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# Optimal Sizing of Mobile Hybrid Off-Grid Multi-Sources Installation

Majdi Saidi, Seifeddine Ben Elghali, Zhongliang Li, Rachid Outbib, Thierry Le Roux and Emmanuel Cardone

**Abstract**—In many situations, the access to energy can be compromised or limited as for refugee crisis zones, rural areas and military camps. Therefore, it is crucial to be able to ensure the basic electric needs with an off-grid power solution. In this paper, an optimal sizing of a mobile renewable hybrid power system is presented. The proposed solution is composed of a container equipped with a diesel generator, batteries and a photovoltaic system. The optimization process takes into account the particularity of the consumer needs and the accessibility to the local renewable energy resources. In order to investigate the solution performances, simulation results under Matlab\Simulink® are presented and analyzed.

**Index Terms**—Optimal sizing, multi-sources, off-grid, batteries, photovoltaic, diesel generator.

## NOMENCLATURE

### Superscript and subscript

<i>bat</i>	Battery
<i>ch</i>	Charge
<i>dch</i>	Discharge
<i>DG</i>	Diesel generator
<i>max</i>	Maximum
<i>min</i>	Minimum
<i>pv</i>	Photovoltaics

### Variable

$\Delta t$	Sampling period
$A$	Surface
$C$	Price per unit
$E$	Energy
$ED$	Energy deficit
$G$	Solar radiation
$N$	Number
$P$	Power
$SOC$	State of charge
$T$	Time length
$t$	Time instant
$\mathcal{T}$	Concerned period

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## I. INTRODUCTION

Nowadays, power generation and power consumption are becoming more and more diversified. Accordingly, the power supply systems are designed more and more smartly to match the power generation and consumption characteristics. Among different power users and unlike the permanent power users, temporary power supply is widely required in a large number of cases, such as construction, outdoor social events, utilities, remote and telecommunications [1], [2]. In practice, as power supply is temporary, the power supply systems are usually required to be mobile rather than fixed, and to be modular and easily scalable [3].

Depending on the specific power level and application, different power sources can be considered for a mobile power system. In most commercial products, such as those used as uninterrupted power supplier, diesel generators are the most used power sources. However, drawbacks of diesel based mobile power supply, such as high pollution and high fuel cost, have evoked extensive consideration of the local available renewable energy as alternative source to reduce or completely replace the use of diesel generator (DG) [4], [5]. In some critical applications, outdoor military and medical centers for instance, the high noise and the high pollution from a DG are even intolerable. In order to overcome the drawbacks of DG, new strategies have to be explored for reducing its use and for improving its functioning. The reduction of DG use can be achieved generating the demanded energy from hybrid systems using renewable resources and energy storage units [6]. The improvement of the DG functioning can be realized by a suitable control and energy management strategy in system level (see [7] and the references therein). Actually, as the growing interests and the technological advances in renewable technologies, it could be predicted that more and more renewable energy will be considered in the mobile power system designs. In the cases where the use of renewable energy is possible and desirable, battery storage is usually accompanied to exploit the renewable energy more sufficiently and to further reduce or eliminate the use of DG.

Some mobile temporary power supply systems, consisting of renewable power sources, have been proposed. These proposals are mainly published in some patents (see for instance [8] [9]). However, most of these designs are limited on the conception level, whereas a quantitative analysis and design for this special type of power system has not yet been pro-

posed. Proper sizing of a such mobile energy system is the key element in the system design. A properly sized energy system can potentially provide more reliable, less costly power with less environmental pollution and even less system investment [10]. In the literature, many studies have been proposed for sizing both grid-connected and standalone hybrid renewable systems [10]–[12]. As in most cases, a sizing problem can be described as a constrained optimization problem. Once the optimization problem is formulated for a specific case, a variety of optimization methods have also been studied and proposed for this application. Although these studies provide abundant references, the sizing of the mobile power system containing renewable sources has not yet been sufficiently investigated. Actually, some special considerations should be taken into account in the design process of a mobile temporary system. For instance, the system should be able to satisfy various uses, which have different requirements. The system should be able to be installed in different installing conditions, e.g., surface limit, weight limit, climatic condition.

