Loss of Load Probability method applicability limits as function of consumption types and climate conditions in stand-alone PV systems

Cristina Cabo Landeira[1], Ángeles López-Agüera[1], Fernando Núñez Sánchez[1]

[1]Sustainable Energetic Applications Group, Faculty of Physics, Santiago de Compostela University
Rúa Xosé María Suárez Núñez, s/n, Campus Vida, 15705 Santiago de Compostela, Spain

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Abstract - *Sizing a stand-alone photovoltaic system requires to provide the final user a suitable solution in terms of production and sustainability. The simplest sizing procedures ensure the system reliability by increasing the energy storage field capability. This decision makes the PV system environmentally unsustainable and economically non-competitive with fossil fuel sources. A more accurate analytical sizing method, based on the Loss of Load Probability (LLP) has been developed to ensure reliability and decreasing the economic cost. This paper is dedicated to evaluate the working limits of the LLP sizing method in terms of climatic variability. The method is also validated for different power consumptions regimes. Economic cost and lifecycle effects are rudely evaluated as a PV system sustainability estimator. Finally, as an application, the LLP method performance is evaluated on a real stand-alone PV system. The full work is based on experimental solar irradiation and power consumption values.*

Key Words: PV sizing; Stand-alone PV system; LLP; Economic cost; Lifecycle

1. INTRODUCTION

The parameter leading the optimization process of a stand-alone photovoltaic system is undoubtedly the sizing procedure, defined as the method used to calculate the capacity of the collection field (solar panels) and the storage field (batteries).

The simplest sizing procedure is the Worst Month Method, WMM. This method presents some weaknesses associated with the initial working hypotheses: Both power and consumption are considered constant throughout the day and, more important, the storage field is assumed as the exclusive power source. Thus, the PV system reliability is based on the oversizing of the storage field capacity, especially in high seasonality climates. As the batteries are the most expensive component of a stand-alone PV system, the use of the WMM sizing leads to an investment increase [1][2]. Moreover, the batteries price is maintained [3][4][5], while the economic cost of solar panels has sharply decreased in the recent years [6][7].

A more sophisticated alternative for the PV system's sizing is the so-called LLP, Loss of Load Probability, method [8][9][10]. This method is based on the built of isoreliability curves for the PV system location. As merit parameters, the (C_S, C_A) pairs representing the storage size, C_S, and the production fields, C_A are obtained. The LLP method avoids the oversizing in accumulation as low C_S values can be selected along the isoreliability curve. Thus, the economic cost, as well as the reliability levels, will be under control.

Nevertheless, the LLP method, like the previous WMM, considers the consumption as constant, as well as the irradiation level throughout the day. Regarding the reliability levels, which are measured in terms of missing energy, the authors claim to be able to control up to 99.99% reliability levels. Studies about the effect of different and more realistic consumption regimen are desirables.

However, when designing a stand-alone PV system, the aim is not only to ensure the reliability and comfort needs, but also the system's sustainability [11][12]. So, the commonly-referred lifecycle analysis, LCA, should be considered. The LCA includes the economic and energetic costs and the greenhouse gas, GHG, emissions impact [13]. The energetic cost, measured with the Energy Payback Time, EPBT, takes into account the energetic return time of production and final dismantling of the PV system. The GHG emission levels measure the climate change mitigation potential in terms of the associated emissions for power production with fossil fuels [14][15]. In the last years, the modules manufacturing, as well as the recycling energy costs, have decreased. But this cost decrease does not extend to the conventional energy storage systems [5][13].

The objective of this paper is to evaluate the validity limits for the LLP sizing method in terms of the climatic conditions of the PV system's location. Likewise, the LLP proposal has been studied according to the consumption types that may appear on a PV system. The case of variable consumption has been analysed as this is the most common for stand-alone PV systems. The results are compared with the LLP predictions regarding a constant consumption. To avoid model-associated dependencies, the entire study is carried out based on experimental solar radiation data. In the case of energy consumption, both experimental data and analytical modelling have been used. In addition, to optimize the sizing method in terms of sustainability, a simple evaluation of the associated economic and energetic costs is developed. Environmental costs are not evaluated. As an application, a real PV installation has been studied in terms of the LLP sizing method and the associated LCA improvements have been assessed.

