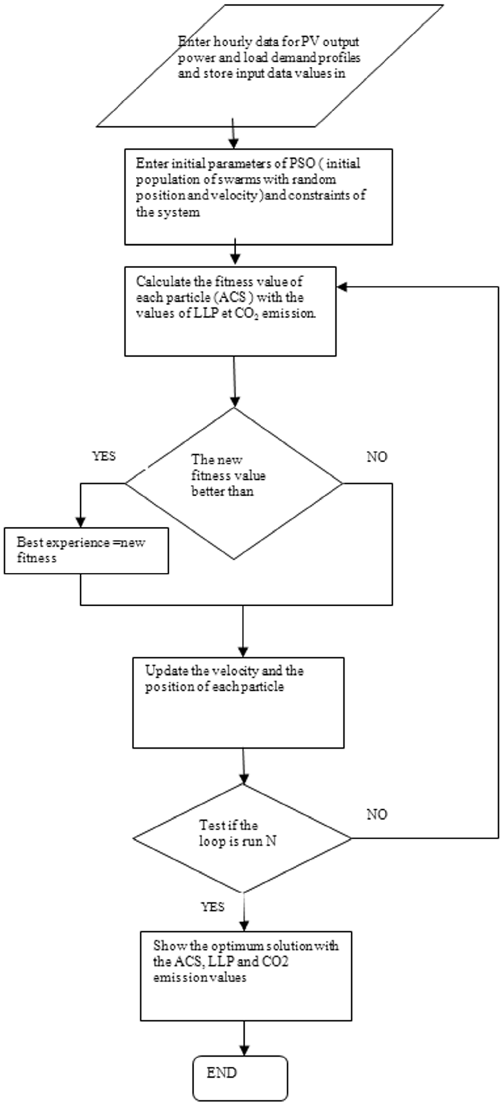

Figure 2: The scheme of optimization using PSO and ε-constraint method.

fuel consumption of diesel generator unit, the CO_2 emission and the yearly unmet load for each particle. Then, these values are sent to the optimization algorithm to check if the particle meets the constraints (the desirable level of unmet load and CO_2 emission). If the particle did not meet the constraints, it is modified and sent back to simulation. Each iteration feasible particles are evaluated in the PSO algorithm based on their fitness until stopping criterion is checked. After terminating the cycle, the solution will be returned.

4. MODELING OF HYBRID PV/DIESEL SYSTEM COMPONENTS

To estimate the hybrid PV/Diesel system performance, different components are modeled first and then their combination can be evaluated to meet the load demand[17].

4.1. PV Model

PV model follows I-V characteristic of a PV cell consists of a diode in parallel with an ideal current source and considers the effect of series (Rs) and parallel resistance (Rsh) as shown in Figure3. This equivalent circuit holds good for a cell, a module or even an array. In a practical PV cell, a series resistance is offered by the semiconductor material, the metal grid, metal contacts and current collecting bus. These resistive losses are lumped together as a series resistor (Rs). Its effect becomes very conspicuous in a PV module that consists of many series-connected cells, and the value of resistance is multiplied by the number of cells. Similarly, a certain loss is associated with a small leakage of current through a resistive path in parallel with the intrinsic device. This can be represented by a parallel resistor (Rsh). Its effect is much less conspicuous in a PV module compared to the series resistance, and it will only become noticeable when a number of PV modules are connected in parallel for a larger system [18].

$$I = I_L - I_0\left(e\frac{q\left(V + I.R_S\right)}{nkT} - 1 \right) + \frac{V + I.R_S}{R_{SH}} \tag{1}$$

where I_L is the PV cell generated current, I_0 is the reverse saturation current, I_D is the diode current, I_{sh} is the shunt current, Rs is the series resistance, R_{sh} is the shunt resistance. This is the single diode model considering both R_s and R_{sh}. The single diode model is suitable for our research because of its simplicity and efficiency in the simulation.