The main objective of the work is to propose the optimal sizing of a mobile power supplier dedicated to a particular use. The considered system consists of photovoltaic (PV) panels, DG and batteries. The optimal sizing is realized by adopting the genetic algorithm, and in consideration of the energy management which is achieved based on a rule-based strategy.

The rest of paper is organized as follows: In Section II, the mobile renewable hybrid system is modeled, and the technological limits of different components are presented. Section III provides the energy management algorithm. In Section IV, the sizing optimization problem is firstly formulated and the solving method is detailed. Then, the optimal results are presented and discussed in Section V. The paper is finally concluded in Section VI.

## II. SYSTEM MODELING AND DESIGN CRITERIA

In this paper, the studied structure is shown in Fig. 1. The system consists of PV system, battery, and DG. According to the particular requirements of users and local renewable resources, different power sources, such as PV system and/or wind turbine and/or hydro-turbine system can be added to the proposed structure.

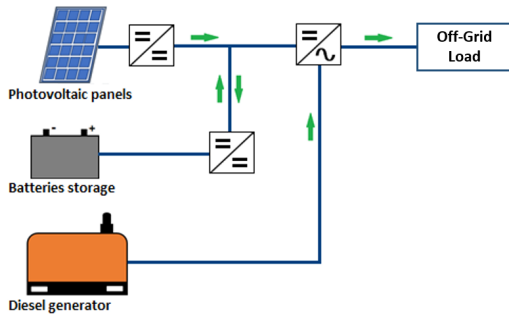


Fig. 1. Mobile Renewable Hybrid Power System

In the sequel, the analysis period will be denoted by  $\mathcal{T} = (0, T)$  where  $T$  is the duration. We define the number of samples by  $N_{\mathcal{T}} = \lfloor \frac{T}{\Delta t} \rfloor$  where  $\Delta t$  denotes the sampling period.

### A. Photovoltaic system

Assuming that PV panels used in the considered system are controlled by a maximum power point track regulator, the power generated by a single panel, denoted  $P_{PV}(t)$  for  $t \in \mathcal{T}$ , is expressed as a function of solar radiation [13], by

$$P_{PV}(t) = G(t)A_{PV}\eta_{PV}, t \in \mathcal{T} \quad (1)$$

where  $G$  represents the solar radiation,  $A_{PV}$  is the surface of the PV panel,  $\eta_{PV}$  is the efficiency of the PV system.

### B. Battery storage system

The technological constraints of the batteries impose some limitation in charging and discharging power  $P_{ch}$  and  $P_{dch}$ , respectively. To take into consideration those limits, the variables  $T_{ch}$  and  $T_{dch}$  are introduced to define the minimum period of charging and discharging, respectively, and we assume that:

$$\begin{cases} T_{dch} \leq \frac{E_{bat}(t)}{P_{bat}(t)} \\ T_{ch} \leq \frac{E_{bat}(t)}{-P_{bat}(t)} \end{cases} \quad (2)$$

where  $E_{bat}$  denotes the energy stored in battery. It is assumed that  $P_{ch}(t) < 0$ , for  $t \in \mathcal{T}$ , in the considered case since the power flows inversely. The state of charge  $SOC$  is the percentage of rest energy in the battery with respect to the full charged energy.

$$SOC(t) = \frac{E_{bat}(t)}{E_{bat}^{max}} \quad (3)$$

Based on (2) and (3), it is deduced that

$$\left\{ P_{bat}(t) \in \left( -\frac{SOC(t)E_{bat}^{max}}{T_{ch}}, \frac{SOC(t)E_{bat}^{max}}{T_{dch}} \right) \text{ for } t \in \mathcal{T} \right. \quad (4)$$

Moreover, we have to consider the state of charge limitation where a minimum and maximum values, i.e.  $SOC^{min}$  and  $SOC^{max}$ , must be set to preserve the battery from deep discharge and over charging.

$$SOC(t) \in (SOC^{min}, SOC^{max}) \quad \text{for all } t \in \mathcal{T}$$

The feasible operating zone of battery is therefore shown in Fig. 2.

