Revue des Energies Renouvelables Vol. 18 N°2 (2015) 179 – 191
DOI: https://doi.org/10.54966/jreen.v18i2.495

Optimal sizing of a stand-alone photovoltaic systems under various weather conditions in Algeria

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(reçu le 02 Novembre 2014 – accepté le 30 Mai 2015)

Abstract - *This paper presents an analytical method for technical-economic optimization of a stand-alone photovoltaic system. The loss of load probability concepts for the reliability and the total system cost for the economic criteria. The main objective of this study is to find the optimum PV generator area and useful battery storage capacity of a stand-alone photovoltaic system. Mathematical equations have been formulated and LOLP curves have been constructed. A set of configuration meeting the desired LOLP are obtained. The configuration with the minimum cost gives the optimal one. A case study has been presented to determine the optimal sizing of a stand-alone photovoltaic system for eight sites located at Algeria and to analyze the impact of different parameters on the system size. This proposed analytical method is rational in terms of reliability and cost and simple to implement for the size optimization of a stand-alone photovoltaic system at any geographical location.*

Résumé – *Cet article présente une méthode analytique pour l'optimisation technico – économique d'un système photovoltaïque autonome. Le concept de délestage de la consommation (LOLP) pour la fiabilité et le coût total du système comme un critère économique. L'objectif de cette étude est de trouver la surface d'un générateur PV et la capacité utile de la batterie optimale pour un système photovoltaïque autonome. Des équations mathématiques ont été formulées et des courbes de LOLP ont été construites. Un ensemble de configuration pour le LOLP désirée a été obtenu. La configuration optimale est celle obtenue avec un coût minimale. Le cas étudié pour déterminer la taille optimale d'un système photovoltaïque autonome pour huit sites cités en Algérie et d'analyser l'influence de différents paramètres sur la taille du système. La méthode analytique proposée est efficace en termes de fiabilité et de coût, et simple d'être implémenter pour l'optimisation de la taille d'un système photovoltaïque autonome à n'importe quel site.*

Keywords: Photovoltaic system – Modelling – Simulation - Optimal size – Optimizations Techniques – Total system cost.

1. INTRODUCTION

The absence of an electrical network in remote regions and the prohibitively high connection cost due to large distances and irregular topography lead often the various organizations to explore alternative solutions [1].

Stand alone photovoltaic (SAPV) systems are increasingly viable and cost effective candidates for providing electricity to remote areas. Such as the ones found in some remote areas in Algeria. This SAPV system typically consists of a PV array, controller, battery storage and inverter for AC loads [2].

The successful operation of the SAPV system is to find the optimum relationship between the PV array and battery storage to meet load demand. Therefore, one optimum sizing method is essential. The sizing optimization method can help to guarantee the lowest investment with full use of the renewable energy systems [3].

In the literature, various techniques of sizing optimization are used of SAPV system can be applied to reach a techno-economically optimum. They must search an optimum combination of two factors: the system cost and power reliability. The relation-ship between the system cost and reliability should be closed studied, so that an optimum solution can be reached.

In our previous works [4], we presented the current status of research on optimum sizing of SAPV systems in period of (1981-2013) and we found a variety of methods such as intuitive, numerical and analytical. The numerical methods have the advantage of being more precise and accurate than the others methods. The drawbacks of these methods are the long calculation times required and the need for long term time series data of solar radiation.

In short, the numerical methods are the more accurate but also the more difficult to put into practice. Analytical methods which use equations to describe the PV system size as a function of reliability. The advantage of these methods is that they combine accuracy and simplicity. They allow the designer to optimize the energy and economic cost of the PV system [5].

The merit of a SAPV system should be judged in terms of the reliability of the electricity supply to the load. This is usually quantified by the concept of loss of load probability (LOLP) [6]. This concept is defined as the relation-ship between the energy deficit and the energy demand, as referred to the load, during the total operation time of the installation [7].

Many of the analytical methods employ this type of methodology for sizing SAPV systems. In [6], a variety of numerical and analytic models for calculating the LOLP are described and evaluated using data for three different climatic condition in Spanish locations (Madrid, Murcia and Santander). For each location, the analytic model requires as input four different coefficients.

The author in [8] presents a model for the LOLP derived by approximating the probability density function of the difference between the daily PV array outputs and the load with two events and by assuming the daily storage charge/discharge process can be represented as a one step Markov process.