2. EXPERIMENTAL SETUP

Most of the published results regarding the method are based on analytical calculations or on climatological models. In this work, and to avoid possible associated biases, a study exclusively based on experimental data is proposed. The radiation data used are collected from a nearby facility. A real PV system allows to obtain the daily consumption values.

2.1 Solar irradiation

The considered solar radiation database is the Meteogalicia's Sergude meteorological station located in Boqueixón (Spain) [16]. With 9 years of historical data, the station is located 5 km far from the PV system. For the analysis, the 8 complete years are considered. Figure 1 shows the solar global horizontal radiation values for the location, G_0.

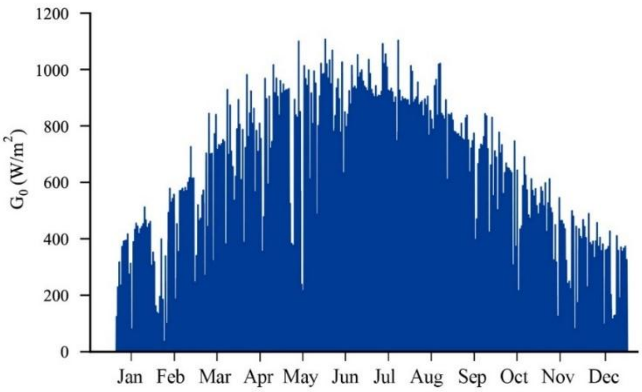


Figure 1. Solar global horizontal radiation daily values for the considered period

2.2 Power consumption data

The data source for power consumption is a single-family home located in Vedra (Spain, coordinates 42.777; -8.459). The Köppen-Geiger climate classification for the location is *Cfb* [17][18]. The power consumption includes illumination and appliances. The power demand profile for the analysis is shown in Figure 2.

The PV system has 24 UMG (upgraded metallurgical-grade silicon) polycrystalline modules plus a test solar panel (Figure 3a) [19][20][21]. The accumulation system for energy storage has 24 OPzS batteries, 660 Ah each, series-connected (Figure 3b) [22]. System sizing was done using the worst month method and considering 3 days for the emergency charge calculation.

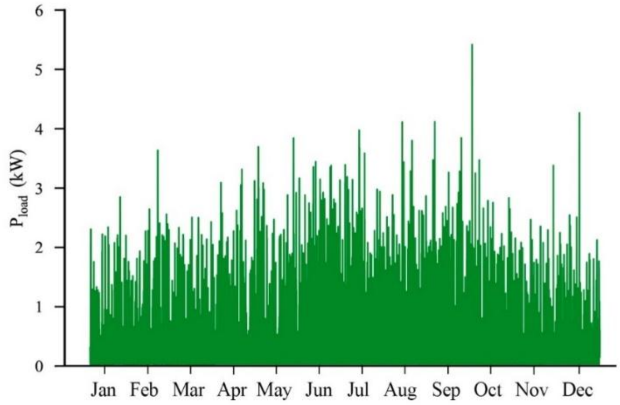


Figure 2. Experimental power load considered for the analysis

Table 1. Photovoltaic solar modules characteristics [23]

Manufacturer model:		Ferrosolar SFS-270 / 270 Wp	
Dimensions (m) / **Weight** (kg):		1,65x0,99x0,046 / 20	
I_{SC}	V_{OC}	I_{MP}	V_{MP}
8,10 A	44,50 V	7,53 A	35,86 V

(a)

(b)

Figure 3. Photovoltaic system array (a) and accumulation system (b)

3. METHODOLOGY

The main objective of this paper is to determine the performing limit for sizing PV systems using the LLP method in terms of climatic variability and consumption regime. For this purpose, the considered variables performing the isoreliability curves algorithm will be defined and the most common final user consumption regimes, catalogued. The economic and energetic associated variables will be defined for a stand-alone PV system.

