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Applications

Dependability Analysis of Stand-Alone Photovoltaic Systems

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Long-term performance of PV stand-alone systems is analysed in this work in terms of dependability. On one side, the quality of a PV system, the energy service supplied to the users, depends on the initial design and sizing and on the component ageing that progressively decreases the availability of supply on demand (energy reliability). On the other side, technical failures lead to system stoppage until repairing is performed (technical reliability), which is crucial in real rural electrification applications. All those factors are analysed together with the basis of an extended field, laboratory and bibliographic review work. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: reliability; dependability; stand-alone

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1. INTRODUCTION

Stand-alone photovoltaic (PV) systems should provide a good quality electricity service to be considered as an alternative to conventional grid extension, for places with no access to electricity. In this way it is promoted in most PV and rural electrification programmes and forums. Quality requirements must aim at daily energy supply to the users, but also to ensure long system lifetimes. Sustainability is then a major objective to achieve. However, sustainability is not yet assured in many PV autonomous installations,[1] where the long-term performance is not always fulfilled and systems end their operation well before initial expectations (i.e 20 years or more of PV modules lifetime). There are economical, financial and social factors behind this situation, but also technical problems still to solve.[2] After years of development and an estimated 3 million PV systems installed throughout the world,[2] experience has not been optimally used. There is still not enough field work done on matters like reliability, maintenance or availability of systems, compared with other technologies and applications. These matters are embraced by the global concept of system dependability.

Systematic dependability studies are nowadays used on almost all energy technologies. They were initially applied to nuclear plants, focusing on risk and accidental analysis.[3] From initial documents, international standards were then developed.[4] Afterwards, from nuclear technology they spread to other energy generation and

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distribution systems,[5,6] basically for the cost estimation of energy losses caused by technical faults. In fact, dependability theories are put into practice for different objectives and complexity degrees, as follows:

- Failure modes identification and valuation.
- Risk and accidental analysis.
- Maintenance planning (scheduled, non-programmed and spare stocks).
- Energy supply interruption.
- Cost estimation of energy shortage.
- Quality improvement for future practices.

In stand-alone PV applications, reliability studies are mostly centred on energy balance estimations with ideal components, by means of the so-called *Loss of Load Probability* (*LLP*)[7,8] or equivalent energy balance parameters, mainly used in sizing applications. However, the effects of PV component evolution on the energy supply or the consequences of technical faults and their maintenance in the field are seldom quantified or even considered.

This article presents a technical approach for improving stand-alone PV system quality through dependability analysis, based on field and laboratory experience. This work has been developed in the frame of the European Union funded project entitled *'Tackling the Quality of solar Rural Electrification'* (Contract No. NNE5/2002/98).

2. GENERAL APPROACH TO DEPENDABILITY ANALYSIS FOR STAND-ALONE PV SYSTEMS

Dependability is a collective term related with the capability of a repairable system to perform as expected during a given time. Formally, it is composed by four concepts: reliability, maintainability, availability and safety.[9,10] Besides, costs are always taken into account as a limiting factor in a practical application of any dependability study.

A dependability approach for autonomous PV systems is proposed in this work, with the scheme shown in Figure 1. In this kind of systems, the interruption of the energy supply to the loads can be caused by:

- a technical failure;
- not enough stored energy (at non-failed states);

On one side, technical failure events must be studied in common with their repairing times, since the definite parameter to evaluate the system behaviour should be the energy availability on demand. On the other side, the energy deficit estimation of non-failed systems is basic in all non grid-connected systems. It is commonly studied only from ideal component characteristics (nominal values). However, PV components change during their operation, decreasing the energy supply and then the initial *LLP* estimations, for a given energy consumption profile. Basic safety requirements are studied here only by their influence on system reliability (fuse blown, e.g.).

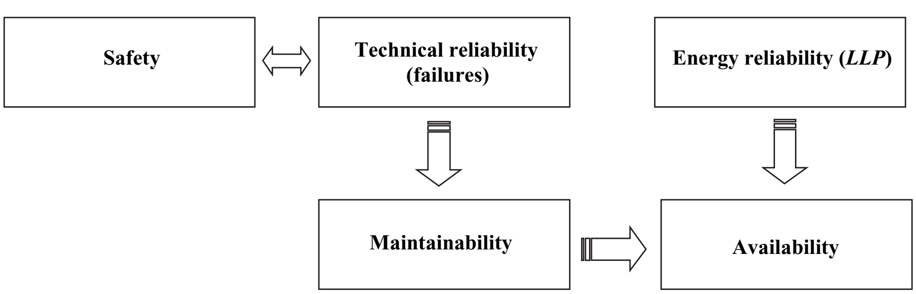

Figure 1. Dependability approach

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A general methodology for the application of system dependability methods can be established. There are some general steps, as follows: scope and objectives, system definition, failure mode identification, data collection and analysis, modelling and evaluation, and conclusions.