In [9], a simple analytical method which allows one to predict the fraction of the load covered by a photovoltaic system as a function PV array area, battery storage capacity, meteorological parameters and the user's load. These methods are based on the graphical information of iso reliability lines. The shape of these lines makes it possible to describe the optimal sizing of system components in an analytic form [10].

In addition to the sizing methods, it's essential for the designers to choose an appropriate optimization technique and take into account the most influential parameters which are suitable for the system sizing. Many optimal sizing techniques were developed based on the worst month scenario [6, 11]. Yearly average month method and worst month method were investigated in [11]. Typical meteorological year data or long period meteorological data were employed by [12].

In this paper, we propose an analytical method to sizing SAPV systems. Firstly, the LOLP is calculated for different size combinations of PV generator area and useful battery storage capacity. Secondary, for the desired LOLP at the given daily energy load, the optimal size combination is obtained at the minimum total system cost at eight selected sites located in Algeria (Algiers, Oran, Chlef, Tlemcen, Laghouat, Ain Sefra, Tamanrasset and Tindouf). Finally, the impact of different parameters on the system size is analysed. The data used in this study were collected from various meteorological locations in Algeria.

2. PROPOSED ANALYSED METHOD

Due to unavailability of long term hourly data, the monthly mean daily solar radiation data is used based on worst month scenario. This method is based on the ideas proposed by Barra *et al.* [13].

The size of SAPV systems is a general concept including the dimensions of the photovoltaic generator capacity 'C_A' and the battery storage capacity 'C_S'. The photovoltaic generator capacity, C_A, is defined as the ratio of the average daily energy produced by the generator to the average daily energy demand.

The battery storage capacity, C_S, is the ratio of the maximum energy that can be extracted from the battery or the useful battery storage capacity 'C_U' to the average daily energy demand. The battery storage capacity represents the number of days of autonomy in which battery can supply the required energy to load without receiving any energy from the photovoltaic generator [10].

The expressions of C_A and C_S are given by [14]:

$$C_A = \frac{\eta \,.\, A \,.\, G_m}{L} \tag{1}$$

$$C_S = C_U / L \tag{2}$$

where, η is defined follows [13]:

$$\eta = \eta_{PV} \cdot \eta_{MPTT} \cdot \eta_{bat} \cdot \eta_{ond} \tag{3}$$

C_U is expressed as found in [7]:

$$C_U = C_{bat} \,.\, DOD_{max} \tag{4}$$

where, L, average daily energy demand (Wh/day); A, area of the photovoltaic generator (m^2); G_m, monthly average daily incident solar radiation on the generator surface, (Wh/m^2.day); C_{bat}, nominal capacity of the battery (Wh); C_U, useful battery storage capacity (Wh/day); DOD_{max}, maximum depth of discharge of battery. η_{PV}, η_{MPPT}, η_{bat} and η_{ond} are the efficiencies of PV generator, the power tracker, the battery storage and the inverter respectively.

The explicit analytical formulas which relates the average fraction of the energy load covered by the SAPV system during the m^{th} month, y_m, with their size is expressed by [13]:

$$(C_A - y_m) \times (1 - y_m) = \gamma \tag{5}$$

This equation represents a hyperbola curve whose asymptotes are the straight lines:

$$y_m = C_A \qquad \text{and} \qquad y_m = 1 \tag{6}$$

The first means that, for small size SAPV system, all the energy produced by the PV generator is transferred to the load. The second comes from the consideration that, for large field areas, the energy supplied by the generator is always able to satisfy the load [6].

Where γ is free parameter depending on the battery storage capacity. Their proposed model is given by [13]:

$$\gamma = a \times \tau^{-b} \tag{7}$$

$$\tau = C_S \cdot K_{tm} \cdot \Delta_m \cdot \eta_{bat} \tag{8}$$

Where, Δ_m, monthly average of the fractional length of the day from sunrise time to sunset time. K_{tm}, monthly average clearness index. a and b, constant parameters.

2.1 LOLP curves

All sizing method requires certain level of reliability that the consumer will tolerate the breakdown of power supply. In this study, the reliability of the system is expressed in terms of loss of load probability (LOLP) index by means of LOLP curves.