4.2. Battery Bank

The energy storage devices are essential to the stand-alone PV generation system. The battery charging and discharging control with the maximum power of PV array is the key point to increase the efficiency of the

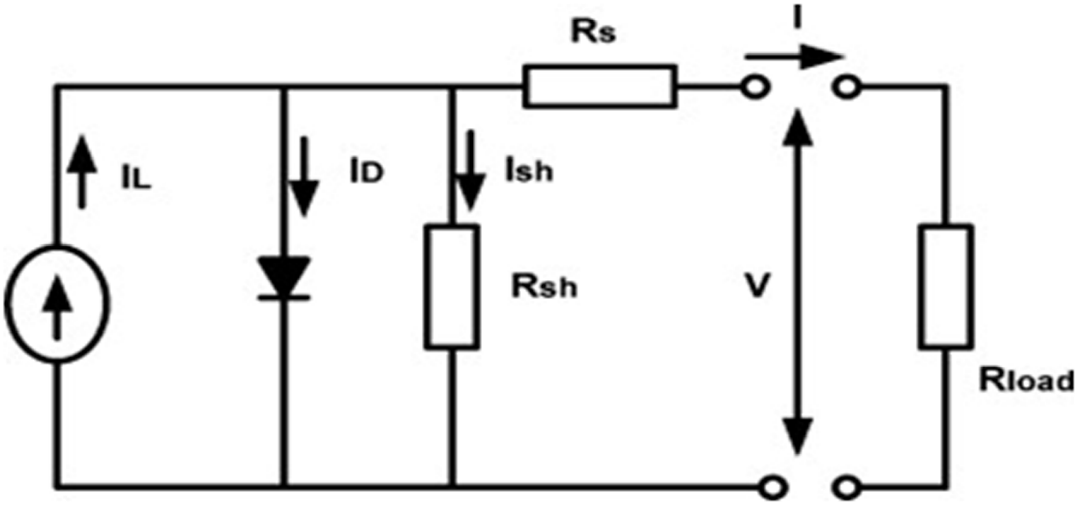

Figure 3: The equivalent circuit of a PV model.

generation system[19]. Energy production and absorption of battery system during the time from t-1 to t is described by the equation below:

$$C_B(t) = C_B(t-1).\ (1-\sigma) + P_{BAT}(t) \tag{2}$$

where; $C_B(t)$ and $C_B(t$-1) are availability power of battery banks at hour t and at the previous hour (t-1), respectively. The term σ is the self-discharge rate of battery bank, in the study it is assumed 0.002.

The value of $C_B(t)$ is between the minimum allowable energy level remained in battery banks (C_{Bmin}), and the maximum allowable energy level (C_{Bmax}):

$$C_{Bmin} \leq C_B(t) \leq C_{Bmax} \tag{3}$$

For longevity of the battery bank, the maximum charging rate (SOCmax) is given as the upper limit, and it takes the value of total nominal capacity in Ah of the battery bank which is defined by the total number of batteries (n_bat), and the nominal capacity of each battery (Cb Ah), as follows [20].

$$SOC_{max} = C_b * n\_bat \tag{4}$$

The minimum permissible state of charge (SOCmin) of battery bank during discharging may be expressed as follows 20:

$$SOC_{min} = n\_bat * C_b\,(1 - DOD_{max}) \tag{5}$$

Where $\mathrm{DOD}_{\max}$ is the maximum depth of discharge in percentage. The battery can have the maximum life if the DOD is set to 30–50 %, for instance, DOD = 30 %. Temperature can also affect the performance of batteries. High temperature decreases the battery lifetime. The batteries are normally installed inside a building where the temperature is not expected to change drastically. It is recommended to keep the battery at 25°C [6].

4.3. Diesel Generator Fuel Consumption

The fuel consumption of the diesel generator, Cons_G (l/h) is modelled as dependent on the output power [21].

$$Cons_G = a_{DG} \times P_{n-DG} + \beta_{DG} \times P_{a-DG} \tag{6}$$

Where $P_{n\text{-}DG}$ (kW) is the nominal power, $P_{a\text{-}DG}$ (kW) is the power output of the diesel generator, α_{DG} and β_{DG} are the coefficients of the consumption curve, defined by the user (l/kWh). The diesel efficiency η_G is defined as power output divide by heating value of fuel consumption calculated using Eq. (7):

$$\eta_G = \frac{P_{a-DG}}{Cons_G \times LHV_{GAS-OIL}} \tag{7}$$

Where LHVGAS–OIL is between 10 and 11.6 kWh/l, α_{DG} = 0.246 l/kWh and β_{DG} = 0.08145 l/kWh[21].

5. OPTIMIZATION MODULE

5.1. The ε-Constraint Method

The ε-constraint method is a simple MOP technique that can be used where one objective is chosen to be optimized and the remaining objectives are considered as constraints bound by given target levels (ε_i)[22]. By varying these levels, the non-inferior solutions of introduced problem can be obtained. Consider the following MOP:

$$Min\{f_1(x), f_2(x), \ldots \ldots \ldots f_k(x)\}$$

Where, x is the decision vector, f_i (i = 1, 2, ..., k) are objective functions.