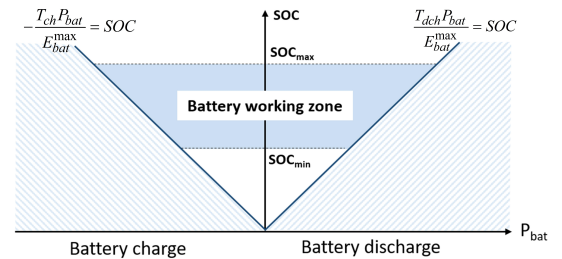


Fig. 2. Battery characteristics

Thus, the instantaneous limits can be expressed by:

$$\begin{cases} P_{bat}^{min}(t) = E_{bat}^{max} \max\left(\frac{(SOC(t)-SOC^{max})}{\Delta t}, -\frac{SOC(t)}{T_{ch}}\right) \\ P_{bat}^{max}(t) = E_{bat}^{max} \min\left(\frac{(SOC(t)-SOC^{min})}{\Delta t}, \frac{SOC(t)}{T_{dch}}\right) \\ t \in \mathcal{T} \end{cases} \quad (5)$$

### C. DG system

The DG characteristics are described by Fig. 3, where the DG efficiency is given according to the power production. The detailed description of the model can be found in [14]. In this study, the curve shown in Fig. 3 is obtained using a look-up table. It can be noticed that the *zone*Ⓘ is characterized by a high decreasing slope and the highest efficiencies are obtained near to the rated output power. Therefore, it is highly recommended to work in *zone*Ⓜ where the diesel efficiency is more than 80%.

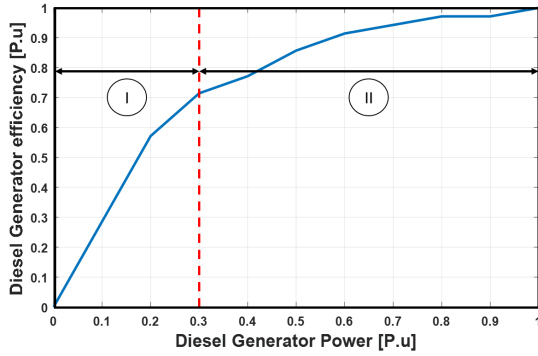


Fig. 3. DG characteristics

## III. ENERGY MANAGEMENT

Energy management must be considered in the process of calculating the sizing criteria. rule-based energy management strategy is adopted for the concerned system. Depending on the different power values and the battery SOC, the load power can be dispatched differently in multiple cases. The energy management strategy is shown as a flowchart in Fig. 4. One objective of the strategy is to use the PV energy as much as possible. Meanwhile, it is also designed to make DG work in the high efficiency or high power zone as possible.

## IV. SIZING OPTIMIZATION

### A. Problem Formulation

The goal of the sizing optimization is to guarantee the load needs during a period  $\mathcal{T}$ , ensure the best working conditions for the DG and minimize the investment cost of the whole installation. In this work, we consider that the solar irradiation  $G(t)$  and the power load  $P_{load}$  are known during the period  $\mathcal{T}$ .

In the sequel, the sizing variables considered are the output rated power of the DG  $P_{DG}^r \in \mathcal{P} = (P_{DG}^{min}, P_{DG}^{max})$ , the number of battery cells  $N_{bat} \in \mathcal{N} = \{0, \dots, N_{bat}^{max}\}$  and the

PV panel total surface  $S_{pv} \in \mathcal{S} = (0, S_{pv}^{max})$ .

In this study, the sizing optimization aims to solve simultaneously three sub-problems under the following constraint

$$\boldsymbol{\theta} \in \Theta \quad (6)$$

with  $\boldsymbol{\theta} = (P_{DG}^r, N_{bat}, S_{pv})^T$  and where  $\Theta = \mathcal{P} \times \mathcal{N} \times \mathcal{S}$ .

More precisely, the objective of the first sub-problem is to minimize the system investment cost, as

$$\begin{aligned} \min F_1(\boldsymbol{\theta}) &= \langle \boldsymbol{\theta}, \mathbf{C} \rangle \\ \text{s.t. } \boldsymbol{\theta} &\in \Theta \end{aligned} \quad (7)$$

where  $\mathbf{C} = (C_{DG}, C_{bat}, C_{pv})^T$  is the vector composed by the prices of different elements.