The LOLP curve represents different pairs of C_A and C_S values which lead to the same value of LOLP for many Algeria locations. The most universal values of LOLP range from $10^{-2} \leq LOLP \leq 10^{-1}$ in domestic application to $LOLP \leq 10^{-4}$ in telecommunication applications [5, 7].

The LOLP curves are expressed by:

$$C_A = y_m + \frac{a \cdot (K_{tm} \cdot \Delta_m \cdot \eta_{bat} \cdot C_s)^{-b}}{(1 - y_m)} \tag{9}$$

Once the LOLP curves are obtained, it’s very simple to design both the capacity of the generator and battery storage capacity.

2.2 System cost

For the desired LOLP, there are many pair’s sets (C_s, C_A), the optimal size combination is obtained at the minimum system cost.

The cost function of the SAPV system is defined as [2]:

$$C_{sys} = \alpha \cdot C_A + \beta \cdot C_s + C_0 \tag{10}$$

Where, C_{sys}, total cost of the SAPV system; C_0, total constant cost including the costs of the controller with MPPT, inverter and installations (US\$); α, unit cost of the photovoltaic field (US\$/W_p); β, unit cost of battery storage (US\$/Wh).

Most of the existing methods found in the literature [5, 6, 15] determined the values of C_A and C_S. The formulated analytical equations for C_A and C_S of the proposed method can also be expressed in terms of PV generator area (A) and useful battery storage capacity (C_U) from {Eq. (1)} and {Eq. (2)} respectively. Furthermore, the cost function can be expressed in terms of A and C_U:

$$C_{sys} = \frac{\alpha \cdot \eta \cdot A \cdot G_m}{L} + \beta \cdot \frac{C_U}{L} + C_0 \tag{11}$$

The minimum cost can be found by equating to zero the derivative of the total cost. So, the condition to obtain the optimum solution of (11) is:

$$\frac{dA}{dC_U} = \frac{-\beta}{\alpha \,.\, \eta \,.\, G_m} \tag{12}$$

{Eq. (12)} is integrated and the analytical relationship between A and C_U is written as:

$$A = \frac{-\beta}{\alpha \,.\, \eta \,.\, G_m} C_U + k \tag{13}$$

The solution of (12) can be solved graphically in the way that the two curves will be drawn in the $A - C_U$ coordinate system. One curve represents different size combinations of the (C_U, A) for the given LOLP. The other curve is the straight lines with a slope of $\left(\frac{-\beta}{\alpha \,.\, \eta \,.\, G_m}\right)$ which are defined by {Eq. (13)}. The tangent point of the two curves corresponds to the optimum size of A and C_U as shown in figure 1.

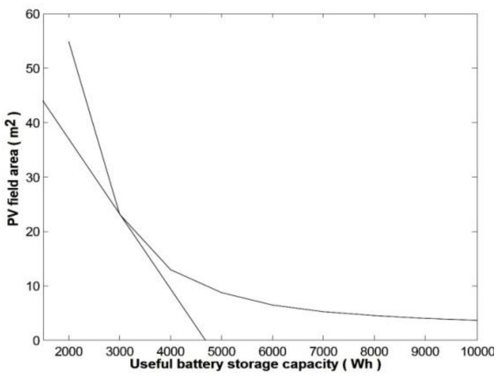


Fig. 1: LOLP curve and cost line with various combinations of A and C_U

Mathematically, the minimum size $(C_{U,opt}, A_{opt})$ is an intersection of a the cost line with the desired LOLP curve for a fixed value of k. Therefore, the value of k is obtained as follows:

$$k = \frac{y_m}{(\eta . G_m / L)} + \frac{a \,.\, J_m^{-b}}{(1 - y_m).(\eta . G_m / L)} C_U^{-b} + \frac{\beta}{\alpha \,.\, \eta \,.\, G_m} C_U \tag{14}$$

With

$$J_m = \frac{K_{tm} \,.\, \Delta_m \,.\, \eta_{bat}}{L} \tag{15}$$

The optimal value of $C_U = C_{U,opt}$ is calculated by equating to zero the derivative of k. So, the expression calculated of $C_{U,opt}$ is:

$$C_{U,opt} = \left(\frac{a \,.\, b \,.\, J_m^{-b} \,.\, \alpha \,.\, \eta \,.\, G_m}{(1 - y_m) \,.\, \beta \,.\, (\eta . G_m / L)}\right)^{(1/1+b)} \tag{16}$$

The optimal value of $k = k_{opt}$ is obtained by putting the value of $C_{U,opt}$ from {Eq.(16)} in {Eq.(14)}.