A solution x^* is said to be non-inferior if there exists no other feasible solution x such that $f_i(x)$ _$f_i(x^*)$ for all i = 1, 2, ..., k, and at least, one inequality is strict.

In the ε-constraint method, if $f_j(x), j$ õ $\{1, .., k\}$ is the objective function chosen to be optimized, and $f_i(x)$ is objective considered as the constraint, we have the following problem[22, 23].

$$Min\{f_1(x)\, j \in \{1, \ldots \ldots, k\} subjectto$$
$$fi(x) \leq \varepsilon_i \;\forall\, i \in \{1, \ldots, k\}, i \neq j, x, \in S$$

Where, s is the feasible solution space, k is the number of objective functions, and ε_i is assumed values of the objective function that must not be exceeded.

5.2. Objective Function and Constraints

The annual cost of the system (ACS) is considered as objective function and CO_2 emission and LLP during one year are considered as the constraint bounds, where x is the vector of the sizing variables $x = \{N_{pv}, N_{bat}, P_{dg}\}$, where N_{pv} is the size of SPV modules, N_{bat} is the size of batteries and P_{dg} is the rated capacity of diesel generator. The system costs consist of the annual capital cost (ACC), annual operation and maintenance cost (AOM), annual fuel cost (AFC), and annual replacement cost (ARC), ACS is calculated using the following equation:

$$ACS = ACC + AOM + ARC + AFC \tag{8}$$

Annual capital cost of each unit that does not need replacement during project lifetime such as DG, PV, and inverter is calculated as follows:

$$ACC = C_{cap}.CRF(i, y) \tag{9}$$

where; C_{cap} is the capital cost of each component in US\$, y is the project lifetime in a year. CRF is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows. This factor is calculated as follows:

$$CRF = \frac{i\left(1+i\right)^{y}}{\left(1+i\right)^{y}-1} \tag{10}$$

where i is the annual real interest rate. Here, annual real interest rate consists of nominal interest i and annual inflation rates f. This rate is calculated as follow:

$$i = \frac{\left(i'-f\right)}{\left(1+f\right)} \tag{11}$$

Annual operation and maintenance cost of system (AOM) as a function of capital cost, reliability of components (λ) and their lifetime can be determined using the following equation[24, 17]:

$$AOM = C_{cap}.(1 - \lambda)/y \tag{12}$$

ARC is annual cost value for replacing battery banks during the project lifetime. Economically, annual replacement cost is calculated using the following equation[24].

$$ARC = C_{rep}.SFF(i, y_{rep}) \tag{13}$$

where $Crep$ is the replacement cost of battery banks in US\$, $yrep$ is the lifetime of battery banks in a year. SFF is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as following[24]:

$$SFF = \frac{i}{\left(1+i\right)^{y}-1} \tag{14}$$

The economic parameters of the system are presented in table 1.

Table 1
Economic parameters of the system.

Nominal interest rate i' (%)[24]	8.25
Inflation rate f (%)[24]	8.17
Project lifetime (years)	20
PV panel lifetime (years)	20
Battery banks lifetime(years)	7
Inverter lifetime (years)	20
Reliability of PV panels	0.98
Reliability of inverter	0.98
Reliability of battery banks	0.98
Reliability of diesel generator	0.9
Cost of PV panel ($/Watt)[25]	2,3
Cost of diesel generator ($/kW)[26]	375
Cost of a battery ($/kW)[25]	426
Cost of an inverter ($/kW)[25]	711
Fuel cost ($/L)[27]	0.14
Emission factor (kg/L)[21]	2.6

5.3. The Problem Constraints

As previously mentioned the problem constraints that should be met are: LLP and CO_2 emissions:

Loss of load probability of the system LLP is defined by Equation (15) and it should be less than allowable LLP reliability index [21, 28].

$$LLP = \frac{\sum_{t=1}^{8760} shortage(t)}{\sum_{t=1}^{8760} D(t)}$$

$$LLP \leq \varepsilon_{LLP} \tag{15}$$

where $D(t)$ is electricity demand, and shortage (t) is unmet load during time period t[21].