The goal of the second sub-problem is to maximize the average of DG efficiency in the concerned period, as

$$\begin{aligned} \max F_2(\boldsymbol{\theta}) &= \sum_{k=0}^{N_{\mathcal{T}}} \eta_{DG}(k\Delta t) \\ \text{s.t. } \boldsymbol{\theta} &\in \Theta \end{aligned} \quad (8)$$

The objective of the third sub-problem is to minimize the loss of power supply probability (LPSP)  $F_3$ , as

$$\begin{aligned} \min F_3(\boldsymbol{\theta}) &= \frac{\sum_{t=0}^{N_{\mathcal{T}}} ED(k\Delta t)}{\sum_{t=0}^{N_{\mathcal{T}}} P_{load}(k\Delta t)\Delta t} \\ \text{s.t. } \boldsymbol{\theta} &\in \Theta \end{aligned} \quad (9)$$

where  $ED$  is energy deficit which can be expressed, for all  $t \in \mathcal{T}$ , by

$$ED(t) = P_{load}(t) - (P_{pv}(t) + P_{DG}(t) + P_{bat}(t)) \quad (10)$$

The defined three sub-problems do not possess necessarily a common solution. Thus, the problem of sizing optimization can be formulated as the following multi-objective optimization problem.

$$\begin{aligned} \min \{F_1(\boldsymbol{\theta}), -F_2(\boldsymbol{\theta}), F_3(\boldsymbol{\theta})\} \\ \text{s.t. } \boldsymbol{\theta} \in \Theta \end{aligned} \quad (11)$$

For ensuring a minimal efficiency of DG functioning and a limited power loss, we consider the following constraints

$$\begin{cases} F_2(\boldsymbol{\theta}) \geq F_2^{min} \\ F_3(\boldsymbol{\theta}) \leq F_3^{max} \end{cases} \quad (12)$$

### B. Solving strategy

In order to solve the multi-objective optimization problem described in (11), Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied. The whole flowchart of NSGA-II based sizing is given in Fig. 5 and abstracted as Algorithm I. The solving strategy is based on simulation results. The post-simulation constraints (12) are added to the problem after several simulation runs. Note that the details on crossover, mutate and evolution procedures used in the algorithm are not provided in this paper, but can be found in [15].

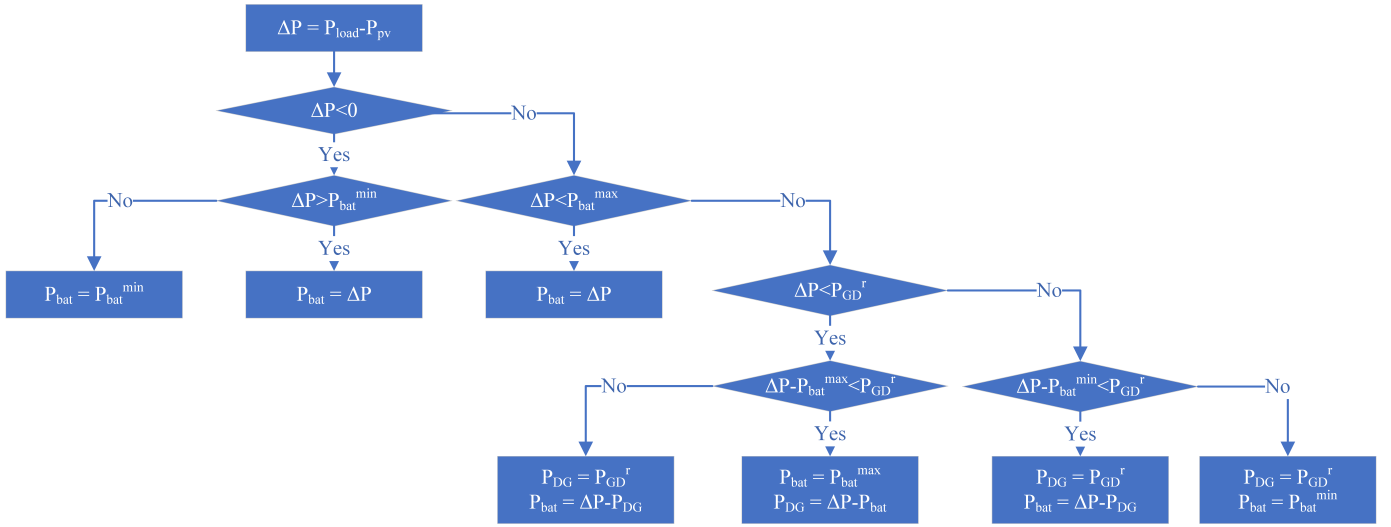


Fig. 4. Flowchart of rule-based energy management

### Algorithm I NSGA-II based system sizing

*/\* it is assumed that technical and economical characteristics of all components are predefined\*/*