Stand-alone PV applications have certain common points between systems installed in different places and with different operating conditions. However, compared with other technologies and applications, disparities are significant: users behaviour, local factors and technology availability are crucial in the long-term performance. Simplifying, autonomous PV systems have similar reliability behaviour in their photovoltaic side, depending on the PV module characteristics but not so much on other system conditions. Then, PV module evolution is equivalent to grid-connected PV systems, where the wider experience on monitoring can be used for faults and degradation data collection. This is not the case of the balance-of-system side, with failure and maintenance characteristics closer to other autonomous energy technologies than to PV grid-connected installations.

Basic components considered in this work are: PV module, battery, charge controller, optionally inverter, lamps, wiring and accessories (fuses, switches, etc).

Field and laboratory research on energy technologies, like stand-alone PV systems, should permit the specification of a detailed list of possible failures. Their effect on global system fault is expressed by means of any of the existing methods, like fault-tree diagrams. However, problems come when trying to quantify the real influence of each failure mode in field operation because data collection and technical analysis of broken components are seldom performed.

3. MAIN DEPENDABILITY INDICES

Two groups of indices are used in the present article. A first group is generally utilised in system dependability analysis, related with technical reliability, failures and maintenance times. The second group proposed in this work, is more specific of PV autonomous installations. It is referred to the energy deficit of a system during its evolution (and ageing) and not only in the design phase as it is the common practice. Both groups finally converge in the energy supply availability parameter.

3.1. Technical reliability and maintainability indices

The time passed from system (or component) installation to first failure can depend on multiple factors. This *Time to First Failure* is then expressed by a random variable T_f, with an associated failure distribution function F(t), as follows:

$$F(t) = P(T_f \leq t) \tag{1}$$

The complementary *reliability function* $R(t)$ is more commonly used. It is defined as the probability that the system (or component) had not failed in a time interval between 0 and t.

Meanwhile, the *failure rate*, $z(t)$, is the probability that the system fails in a time interval $(t, t + \Delta t)$, when it was functioning at time t. It is expressed in t^{-1}.

Similar expressions than the ones for the operating phase are established for the maintenance phase:

- Repairing (maintenance) time, T_{M}
- Maintainability distribution function, $M(t)$
- Repairing rate, $\mu(t)$

Both factors, technical reliability and maintainability, determine the technical availability of the system, $A_{\mathrm{failures}}(t)$, as the ratio between non-failed state time over the total time considered.

Apart from these time-dependent variables, their associated mean-time parameters are also used for long-term analysis:

- Mean Time To Failure, MTTF.
- Mean Time Between Failures, MTBF.

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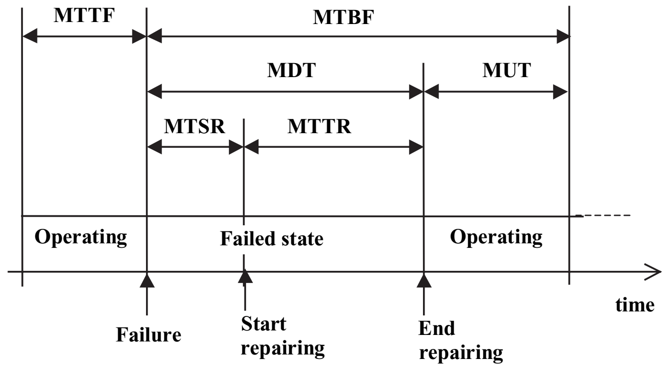

Figure 2. Mean-time variables in a repairable system operating sequence

- Mean Down Time, MDT.
- Mean Time to Start Repairing, MTSR.
- Mean Time To Repair, MTTR.
- Mean Up Time, MUT.

The time sequence of these parameters is schematised at Figure 2.

The use of mean-type parameters permits a general comparison among cases with similar failure distribution, although of different value. They present special interest for the study of constant-rate failures, characterised by exponential distributions. In non-repairable or long-lasting repair systems, parameter MTTF is used for system operating life studies. For repairable systems, the MTBF parameter turns out to be more useful, since it includes the maintenance phase, which is commonly long in stand-alone installations. In this sense, the maintenance phase, estimated by the non-operating time (MDT), should consider all time elapsed from the failure event until the system is put into operation, and not only the repairing tasks, which are not usually very complicated in this type of systems.