Finally, substituting both the values of k_{opt} and $C_{U,opt}$ into {Eq.(13)}, the optimum PV generator area ($A = A_{opt}$) is expressed as:

$$A_{opt} = \frac{y_m}{(\eta . G_m / L)} + \frac{a \,.\, J_m^{-b}}{(1 - y_m).(\eta . G_m / L)} \left(\frac{a \,.\, b \,.\, J_m^{-b} \,.\, \alpha \,.\, \eta \,.\, G_m}{(1 - y_m) \,.\, \beta \,.\, (\eta . G_m / L)} \right)^{(1/1+b)} \tag{17}$$

After getting the optimal point ($C_{U,opt}$, A_{opt}), the optimum number of PV module can be calculated by dividing the A_{opt} by the area of a single PV module. Similarly, the optimum number of batteries can be determined by dividing the $C_{U,opt}$ by the capacity of a single battery [10].

3. CASE STUDY BASED ON ALGERIA WEATHER CONDITIONS

The optimization of a SAPV system based on various climatic zones in Algeria is given to show the application of the above introduced method.

The parameter used to define the different climatic zones is the monthly average clearness index for all the considered sites. There exist four zones for different climatic conditions in Algeria which are bound in the following limits [16]:

Zone I	$K_{tm} \leq 0.548$
Zone II	$0.548 < K_{tm} \leq 0.609$
Zone III	$0.609 < K_{tm} \leq 0.671$
Zone IV	$K_{tm} > 0.671$

In this study, the database of monthly average daily solar radiation on the photovoltaic field of the worst month and the monthly average clearness index are available corresponding to the following sites in [16, 17].

The geographical data for the eights sites located in Algeria is shown in **Table 1**. As it can be observed in this table, the locations chosen have different climates and are widespread over diverse latitudes. The climatic zones repartition for the selected sites are:

Zone I	Algiers, Oran
Zone II	Chlef, Tlemcen
Zone III	Laghouat, Ain Sefra
Zone IV	Tamanrasset, Tindouf.

The daily energy demand is assumed to be constant over the year. The mean daily energy demand of 1000 Wh/day for domestic purpose was considered.

3.1 Impact of power reliability on system configuration

Applying the previous explained methodology many different LOLP curves have been calculated.

Table 1: Geographical data for the selected sites [17]

Name of site	Latitude (°)	Longitude (°)	Altitude (m)
Algiers	36.43 N	3.15 E	25
Oran	35.38 N	0.70 W	99
Tamanrasset	22.47 N	5.31 E	1378
Tlemcen	34.52 N	1.19 W	810
Ain Sefra	32.45 N	0.34 W	1072
Tindouf	27.40 N	8.09 W	402
Laghouat	33.38 N	2.52 E	767
Chlef	36.08 N	1.17 E	112

The simulation results, related to the system configurations that guarantee the desired LOLP's (0.01, 0.05 and 0.1) for some of the locations studied (Algiers, Chlef, Laghouat, Tamanrasset) are shown in figure 2.