**1: Get data**  $G, P_{load}$  */\* For  $t \in \mathcal{T}^*$ ,*

**Initialize**  $j = 1$

**2: For**  $i:=1$  **To**  $N_{individual}$

**Generate**  $Pop^{(i)} = (P_{DG}^{(i)}, N_{bat}^{(i)}, S_{pv}^{(i)})$

**4: Check the pre-constraints** */\*see (6)\*/*

**5: Run energy management** */\*use rules described by Fig. 4 \*/*

**6: Check the post-constraints** */\*see (11)\*/*

**7: Calculate**  $F_1^{(i)}, F_2^{(i)}, F_3^{(i)}$

**8:  $Pop_1^{(i)} = \text{Crossover}(Pop^{(i)})$**

**9:  $Pop_2^{(i)} = \text{Mutation}(Pop^{(i)})$**

**10:  $Pop^{(i)} = \text{Evolution}(Pop^{(i)}, Pop_1^{(i)}, Pop_2^{(i)})$**

*/\*The technical details of the above three functions can be found in [15] \*/*

**11: EndFor**

**12:  $j = j + 1$**

**13: If  $j \leq N_{iteration}$  Then Goto 4**

**Else Return**  $(Pop^{(i)}, i = 1, \dots, N_{individual})$

**EndIf**

## V. RESULTS AND DISCUSSION

### A. Studied case

The proposed sizing strategy is applied to one case where a mobile hybrid energy system is designed for one manufacturer of industrial products. The data of the load power and the local solar radiation in one year are recorded with the sample time  $\Delta t = 1h$ . The technical parameters of the concerned PV panel and battery are listed in Table I.

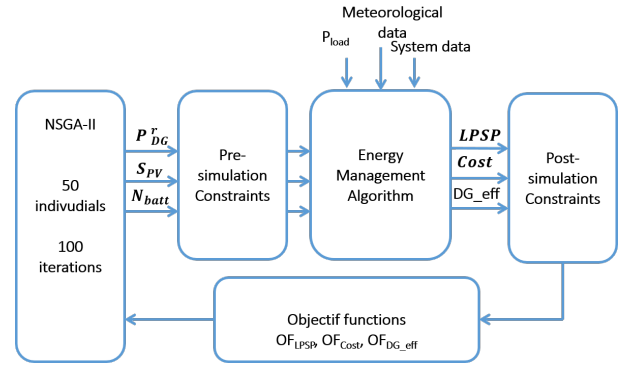


Fig. 5. Optimal sizing process

TABLE I  
TECHNICAL PARAMETERS OF THE SYSTEM

$A_{PV}$	$\eta_{PV}$	$SOC^{max}$	$SOC^{min}$	$T_{ch}$	$T_{dch}$	$E_{bat}^{max}$
1.64 m <sup>2</sup>	0.17	1	0.4	2 h	0.5 h	0.5 kWh

### B. Energy management results

To verify the effectiveness of energy management strategy, the power separation, SOC, battery power, and DG efficiency of 24 h with one solution in the optimal sizing set are shown respectively in Fig. 6, Fig. 7, Fig. 8 and Fig. 8. It can be seen that  $SOC$  evolves between the limits and the functioning power points of battery are all within the feasible functioning zone. The DG efficiency is maintained at relatively high values (higher than 0.8) when DG is activated.