3.1 Variable definition

The LLP (Loss of Load Probability) PV sizing method [8][9][10][24], takes into consideration the PV system reliability by precisely estimate the fraction of missing energy into a defined time interval. The time interval is usually annual but, to increase the method sensitivity to climatic variations, a daily frequency will be considered in the analysis. The LLP is usually expressed as shown in Eq. 1.

$$LLP = \frac{\sum_{i=1}^{N} E_D(i)}{N} \qquad \text{Eq. 1}$$

where E_D is the energy deficit, expressed as the ratio between the total PV array energy production, E_{Prod}, and the energy consumption E_{Cons} (Eq. 2). It must be noticed that E_{Prod} is the sum of the PV modules production, E_{PV}, and the stored available energy, E_{Batt}.

$$E_D(i) = \frac{E_{Prod}}{E_{Cons}} = \frac{E_{PV} + E_{Batt}}{E_{Cons}} \qquad \text{Eq. 2}$$

Therefore, the energy deficit is function of the accumulation system's State of Charge (SoC). Defined in Eq. 3, depends on the previous charge state, the difference between available and demanded energy and C_U, the maximum extractable energy from the accumulation system. Thus, it can be seen that the SoC depends on C_S and C_A.

$$SoC(t) = \min\left(SoC(t-1) + \frac{E_{Prod}(t) - E_{Cons}(t)}{C_U}, 1\right) = f(C_S, C_A) \qquad \text{Eq. 3}$$

Unlike other authors [10][24], an analytical method was used to reach a relation between C_S and C_A. This relation allows to calculate the isoreliability curves. The software scheme is detailed in [25]. While C_S is function of the accumulation system, C_A depends on the PV array and the installation's location climate [26]. By following the method, the isoreliability curve is defined (Eq. 4).

$$C_A = a\, C_S^{-b} \qquad \text{Eq. 4}$$

where a and b only depend on the latitude and the clearness index, K_T [27][28].

3.2 Power consumption types

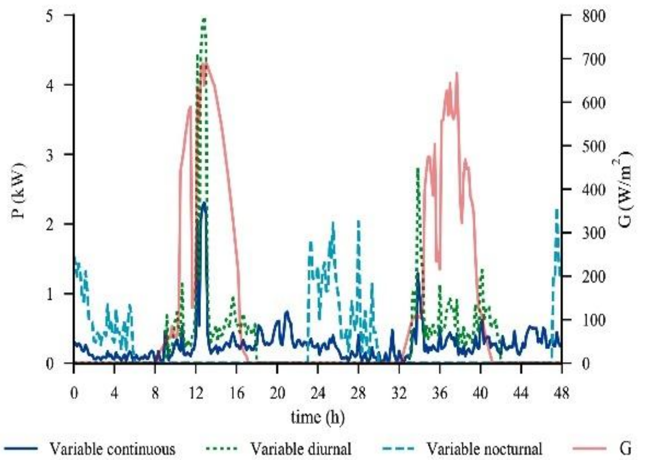
When studying the LLP method, most authors consider constant power consumptions distributed over the 24 hours of a day [8][29][30], while others consider diurnal [31] or nocturnal [32] power demand schemes. Other authors analyse different consumption profiles generated after simple geometrical distributions with profiles repeating along the year [33][34][35][36]. But no one of these hypotheses represents a real consumption profile nor consider seasonal variations.

The consumption types [37] can be classified according to with its mode, frequency and reliability. Regarding the mode, constant and variable are defined. According to the frequency of use, diurnal, nocturnal and daily categories are considered. The reliability, defined as the system's failure probability, depends on the restrictions derived from the installation's application. In the LLP sizing method, this parameter is fixed by the designer as a function of the acceptable failure rate for the final application.