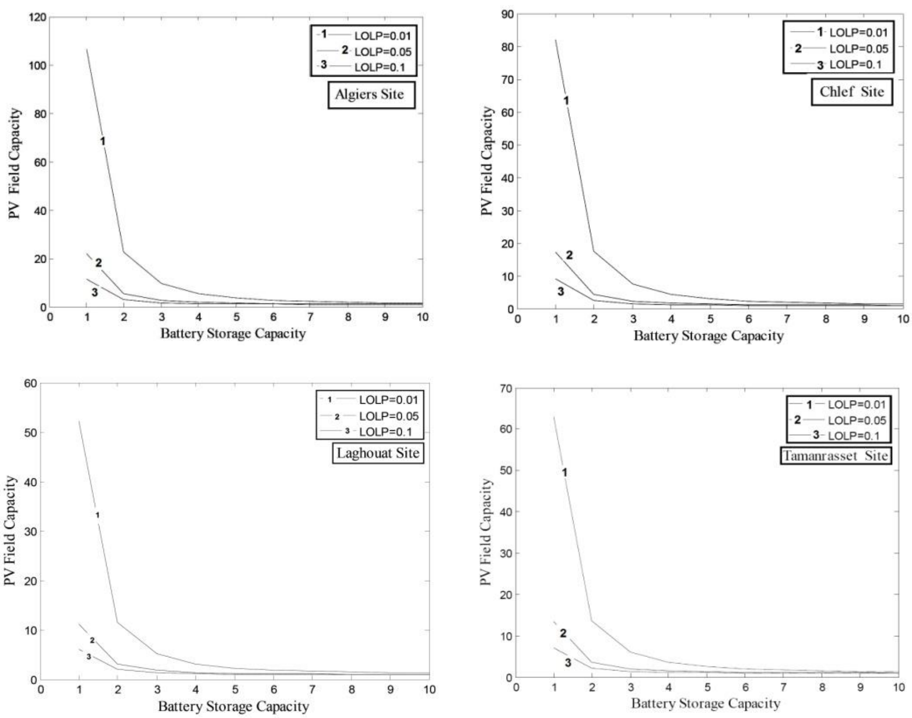
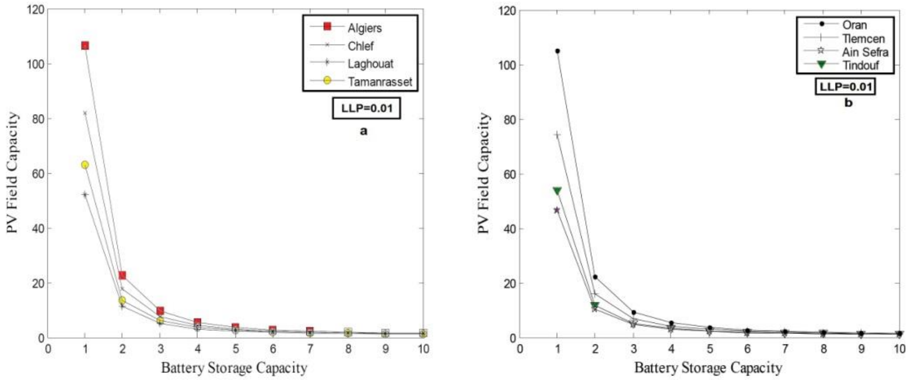


Fig. 2: LOLP curves for Algiers, Chlef, Laghouat and Tamanrasset

For each location, the curves are hyperbolic nature. Each point of them represents the system size (C_S , C_A) that guarantee the desired LOLP value. Different values of LOLP are used varying from 0.01 to 0.1. It's obvious that the PV generator capacity size significantly decrease when the given LOLP value is taken higher.

This diminution depends on the site. Based on these results, the curves can be divided in two intervals and their limits depend on the site. In the first interval, by increasing a battery storage capacity, there is remarkable PV generator capacity decrease, while in the second interval, the PV generator capacity decreases gradually and remains almost constant, with the increase of battery storage capacity.

Figure 3 shows the LOLP curves for the locations considered in this study, with LOLP value of 0.01. There are differences in the PV generator capacity for the different days of autonomy considered depending on whether the locations are Algiers or Laghouat in Fig. 3**a** and Oran or Ain Sefra in Fig. 3**b.** This confirms that the locations belong to different climatic areas. According to these results, the size of PV generator capacity almost more important at the sites of Algiers and Oran than the other sites, while at Laghouat and Ain Sefra sites is relatively low.

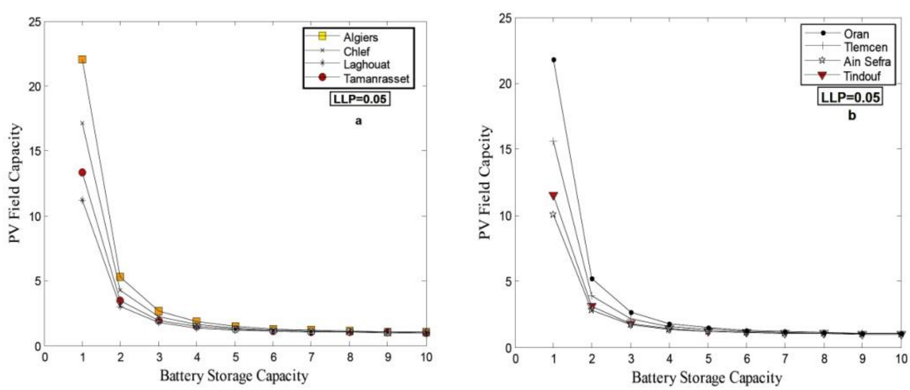


-3**a-** -3**b-**

Fig. 3: LOLP curves for differents locations for LOLP=0.01

This can be explained by that the locations of Algiers and Oran or Laghouat and Ain Sefra belong to same climatic areas.