### C. Sizing results

Fig. 10 shows the front Pareto optimal solutions. It can be noticed that for lower LPSP values, the total cost investment can vary in a wide range. In our study, we choose a solution

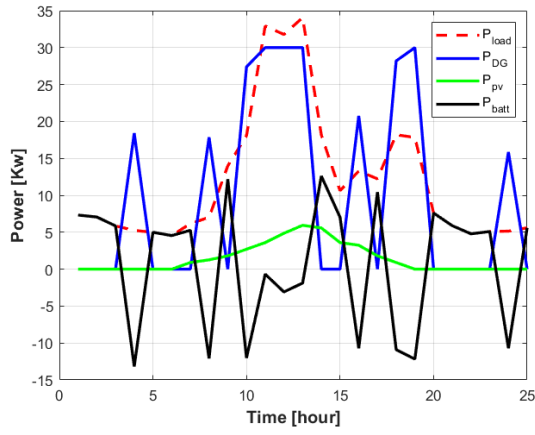


Fig. 6. Power flow during 24 hour

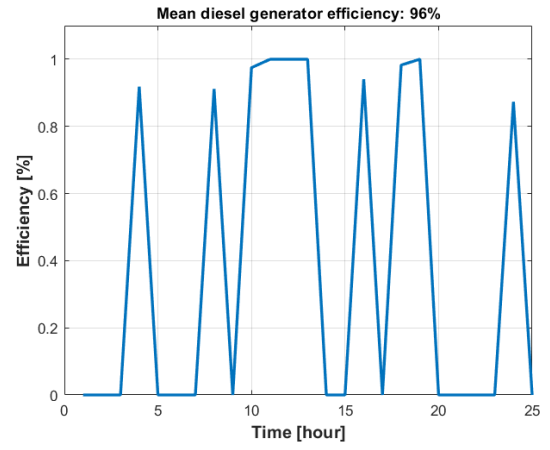


Fig. 9. DG efficiency

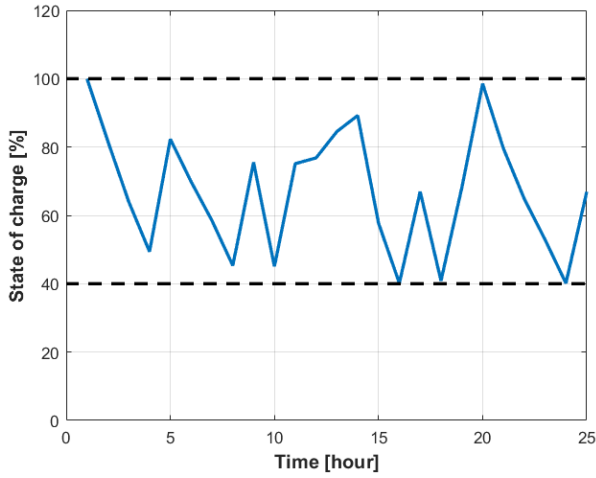


Fig. 7. State of charge

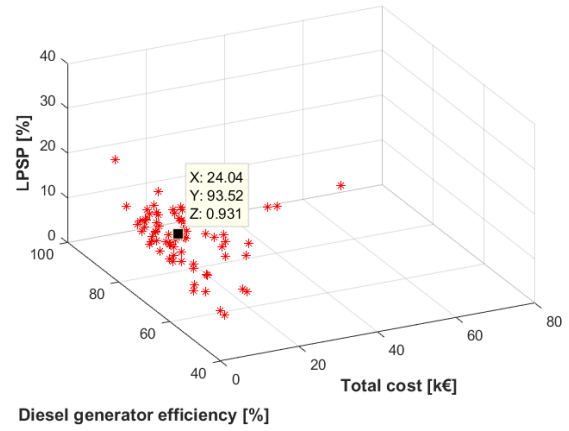


Fig. 10. Optimization results

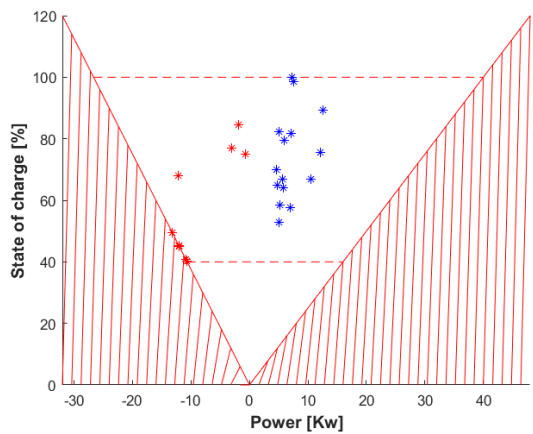


Fig. 8. Battery function points

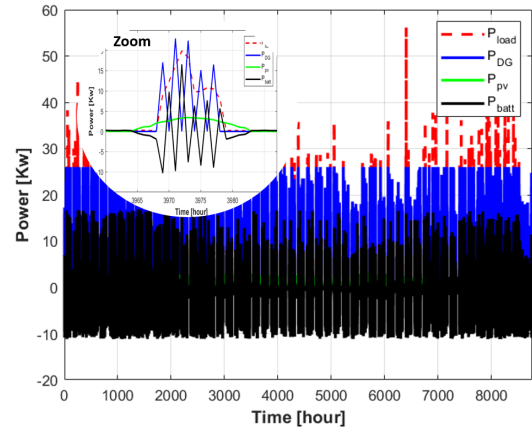


Fig. 11. Hybrid system power

with an LPSP value of 0.9%, and a total cost of 24k. The three criteria corresponding the solution is shown in the figure.

Only the peak load consumption is not guaranteed, as shown in Fig. 11. The adopted energy management allowed a high efficiency of the DG with a mean value of 93% during the period  $\mathcal{T}$ .

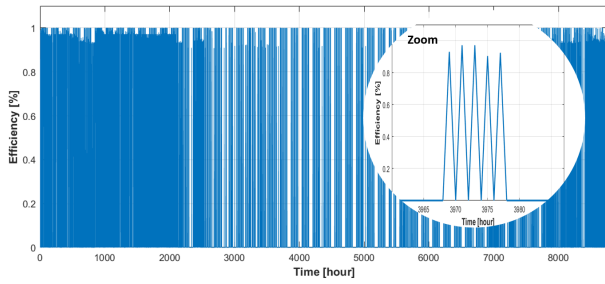


Fig. 12. DG efficiency