The mean technical availability (failure and repairing) over a long time period is then:

$$A = \lim_{t \to \infty} A(t) = \frac{\mathrm{MUT}}{\mathrm{MDT} + \mathrm{MUT}} = \frac{\mathrm{MUT}}{\mathrm{MTBF}} \tag{2}$$

3.2. Energy reliability indices

In many technologies the energy resource is not limited in normal circumstances and in the time-period of analysis. Technical failures are the main (or unique) final cause of lack of supply. However, in all autonomous systems, and specially the ones with short storage times (hours or days), the effect of energy generation/consumption ratio should be considered. In this context, main indices associated with ideal system sizing and radiation and consumption predictions are the following:[7]

- Normalised PV generator size, C_A

$$C_A = \frac{\text{Mean daily energy produced}}{\text{Mean daily energy demand}} = \frac{P^*_{\mathrm{NOM}} \cdot \overline{G_{dm}}(\beta)/I_{\mathrm{STC}}}{L} \tag{3}$$

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where:

$$P^*_{\mathrm{NOM}} : \text{PV generator nominal (W)}$$
$$\overline{G_{dm}}(\beta) : \text{Mean daily irradiation } (\mathrm{W \cdot h/m^2/day})$$
$$I_{\mathrm{STC}} : \text{Irradiance at Standard TestConditions } (1000\,\mathrm{W/m^2})$$
$$L : \text{Mean daily consumption } (\mathrm{W \cdot h/day})$$

- *Normalised storage capacity, C_S (Autonomy)*

$$C_S = \frac{C_B \cdot \mathrm{DOD_{max}}}{L} = \frac{\text{Maximum useful energy}}{\text{Mean daily energy demand}} \tag{4}$$

where:

$$C_B : \text{Nominal battery capacity } (\mathrm{A \cdot h})$$
$$\mathrm{DOD_{max}} : \text{Maximum depth of discharge}$$
$$L : \text{Mean daily consumption} (\mathrm{A \cdot h/day})$$

- *Loss of Load Probability, LLP:*

The ideal (or design) loss of load probability is calculated as through an energy balance over long periods, as the ratio between the energy not supplied to the users and the energy demand:

$$\mathrm{LLP_{month}} = \frac{\int_t \text{energy deficit}}{\int_t \text{energy demand}} \tag{5}$$

The relation between LLP and generator and storage parameters come up from their own definitions, within a simulation process with radiation and consumption data as inputs. Monthly LLP values are more appropriate for this kind of analysis, since the lack of energy in stand-alone PV systems is more probable in certain periods of the year, with lower solar radiation (or high consumption).

There is a certain dependency of LLP calculations on the radiation database selected and also on the consumption profile estimations.[11] However, the application of these methods can be very useful for comparing different systems operating at the same 'external' conditions. In fact, in this line are embedded all the dependability tools applied here.

From this ideal reliability framework, the influence of system losses, appearing even in new and optimum systems, should be accounted. The so-called *Performance Ratio*, *PR*, includes the effects of temperature, shading, dust, charge controller internal losses, wiring losses, etc. Values around 50–60% are common in good stand-alone applications.[12]

This article proposes an improvement of previous reliability models by considering real conditions: the effects of component degradation over time and deviations from nominal values. As it was mentioned before, in practice a substantial share of solar systems for rural electrification operate sub-optimally, providing less services than in the case when everything works well. Three more influencing factors are then presented.

- *PV generator power factor, $r_G(t)$*

Real power of PV modules can be different from its nominal value, even brand new, as in Figure 3, where power deviations of 1024 PV modules are shown.

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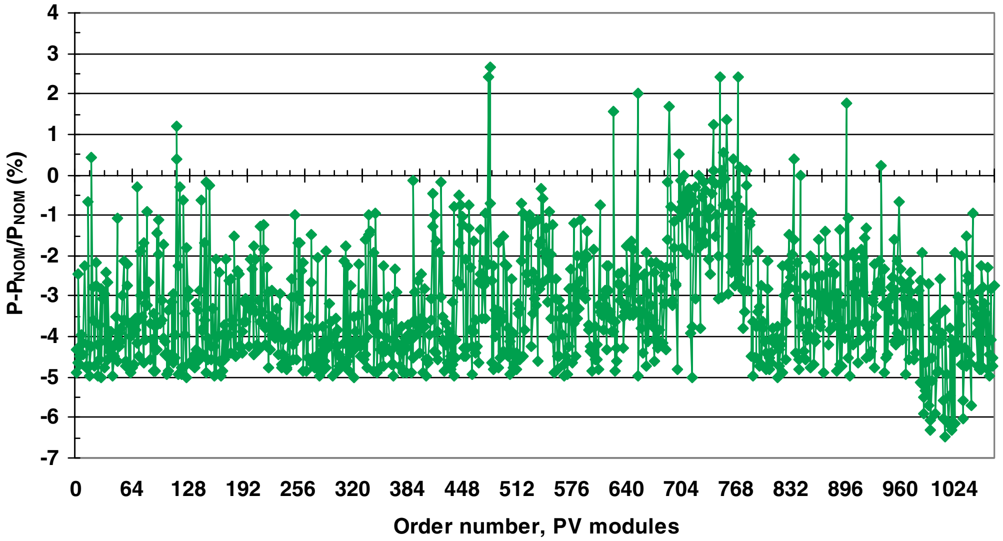