The results obtained for the previous mentioned locations with a LOLP value of 0.05 are illustrated in Figure 4. In this case, the PV generator capacity are more decrease according to location than in the case of LOLP=0.01 which is confirm by {Eq. (9)}.



-4**a-** -4**b-**

Fig. 4: LOLP curves for differents locations for LOLP=0.05

For all the considered sites, the different values of LOLP for different size combinations of useful battery storage and PV generator area is illustrated in figure 5.

The simulation results show that the system sizing (C_U , A) depends on the system reliability.

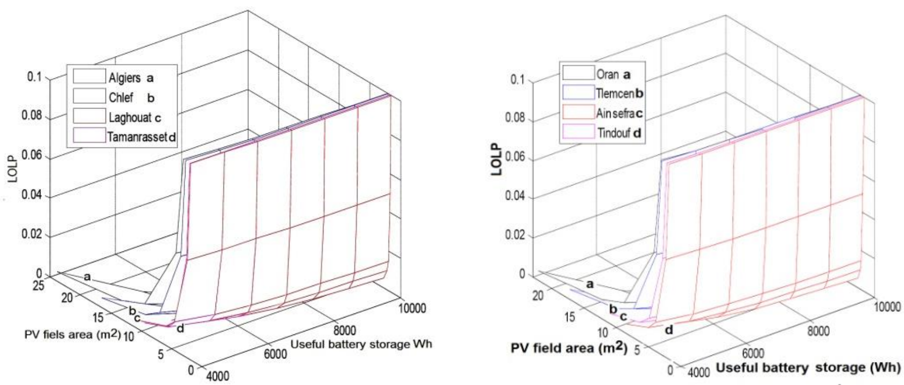
We can be seen that the LOLP is inversely proportionel to the system sizing. With high LOLP values, the PV generator area increases with the LOLP diminution. For lower LOLP values, a considerable increase in the PV generator area in encountered with LOLP diminution in all the considered sites.

3.2 Impact of function cost on system configuration

The function cost is utilized as an economic criteria, the optimal system configuration is the one which has the lowest cost.

At constant load and given LOLP (LOLP = 0.01), the optimal PV generator area (A_{opt}), optimal useful battery storage ($C_{U,opt}$) and optimal total cost of SAPV system without taking consideration total constant costs ($C_{opt} = C_{sys,opt} - C_0$) were calculated at different values of α and β. The simulation results are presented in **Table 2**. According to these results, we can be seen that:

- If α is constant and β varied: increase of β decrease the value of C_U and vice versa (α = 8 and β = 0.2, 0.6).
- If β is constant and α varied: decrease of α increases the value of A and vice versa (β = 0.2 and α = 5, 8).
- If the optimum cost at α and β is calculated, $C_{opt}(\alpha_1, \beta_1)$, the optimum cost at α_1 = x. α and β = x. β is $C_{opt}(\alpha_1, \beta_1)$ = x. $C_{opt}(\alpha, \beta)$ Case: α = 4 and β = 0.3, α = 8 and β = 0.6.
- In general, the southern locations show lower optimum size ($C_{U,opt}$, A_{opt}), as Tindouf and Tamanrasset, than the locations of the north, as Algiers and Oran, whose solar potential is lower.



-5a- -5b-

Fig. 5: Different size combination of useful battery storage and PV generator area at different LOLP values

Figure 6 shows the impact of the LOLPs on the optimal cost of energy for the considered sites. It’s clear that the C_{opt} is found to be sensitive to the desired LOLPs.

It’s observed that with a value of 0.05 instead of 0.01, the optimal cost of energy will get reduced for the different sites. Ain Sefra, Laghouat and Tindouf have the lowest optimal cost than the others sites.