The Fig. 13 and 14 show that battery limits are respected according to the SOC value and charging and discharging power limits. However, in Fig. 14, we note that the discharging operating points are far away from the discharging limit. Therefore, it could be more financially interesting to use another battery technology with different discharging constraints.

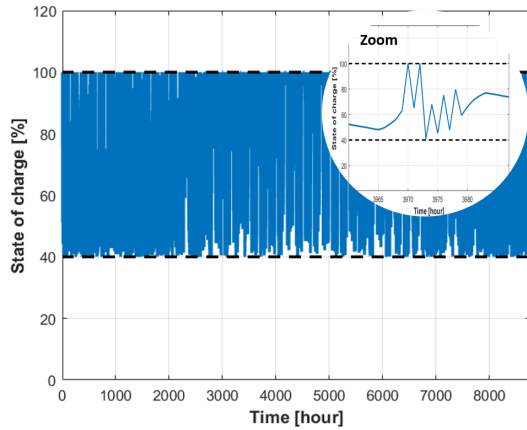


Fig. 13. Battery state of charge

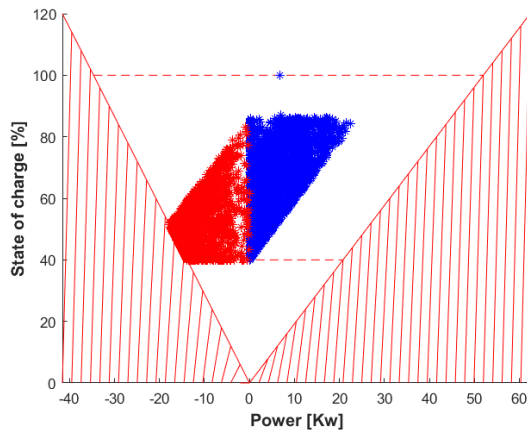


Fig. 14. Battery function points

## VI. CONCLUSION

In this study, a sizing optimization problem of a mobile renewable hybrid off-grid power system is studied. A multi-objective NSGA-II is proposed to solve the problem according to the system constraints. The optimization process takes into account the energy management to ensure a high operating efficiency of the DG and to maximize the photovoltaic contribution. This study can be extended to any other type of renewable energies (wind turbine, hydro power, etc.), depending on the local renewable resources, and it can be adapted to any particular consumer needs.

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