Figure 3. Power deviations of 1024 crystalline PV modules, Example

When PV modules are in use, they experience a progressive degradation, decreasing the energy generation. The normalised generator size, C_A, is then modified by this $r_G(t)$ parameter, which decreases with time because of module degradation:

$$r_G(t) = \frac{P(t)}{P_{\text{nom}}} = \frac{P_0 - \Delta P(t)}{P_{\text{nom}}} = p_0 - \Delta p(t) \tag{6}$$

where:

$$P_{\text{nom}} : \text{Nominal PV module peak-power}$$
$$P_0 : \text{Real PV module peak-power(initial)}$$
$$\Delta P(t) : \text{Power losses over time}$$

- *Storage capacity factor, $r_B(t)$*

Batteries experience a strong loss of capacity during their operation from initial real conditions. The delay of battery replacement increases the influence of capacity loss. A battery capacity correction factor, $r_B(t)$ is defined as:

$$r_B(t) = \frac{C(t)}{C_{\text{nom}}} = \frac{C_0 - \Delta C(t)}{C_{\text{nom}}} = c_0 - \Delta c(t) \tag{7}$$

where:

$$C_{nom} : \text{Nominal battery capacity}$$
$$C_0 : \text{Real battery capacity (initial)}$$
$$\Delta C(t) : \text{Capacity losses over time}$$

- *Regulation against battery deep-discharge*

Useful battery capacity in a stand-alone PV system equipped with a charge controller is determined by the Low Voltage Disconnection (LVD) set-point adjusted in it. In fact, the maximum depth of discharge (DOD_{max})

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estimated in the design tasks can differ from real maximum discharge permitted by the charge controller ($\mathrm{DOD}_{\mathrm{max,r}}$) if both components are not selected in common.

The normalised battery capacity factor can be modified by a charge controller correction factor, $r_R(t)$, which is:

$$r_R(t) = \frac{\mathrm{DOD}_{\mathrm{max,r}}}{\mathrm{DOD}_{\mathrm{max}}} \tag{8}$$

Then, by considering real components in the system, the previously defined generator and storage parameters, C_A and C_S, are substituted by time-dependent ones, C_{At} and C_{St}:

$$C_{At} = C_A \cdot PR \cdot r_G(t) \tag{9}$$

$$C_{St} = C_S \cdot r_B(t) \cdot r_R(t) \tag{10}$$

Reliability estimations (LLP) are then modified since energy deficit (generation-consumption balance) varies with component ageing and real values. These general models are applied to some practical scenarios in the next section.

4. APPLICATION TO STAND-ALONE PV SYSTEMS FOR RURAL ELECTRIFICATION

The proposed dependability methods are now applied to stand-alone PV systems, mainly for rural electrification. The analysis of other PV off-grid applications, like mini-grids or professional systems is equivalent, just by including the proper components and associated field data on failures and maintenance times, if available. Although differences between systems are significant, due to the 'local factors', a general view of their dependability behaviour can be obtained. First and crucial point is field data collection.

4.1. Failure modes identification and diagrams

In stand-alone PV installations (without supporting generator), a complete component failure usually leads to an energy supply interruption, immediately or in the short term. PV module, battery, charge controller, inverter (if it is included) and wiring are all essential for the system performance. It is called a 'series' configuration, where no redundant (or parallel) components are installed. Loads can be considered as series and/or parallel components, depending on their type, mobility and functionality (domestic lamps, TV, refrigerator, etc).

Failures can be dealt with into different levels of detail: system level (failed system or not), component level (failure on PV module, battery, charge controller, etc.) or internal level (by specifying the failure origin within a component). The slender information coming from the field is mostly referred to the system level and component level, but seldom to internal failure description. Besides, published data related to maintenance times after failure are almost inexistent. In this context, different dependability models are proposed and applied from available data, leaving an open door for changes according to future data collection.