Table 2: Optimal system configuration at different values of α and β

Nom Site	α	β	$C_{U,opt}$	A_{opt}	C_{opt}
Algiers	4	0.3	11931	3.1076	**0.91024**
	5	0.2	14443	2.7959	**09.1000**
	8	0.6	11931	3.1076	18.2047
	8	0.2	16661	2.6375	12.7073
Oran	4	0.3	11604	3.1111	**08.9613**
	5	0.2	14047	2.8052	08.9862
	8	0.6	11604	3.1111	17.9226
	8	0.2	16204	2.6498	12.5760
Chlef	4	0.3	10749	2.8392	**08.5929**
	5	0.2	13012	2.5753	0.8.6888
	8	0.6	10749	2.8392	17.1850
	8	0.2	15010	2.4411	12.2330
Tlemcen	4	0.3	10426	3.2098	**08.4536**
	5	0.2	12621	2.9181	08.5764
	8	0.6	10426	3.2098	16.9071
	8	0.2	14559	2.7698	12.1033
Laghouat	4	0.3	09349.2	2.3277	**07.9895**
	5	0.2	11318.0	2.1328	08.2020
	8	0.6	9349.2	2.3277	15.9791
	8	0.2	13056.0	2.0337	11.6713
Ain Sefra	4	0.3	09026	2.2088	**07.8502**
	5	0.2	10926	2.0288	08.0895
	8	0.6	09026	2.2088	15.7005
	8	0.2	12604	1.9373	11.5416
Taman.	4	0.3	09907.7	2.1598	**08.2303**
	5	0.2	11994.0	1.9708	08.3962
	8	0.6	09907.7	2.1594	16.4605
	8	0.2	13836.0	1.8748	11.8954
Tindouf	4	0.3	09439.7	2.5861	**08.0286**
	5	0.2	11427.0	2.3680	08.2334
	8	0.6	09439.7	2.5861	16.0571
	8	0.2	13182.0	2.2571	11.7077

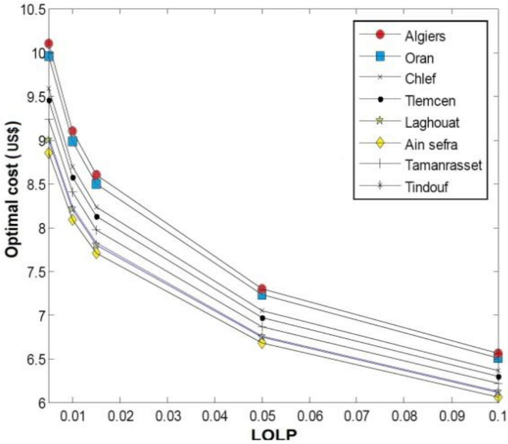


Fig. 6: Impact of LOLP on the optimal cost of energy

3.3 Impact of load on system configuration

At various daily energy load (500, 1000 and 1500 Wh/day) with α and β constant, the PV generator area and useful battery storage capacity is illustrated in figure 7. It's obvious that the increase of load will increase the PV generator area and useful battery storage capacity, corresponding to the optimal combination.

Figure 8 presented the optimum cost (C_{opt}), as a function of daily energy load for different sites. It's clear that, the optimum cost is remaining constant with increase in the load. This figure shows that Algiers site has the higher cost than the others sites. Contrary, Ain Sefra site has the lower cost.