The number of kg produced CO2 by diesel generator is considered to represent the pollutant emission and it is calculated using Equation[21, 28] The CO2 emission should be less than allowable emission level:

$$CO_{2_{emission}} = \sum_{t=1}^{8760} fuel_{cons}(t) \times EF$$

$$CO_{2_{emission}} \leq \varepsilon_{CO_2} \tag{16}$$

EF is the emission factor for a diesel generator, which depends on the type of fuel and diesel engine characteristics. Here this is considered as 2.4-2.8 kg/L rang[21].

Some other feasible operation constraints should be considered:

The constraints of the number of PV modules and batteries and capacity of DG:

$$n_{mod}, n_{bat}, P\_d \geq 0 \tag{17}$$

The constraints of the capacity of batteries:

$$G_{Bmin} \leq C_B(t) \leq C_{Bmax} \tag{18}$$

The energy flow (energy produced by or entered to each component) in every time ($Ej(t)$) should be less than the capacity of the component. Where, Δt is the time interval that is 1 h.

$$E_j(t) \le P_j \times \Delta t \tag{19}$$

6. PARTICLE SWARM OPTIMIZATION ALGORITHM

PSO is a meta-heuristic optimization technique, PSO is inspired firstly by general artificial life, the same as bird flocking, fish schooling and social interaction behavior of human and secondly by random search methods of the evolutionary algorithm [29].

It does not require good initial solutions to start its iteration process. The particle moves towards an optimum solution through its present velocity and its individual best solution obtained by itself in each iteration and global best solution is obtained by all particles. In a physical dimensional search space, updated position and velocity of the ‘ith’ particle are represented as:

$$v_i^{k+1} = K\left[v_i^k * \omega + C_1 * R_1 * \left\{p_{best}(i) - x_i^k\right\} + C_2 * R_2 * \left\{g_{best} - x_i^k\right\}\right] \tag{20}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{21}$$

Where $x_i = [x_{i1}, x_{i1}, \ldots\ldots\ldots\ldots\ldots\ldots x_{id}]$

$v_i = [v_{i1}, v_{i1}, \ldots\ldots\ldots\ldots\ldots\ldots v_{id}]$ Here 1, 2,……..d shows possible dimensions for $i = 1, 2, \ldots n$ particles with position ‘x’ and velocity ‘v’

$p_{best}(i) = \left[X_{i1P_{best}}, X_{i2P_{best}}, \ldots\ldots X_{idP_{best}}\right]$ represent individual best positions of particle i.

$g_{best} = \left[X_{1G_{best}}, X_{2G_{best}}, \ldots\ldots X_{nG_{best}}\right]$ represent the global best positions. k represents the iteration number for total n iterations.

ω is inertia weight, K is constriction factor, C_1 C_2 are non negative coefficients called acceleration factors, R_1 R_2 are two random numbers different from each other and generally distributed in the range [0,1]. Suitable selection of ω provides a balance between global exploration and local exploitation reduces the total number of iterations[30].

7. RESULTS AND DISCUSSION

The PSO and the ε-constraint method have been applied to determine the optimal configuration of a hybrid system including PV panels, batteries and diesel generator, the system is designed to supply power for the

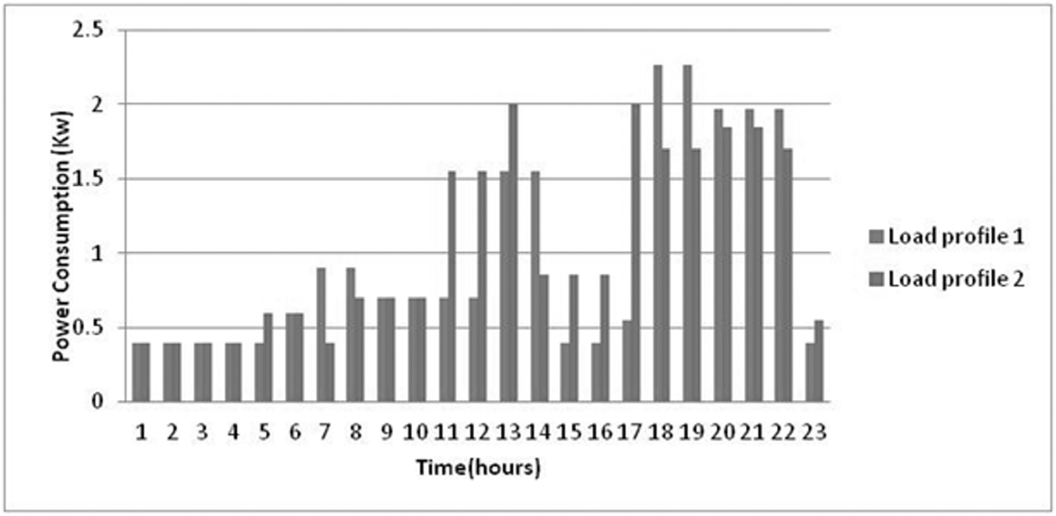

Figure 4: Load profiles variations of the remote village Ilamane (province of Tamanrasset, Algeria)