As seen, previous papers consider an average power consumption value as an initial hypothesis. This is equivalent to consider a constant demand profile. But, in real conditions, the power demand profile is variable. This is relevant when considering rural electrification installations, which are the most frequent stand-alone PV systems.

An extra weakness of considering an average consumption value is the impossibility to distinct the mainly diurnal or mostly nocturnal power consumption profiles. For both cases, the average value constitutes an extremely biased estimator.

(a)



(b)

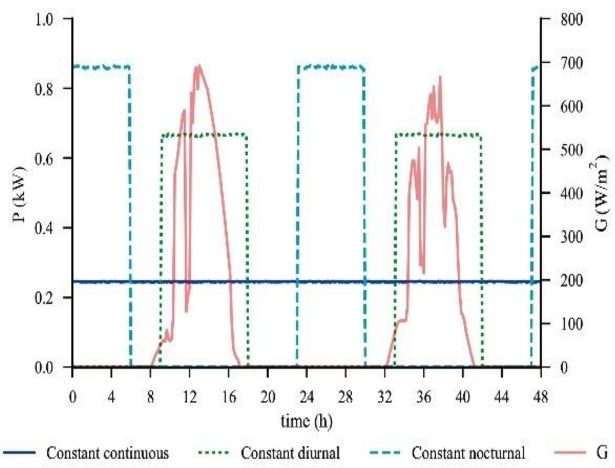


Figure 4. Power consumption profiles. Variable (a) and constant (b)

To visualize the power consumption types, Figure 4 shows the different power profiles together with the solar global radiation. The daily, diurnal and nocturnal variable consumption type corresponds to experimental set-up described before. For the constant power consumption types, the profiles were created considering a constant value with a 1.14% noise. For all the power consumption scenarios, the daily total consumption is equal to the daily average value for the worst month, L.

This paper will study the effect of a variable daily power consumption profiles in PV sizing obtained with the LLP method. Thereby, the validity of the hypothesis of a constant consumption regime can be evaluated.

3.3 Multidimensional costs

A precise calculation of each component of the multidimensional cost is a complex process. But a simple evaluation of the energetic and economic parameters can be done. Starting with the economic calculation and considering only the modules and batteries cost, the economic investment, $Cost_{Econ}$, can be written as shown in Eq. 5.

$$Cost_{Econ} \sim Cost_{PV}\ C_A + Cost_{Batt}\ N_{Rep}\ C_S \qquad \text{Eq. 5}$$

where $Cost_{PV}$ is the cost per unit of PV installed power, $Cost_{Batt}$ is the battery cost and N_{Rep} the number or batteries replacements during the installation lifetime. N_{Rep} value is fixed after the selected batteries technology, considering a 30 years lifespan for the PV system.

As a first approximation, and based upon previous installations experiences, some hypotheses can be assumed:

- Current cost for an installed power unit (Wp) of polycrystalline modules is approximately equal to a Lead-Acid battery storage capacity unit (Eq. 6). This value is expressed as $Cost_{Ref}$ is the reference energetic cost per installed modules and batteries unit.

$$Cost_{PV} \sim Cost_{Batt} \sim Cost_{Ref} \qquad \text{Eq. 6}$$

- Lifespan for a Lead-Acid battery is estimated in 10 years. Thus, the accumulation system should be replaced at least 3 times during the PV system lifespan. N_{Rep}=4 will be considered for security.