In a fault tree diagram as the one shown in Figure 4, each component is considered as a whole, with no internal specification.

If there are enough data available and the objectives of the analysis do require it, the numbered failure modes of Figure 4 can be explained by more specific ones. For example, a module failure can be caused by its breakage or by a power loss (down to a certain acceptable limit or to real replacement time). In the same way, a battery failure can have its origin in a sudden battery breakage or a strong capacity loss. Then, the fault-tree diagram extends to a lower level as it is shown in Figure 5 for those two components. Charge controllers, inverter, wiring

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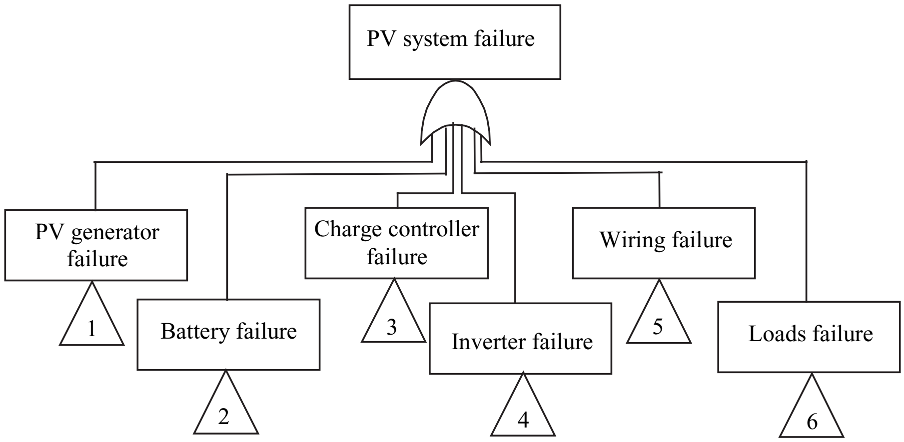

whole, with no internal specification.

Figure 4. Fault tree analysis, first level

and loads (considered here as a unique element) are more likely to be in two states (working/not working), but further levels are also possible.

4.2. *Data collection and analysis*

According to the main factors of energy shortage considered in this article, data on ageing and failures of stand-alone PV systems and components have been collected by means of a wide bibliographic review but also from field and laboratory work. It should be said that despite the long experience of this technology and application, there is still a lack of data on system faults and maintenance times. Specific tasks on data recording should be implemented in future actions in order to benefit from their experience. Existing data are generally scattered and non-homogeneous, taken from projects with a low number of systems, which reduces their statistical value. However, it is worthwhile to present them as a first stage for future evaluation and failure data recording extension. Some interesting trends can be established from this initial information, as it is shown in the following points. Some field data on energy consumption has been also collected, since it is a key factor on PV system operation.

4.2.1. *PV modules*

Modules are commonly mentioned as the most reliable element within the PV system. However, possible failure events should be considered in long-term analysis, with a special relevance for large-scale initiatives.

Sudden breakage is the main cause of PV module replacement, with different origin: vandalism, lightning, installation problems or manufacturing defects. Breakage failure rates from different projects are shown

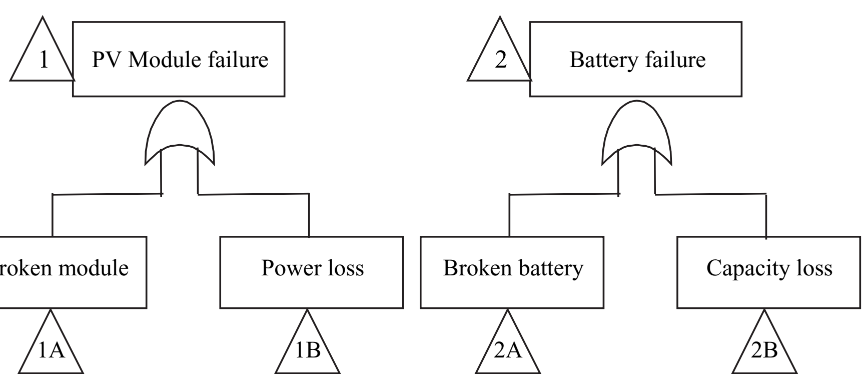

Figure 5. Fault tree analysis. Second level for PV module and battery

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Table I. PV module failure data[13–16]

Data origin	Type	Years in operation	percentage of broken modules, per year
LEEE-TISO, 2000	c-Si	18	0·15
EEUU, 1996	c-Si	10	0·4
	c-Si	14	0·2
Indonesia, 1999	c-Si	9	0
Private sector, Kenya, 2002	a-Si	2	10

in Table I. Low rates, between 0% and 0·4% of failed modules per year, are referred for crystalline silicon technology. In the case of amorphous technology the unique reference found corresponds to various manufacturers of the Kenyan private market. The high failure rate such as the one found in Kenya, can be reduced substantially when proper quality controls are implemented and by selecting manufacturers and models with acceptable characteristics.