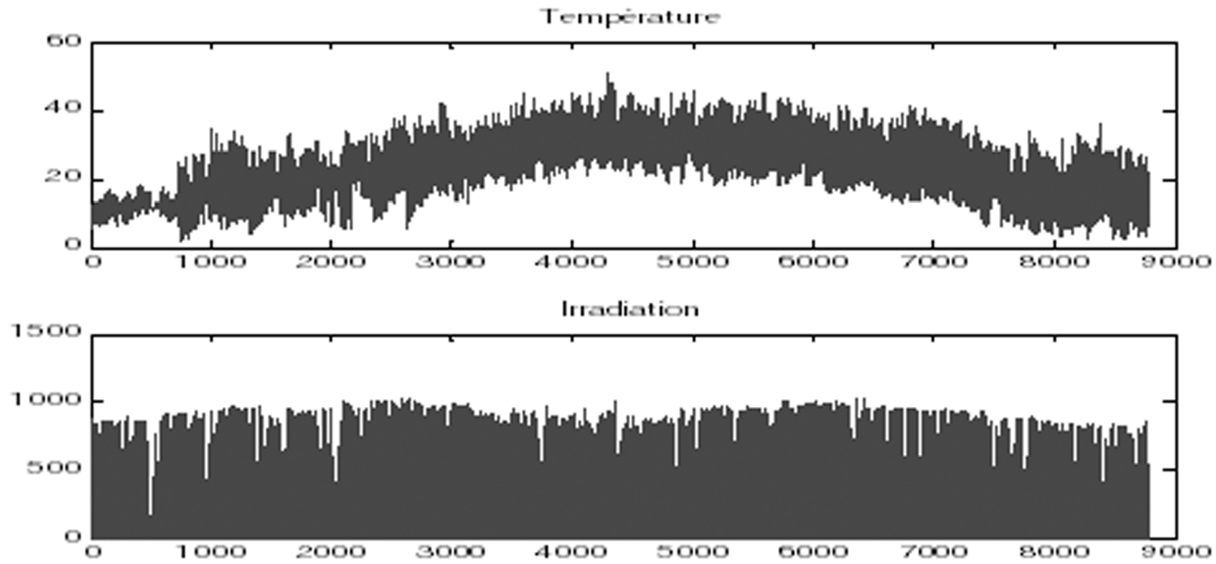

Figure 5: Meteorological data of the site village of Ilamane (province of Tamanrasset, Algeria).

remote village Ilamane, province of Tamanrasset in the south of Algeria (latitude 23.12°N and longitude 5.27°E). Two daily load profiles variation are represented (winter and summer daily load profile) by a constant sequence of power over a step of time of one hour as shown in Figure 4. The suggested load profiles have been derived based on standard of living, traditions, behavior and habits. The system peak demand is small, of the order of 5 kW.

Figure 5 shows the meteorological characteristics (ambient temperature, and daily radiation) of the site. One year real meteorological data (insolation and temperature) are considered.

The Program has been coded in MATLAB. The performance of algorithm has been checked using MATLAB on a core i3, 2.13 GHz, 3 GB RAM.

The swarm size of PSO algorithm consist of 30 particles, the particle is a vector of three elements [the size of PV panels, the number of batteries, and the capacity of diesel generator], and each vector represents a certain configuration of the system. The best interval for PSO parameters ω, c1 and c2 are suggested According to literature: Acceleration coefficients C_1 and C_2 are set within the range of [0-4]. In this study we use the formula suggested[31]:

$$\omega(i) = \omega_0 * \exp\left(\frac{i}{\max\ i}\right)^n \tag{22}$$

where ω_0 is initial weight, *i* is iteration number, max i is maximum iteration number and n is curve shape control power. Economic parameters considered for system optimization are shown in Table 1. For a different range of CO_2 emission level and LLP, the results are presented in Table 2 and Figure 6.