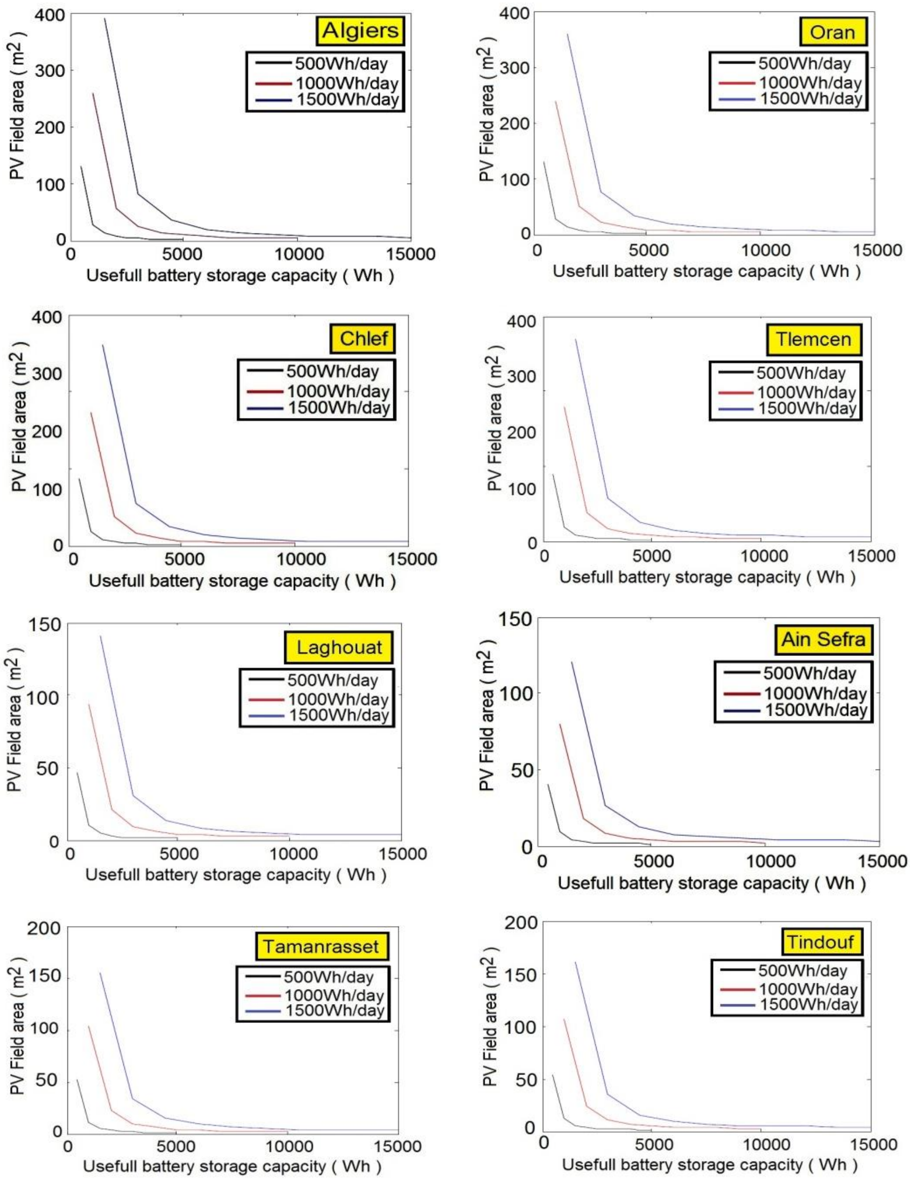


Fig. 7: Impact of load on the LOLP curves for considered sites

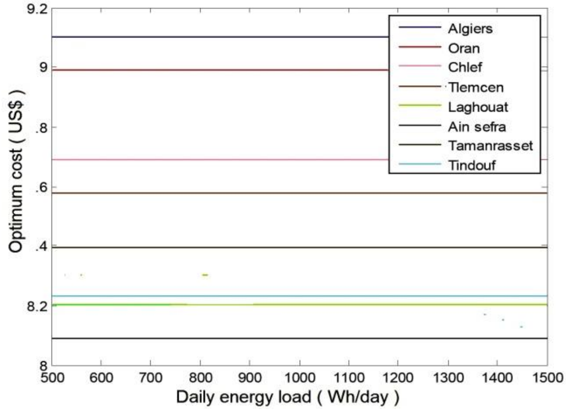


Fig. 8: Impact of load on the optimum cost for considered sites

4. CONCLUSION

This paper presents the sizing and techno-economical optimization of a SAPV systems for eight sites located in Algeria. A proposed analytical method has been developed for the optimal sizing based on reliability and cost by using monthly average daily data of solar radiation in the worst weather conditions.

According to the results, related to the considered sites, it can be concluded that:

- The optimal configuration system size depends on the site.
- The computed optimal PV generator area and the useful battery storage capacity were calculated at the tangent point of the desired LOLP curves. In general, the southern locations show lower optimum size ($C_{U_{opt}}$, A_{opt}) than the locations of the north (case of Tindouf and Tamanrasset)
- For all considered sites, the optimum combination increase with increase in load.
- At Ain Sefra site, the optimal cost (C_{opt}) is found to be the lowest due to the high available solar potential. Hence, the system size is reduced.
- For all considered sites, the optimal cost is remains constant by change in load.

This proposed analytical method can be applied to any locations taking account of the weather conditions, clearness index, efficiencies and costs of the components of size optimization of SAPV system.

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