Disparities between real and nominal PV module power (new and in their evolution) are not usually considered in system field analysis. However, low power outcomes as an important aspect in the long-term, not only in performance studies but also for reliability ones, by means of the mentioned influence on the energy balance. Some examples of underrated crystalline modules are shown in Figure 6, with real power values out of the common $\pm 5\%$ or $\pm 10\%$ range specified by the manufacturers.

This situation seems to have improved during the last years due to the extension of quality controls. However, the risk of underrated PV modules in the rural electrification market turns higher in periods with an excess of demand (mainly in the grid connected market) and/or lack of enough raw material (solar degree silicon).

Presently, most amorphous silicon manufacturers account for the strong initial degradation by overrating the modules. In these cases, nominal values are referred to the stabilised power, after some months of sun exposure. Actually, all PV modules suffer a progressive power loss in outdoors conditions. Evaluations at different laboratories resulted in yearly power loss from 0·5% to 2%, for crystalline silicon technology, as it is shown in Figure 7. Amorphous silicon technology shows higher degradation rates.

Degradation rates found in literature are constant with time so, real power follows a linear decreasing. According to these data and considering previous comparison between real and nominal power, the effects of PV module power on times of replacement and energy supply can be evaluated, with a decreasing generator parameter, C_{At} and increasing LLP.

Besides degradation, power output of PV modules in the field is usually reduced by dust. In a humid tropical environment dust collection can reduce output by about 10%. Rain water will clean the modules to a certain extent, but not completely. To maintain sufficient output regular cleaning is required.

4.2.2. Batteries

Some mean lifetime data of non-professional applications can be found in literature. The use of SLI batteries in small PV systems implies a replacement interval between 2 and 4 years, as it is shown in Table II. Batteries turn to be the most problematic component of stand-alone PV systems.

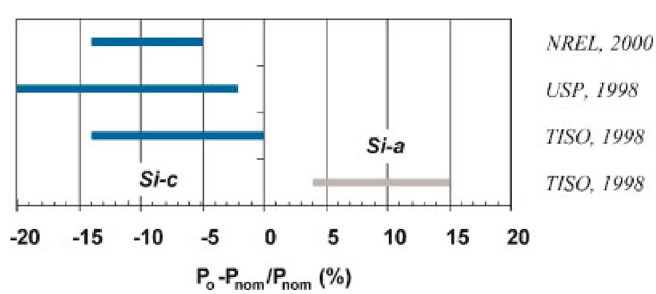

Figure 6. Real versus nominal power of new PV modules (laboratory data)

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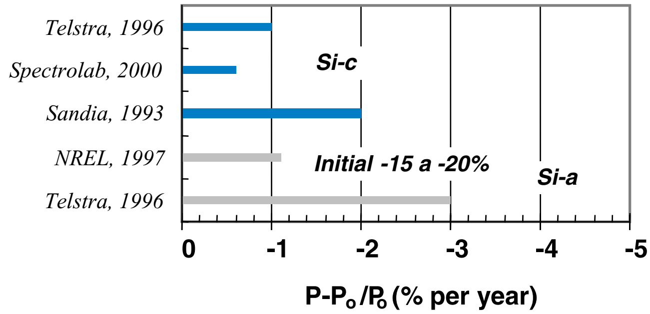

Figure 7. Power loss of PV modules in operation

A detailed literature survey on battery lifetime, mostly centred on professional applications have been performed in the framework of the 'Benchmarking' project.[22] Batteries in operation up to 8 and even 12 years are referenced for professional or medium-high power PV systems using stationary models. Regarding small rural PV applications, lifetimes between 2 to 4 years are mentioned, in accordance with data collected in Table II.

In the field, battery replacements take place at very different circumstances and different states of health. The criteria of battery capacity (a certain percentage of the nominal value) is usually not followed. First, because it is not easy to know the real battery capacity in the field; and second, because acceptance of early loss of load is sometimes influenced by the availability of spare parts or enough financial resources. For PV rural electrification systems with 3 to 4 days of autonomy in design, battery degradation will become noticed by the user when the useful capacity has decreased about a third of the nominal battery capacity. Whenever users have to bear the full cost of battery replacement, they will tend to postpone replacement until the possible daily consumption is much lower than the original amount. Therefore, a remaining capacity of 20% of nominal capacity is much more likely to occur in practice than the 80% figure, which is often quoted as a design criterion for professional practices (see Figure 8). However, data from the field seem to point that real consumption in rural electrification is commonly lower than expected, with references of real energy consumption a 60% of initial estimations.[23] So, many PV systems are initially (but unsconsciously) oversized.