The results show that the input parameters (ε_{co2}) is the most likely to affect the system behavior than the ε_{LLP}, for ε_{LLP} constant and ε_{co2} ranges from 90 Kg/yr to 3000 Kg/yr ,the ACS is changing from 3925.53$ to 2355.32$ (figure 6). And for ε_{co2} constant and ε_{LLP} ranges from 0% to 5% the results are the same.

It can be observed that the last configuration ($N_{pv} = 76$, $N_{bat} = 48$, $P_{dg} = 2$ kW) with ($\varepsilon_{co2} = 468$ kg/yr and $\varepsilon_{LLP} = 5\%$) has the minimum ACS and all power generators are enough to satisfy the load demand without any unmet load. The designers can select other configurations which fits their desire

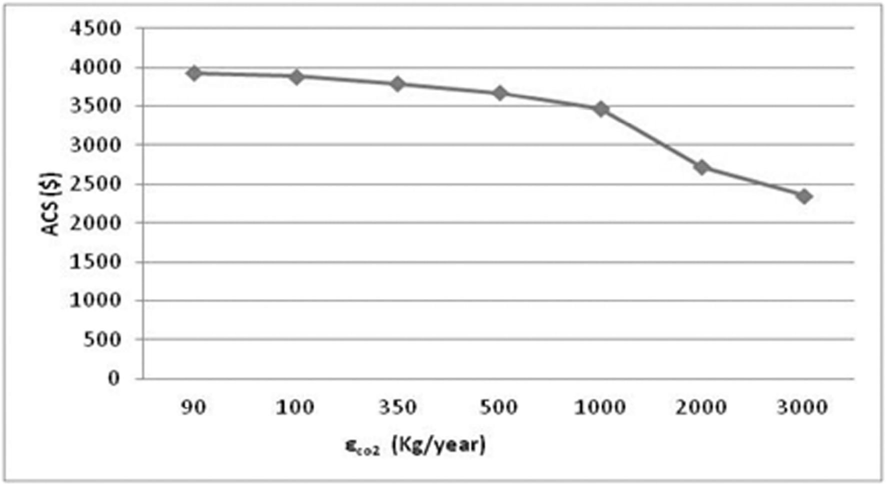

Figure 6: Cost of the system variations with the ε_{co2}

Table 2
The results of the simulation obtained from different constraints.

ε_{CO2} (kg/yr)	ε_{LLP} (%) (kW)	PV power	Battery bank capacity (kW)	Diesel generator (kW)	Inventer capacity (kW) (kg/yr)	Annual CO2 Emission	ACC (US$)	AOM (US$)	ARC (US$)	AFC (US$)	ACS (US$)	LLP (%)
3000	5%	5.07	2	2	5.5	2990.2	1392.56	20.34	871.65	70.77	2355.32	0%
2000	5%	4.12	3.26	2.55	5	1941.9	1161.22	22.66	1488.74	45.96	2718.58	0%
1000	5%	4.12	5	2.3	5.5	999.1	1154.52	26.65	2264.23	23.64	3469.04	0%
500	5%	4.12	5.48	2.17	6	496.09	1148.74	27.57	2488.23	11.74	3676.28	0%
350	5%	4.12	5.76	2	6	134.51	1143.07	27.96	2614.77	3.18	3788.98	0%
100	5%	4.19	5.86	2.76	6	96.45	1185.75	29.84	2666.58	2.28	3884.45	0%
90	5%	4.14	6	2.62	5.5	89.39	1169.77	29.8	2723.57	2.11	3925.25	0%
90	2%	4.14	6	2.63	5.5	89.68	1170.02	29.82	2723.57	2.12	3925.53	0%
90	0%	4.14	6	2.63	5.5	89.68	1170.02	29.82	2723.57	2.12	3925.53	0%

8. CONCLUSIONS

In this paper, PSO algorithm and ε-constraint method are used to search for optimal sizing of a standalone hybrid PV/diesel system with battery storage to electrify a small village in the southern of Algeria. Hybridizing PSO with other algorithms can complicate the system, but in our case, the ε-constraint method is used to handle constraints and multiple objectives of the system with simplicity and computational efficiency. The simulation results show that the CO_2 emissions constraint ε_{co2} strongly affect the cost of the system, the size of the battery bank and the size of the PV panels. The size of the battery bank effectively changes the quantity of the CO_2 emissions emitted by the hybrid system but it is more costly than diesel generator.

This methodology can be used for other composition of hybrid systems in any region considering the meteorological data and the load demand.

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