- For medium-irradiation regions, the reference power for modules and batteries is almost equal in terms of nominal power. Under these circumstances, the economic cost can be expressed as shown in Eq. 7.

$$Cost_{Econ} \sim Cost_{Ref}\left(C_A + N_{Rep}\ C_S\right) \qquad \text{Eq. 7}$$

For the energetic cost, researches state that the cost of manufacturing a power unit of a PV module doubles the cost for a Lead-Acid battery unit [38][39]. This cost involves the manufacturing plus the recycling of each element. Following the same procedure than in Eq. 5, and considering the batteries replacement number for the system lifespan, Eq. 8 can be written.

$$Cost_{Energy} \sim Cost_{Ref}\left(E_{Manuf}\ C_A + N_{Rep}\ C_S\right) \qquad \text{Eq. 8}$$

4. RESULTS

4.1 Climate sensitivity

Previous research papers consider solar radiation values for a given location to calculate the power production. While some authors use experimental data sources [40], others utilize model-based irradiation values [37][41]. For both cases, average values are considered, it is, the climate-associated variations are not considered.

This section evaluates the climatic variations effect over the isoreliability LLP curves. For this purpose, the curves calculation for different reliability values is performed using 8 years or experimental data records [8].

For the assessment, constant and variable consumption modes for LLP reliability values from 0.1 to 0.001 are studied for the three frequencies (daily, diurnal and nocturnal). Figure 5 shows the isoreliability curves for the daily variable (a) and constant (b), plus the variable diurnal (c) and nocturnal (d) consumption types.

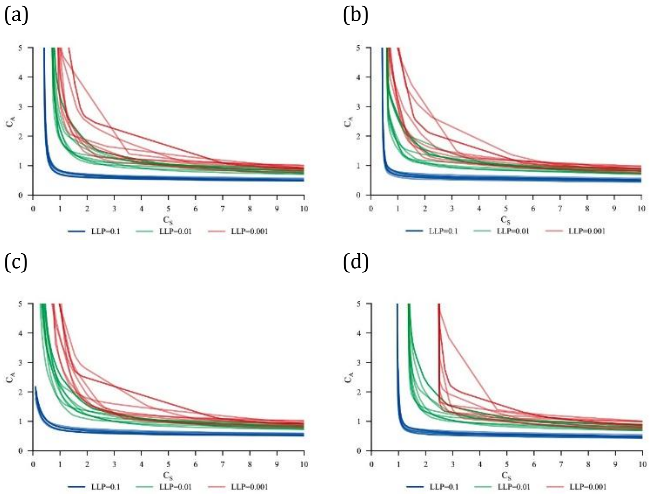


Figure 5. Climate variations effect for (a) Variable continuous,

(b) Constant continuous, (c) Variable diurnal, (d) Variable nocturnal

Results are similar for all the cases. Climatic variations are not remarkable when considering low-reliability values (LLP=0.1). But as the reliability requirements increase to LLP=0.01, the climatic dependence is clearer. This climatic variation effect leads to no concluding results when requiring high reliability, it is, LLP=0.001. For this case, the climate-associated variation is higher than the reliability.

After these results, it can be concluded that using average solar radiation values conceals the effect of this variable on the isoreliability curves calculation. Considering the climate variations, the LLP method is not accurate for high reliabilities, being its validity limit 0.01.

4.2 Power consumption type sensitivity

Aiming to analyse the effect of different consumption types on the isoreliability curves, a dedicated analysis has been developed. Figure 6 shows the corresponding values. For the analysis, a reliability of 0.1 has been selected to avoid the climate-associated variations.

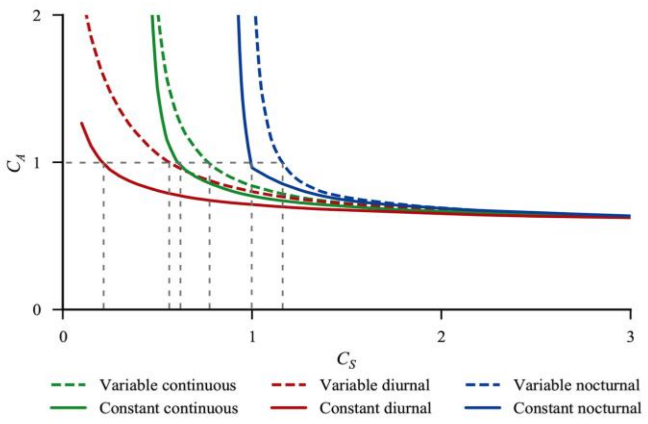


Figure 6. LLP=0.1 for all the considered consumption types

After the Figure 6 plot, some results can be extracted:

- An asymptotical tendency of the PV array to C_A=1 appears for any C_S value over 1.5 times the accumulation system.
- Higher discrepancies appear when increasing the PV modules number. This is important considering the new paradigm, where the tendency is to increase the PV array size.
- The power consumption type variations are remarkable.
- Main discrepancy appears for diurnal consumptions. The huge difference between constant and variable makes that, for the same C_S value, 60% more PV modules are required when considering variable diurnal consumption. Even considering the diurnal frequency scenario, an acceptable reliability requires a battery system.
- For the continuous consumption profiles, even if the effect of the mode (variable or constant) is lower, differences are observed close to the inflexion point.
- Depending on consumption type, the accumulation system increases.

Table 2 shows the numerical results. This result can be compared with the Worst Month Method value, defined by the pair (C_S, 1) where C_S corresponds to the emergency charge, QE. The emergency charge value varies between 2 and 5 depending on climate type. In terms of isoreliability, unless for the nocturnal consumption types, QE can be fixed in C_S=1 and the reliability will be ensured by increasing the PV array size.

Table 1. Storage field size in term of WMM units for C_A=1

	C_S (WMM units)	
	Constant consumption	**Variable consumption**
Daily	0.6	0.75
Diurnal	0.2	0.55
Nocturnal	1.0	1.2

4.2 Optimization of pairs (C_S, C_A) in terms of multidimensional costs

After the presented equations, the most suitable pair (C_S, C_A) in economic and energetic terms can be defined. Since it is known that PV modules have a lower price than accumulation systems, combinations favouring C_A over C_S moving on a same isoreliability line will be advantageous for the system's sustainability (Figure 7).

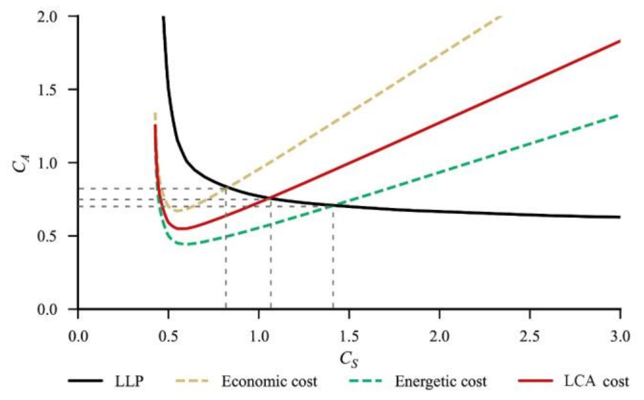


Figure 7. Multidimensional costs for variable continuous power consumption with LLP=0.1

The relevance of the system's sizing optimization by increasing the PV modules instead of batteries is even more relevant when considering highly irradiated regions. For these regions, less PV installed power is required to reach the same production than in lower irradiated areas. This represents a paradigm shift as, for several years, the tendency led to add batteries to increase reliability due to high PV modules prices. As solar panels cost decreased, the low accumulation is now the region of study to reach more sustainable results.

Figure 7 shows the isoreliability curve for LLP=0.1 together with LCA costs tendency, obtained from the convolution of both economic and energetic components. As expected, the total costs constantly increase with the accumulation capacity. Table 3 numerically shows the optimal (C_S, C_A) pairs when economic and energetic costs are independently considered. Notice that the size of the production and storage field are measured in WMM units.