Sudden and complete battery breakage can happen, although the experience shows that capacity loss is a more common cause of replacement. In these cases, the energy supply worsening due to capacity losses is dealt with in the energy deficit analysis (section 4.3).

Real battery capacity must be consider as a main influencing factor even before the installation phase. Ampere-hour capacities of new batteries do not necessarily comply with manufacturer specifications as it is reflected in Table III, with tests performed at IES-UPM, Fraunhöfer-ISE and ECN laboratories.

Table II. Battery lifetime (field data)[15,17–21]

Data origin	Type	Time in operation
Sukatani	Solar modified	4 years
	SLI	3 years 6 months
Fraunhofer-ISE	SLI	2–3 years
PRONASOL	SLI	2 years 6 months
Bolivia	SLI	6–9 years
Brasil	SLI	2 years 5 months
Puno, Perú	SLI-solar	>3 years
Jujuy, Argentina (EJSEDSA/IES)	SLI	4 years

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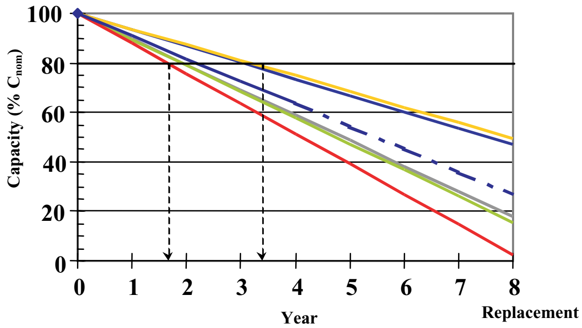

Figure 8. Linear battery capacity loss until substitution (real data of remaining capacity at replacement)

Table III. Real versus nominal capacity of new batteries (laboratory data)[24,17,25]

Data origin	Number of batteries	C/C_{nom} (%)
IES-UPM	18	55–101
Fraunhofer-ISE	6	70–95
ECN	8	88–112

Once in operation, all batteries suffer a progressive capacity loss, caused by different degradation processes (corrosion, sulphation, stratification, etc.). The level of degradation depends on multiple factors: battery type and constitution, operating conditions, associated regulation, temperature, etc.

Battery degradation in the field can be approached by measuring the capacity of batteries once they have been retired from the installation. Disparities are found (see Figure 8), with cases of very low useful capacity batteries still in operation. Taking as hypothesis a linear capacity decrease, values between 6% and 12% of capacity loss per year are obtained (Table IV). Battery lifetime in operation will depend on the remaining capacity at replacement. Capacity-loss rates are expressed by decreasing C_{St} and increasing LLP values. However, more measurements are needed to have more consistent information.

This linear evolution is not always close to real battery behaviour in the field. In fact, a significant capacity loss is produced at overcharge or deep-discharge conditions, increasing with high temperatures. A good charge regulation[26] and regular operating profiles reduce the high-degrading situations. The linear approach is then a better representation.

4.2.3. Charge controllers

Electronic devices usually have random failures, without clear time-dependency. Field data on failure rates of charge controllers follow this behaviour, as it is shown in Table V. However, some particular failure causes, like lightning or vandalism, can be associated to a certain period and place.

Apart from their own failures, the relevance of charge controllers lies on their battery control function, determining battery lifetime and useful energy available for consumption. A more detailed analysis on this question can be found in a previously published work.[26] As it is shown in Figure 9, variations in the LVD set-points strongly affects the maximum battery depth-of-discharge and, so, the useful energy. The initially adjusted

Table IV. Battery capacity mean yearly loss in operation (field data[15,19])

Data origin	$\Delta C/C_{nom}$/year (%)
Bolivia IES	−6 to −12
Sukatani	−9

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Table V. Charge controller failure data (field data[15,27,21,28])

Data origin	Number of units	Years in operation	% of broken units per year	Incident
Indonesia	62	9	2	Substitution
			2·5	By-passing
Perú	192	Not specified	43	Diverse
Perú	421	3	5	Diverse
Argentina	13	3,5	2	Substitution

LVD threshold can change during system operation in the field (manually or caused by component fatigue) and even more, it can be different than the one used for useful battery capacity estimations. As an example, data from a field experience[15] showed changes in the LVD values from the designed 11·6 V to a 11 to 11·8 V range for the different charge controllers. These situations are represented by C_{St} parameter variations, through the proposed r_R(t) factor. Periodical set-point measurements should be done in order to check their operating values and to made modifications if this option is included.