Table 3. Optimal (C_S, C_A) pair for economic and energetic independent analysis

	C_S (WMM units)	**C_A** (WMM units)
Economic cost	0.8	0.80
Energetic costs	1.4	0.70
LCA global costs	1.1	0.75

As results, the best compromise in term of LCA global costs obtained for the LLP= 0.1 isoreliability curves as it considers a production field 25% smaller than the calculated using the WMM method. The optimal storage field is equivalent to an emergency charge of 1.1 days, in comparison to the 3 days proposed for a medium irradiation place when WMM is used.

4.4 Application example

To resume the relevance of an optimal sizing design for a stand-alone PV system, the experimental setup under study has been used as example. This PV system was designed for powering a familiar house using the WMM sizing method. The consumption regime is daily variable. The installation, put into operation in 2015, is continuously working without noticeable failures.

Figure 8 shows the isoreliability curves for different reliability values as well as the LCA costs tendency for the same installation. By applying the LLP sizing procedure, the installation's reliability calculation led to an LLP=0.0025 (Figure 8, blue square). It corresponds to a 99.75% reliability level, a clearly excessive value for a domestic installation.

But the most relevant result of using the LLP procedure is that, considering the LCA cost curve, the same reliability could be reached with the pair (1.00, 2.35). The evaluated cost reduction is close to 46% (Figure 8, orange circle).

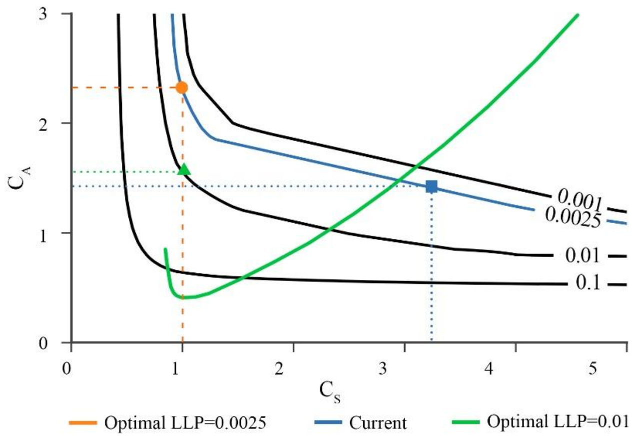


Figure 8. Domestic PV installation reliability and LCA curves

However, it is necessary to remark that the reliability considered as adequate for domestic applications is 99%, which correspond to an LLP of 0.01. Under these conditions, the best compromise between production and LCA costs corresponds to the pair (1.00, 1.60) (Figure 8, green triangle), which is equivalent to around 60% of economic cost reduction.

5. CONCLUSIONS

This paper evaluates the performance of the Loss of Load Probability sizing method for stand-alone PV systems. The operating working limits have been analysed as function of the climate conditions and the most frequent power consumption profiles. Results are obtained from solar radiation and power consumption experimental data.

The LLP sensitivity has been evaluated as function of the climatic variability. For this purpose, a database of 8-years meteorological data has been considered. As main result, the working reliability limits of the LLP method is 0.01.

The performance of the LLP method is evaluated for different consumption regimes. For variable power consumption regime, the storage capacity needs to be increased with respect to a constant power consumption one. The obtained results show an increase of around 20% for daily and nocturnal consumption frequency. This effect is more remarkable for diurnal frequency.

To evaluate sustainability, a rude costs analysis has been performed, comprising both economic and environmental terms (LCA costs). The best compromise between production and cost shows for a LLP=0.1 system reliability, a decrease of 25% on the production field. The optimal storage field is equivalent to an emergency charge of 1.1 days, in comparison to the 3 days proposed for a medium irradiation place when MWW is used.

As an application, the LLP method has been applied to an experimental PV system sized with the Worst Month Method. Using the obtained isoreliability curve and the LCA associated cost, a cost reduction of 46% can be proposed with the same reliability level (99.75%). This reduction will increase up to a 60% considering an LLP=0.01, more adequate for domestic applications.

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