4.2.4. PV systems data collection

Although the lack of reported data on failure events has been already emphasized, there are some interesting experiences on field data registration.

A performance and reliability database has been developed since 1999 by Sandia National Laboratories, mainly centred on residential off-grid applications in the United States.[29] Annual operation and maintenance costs of 5%–6% of the initial capital costs are referred. Besides, Task 2 of the IEA PV Power Systems Programme has monitored 400 PV installations since 1999 of different applications,[30] including more than 30 stand-alone systems installed worldwide.[31] As a valuable and less disseminated work, the Universidad Nacional de Ingeniería of Lima, has collected failure data from 421 systems installed in the Peruvian region of Puno. They are summarized in Figure 10.

First conclusion comes from differences between components, in trends and absolute values. It is shown that PV module failure rates are very low, and constant with time, compared with other components. Meanwhile, charge controller failures do not increase with time, either, as it was predicted. In the case of lamps, and even more of batteries, there is an increasing trend because of component degradation before failure and replacement. The inclusion of lamps as a PV system component, which is no usual, is based on the fact that in many rural areas the electrification has reached with the PV project. Also because the PV system performance depends on lamps quality and their availability in the local markets. This kind of information, extended during a wider time period, result to be very useful to study PV systems performance in long-term analysis. It is worthwhile also for spare parts and maintenance planning, and for the design and component selection of future systems.

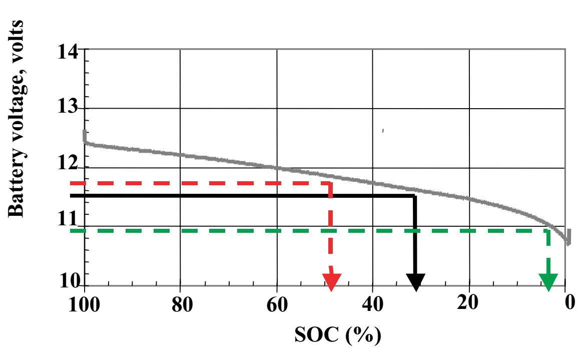

Figure 9. Charge controller influence on useful stored energy (minimum state of charge permitted). Field data applied to a common battery discharge curve

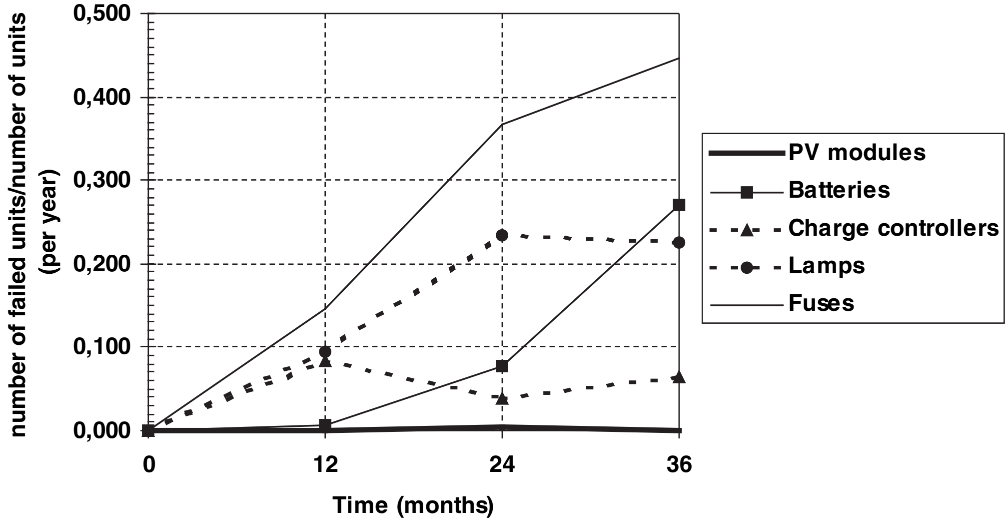

Figure 10. Failure rates on 421 PV systems in Puno-Perú (field data[21])

4.2.5. Maintenance data collection

Maintenance times after failures vary from some minutes up to several months. Sixty days and even more are referred in literature,[32,33] in rural electrification applications. However, contractual requirements for maintenance times are much shorter in some cases, like the 5–9 day requirement in the case of Jujuy, Argentina. The financial resources dedicated to systems maintenance and the availability of spare parts and trained technicians are basic in order to decrease system unavailability. Concerning batteries, as it was mentioned, replacements take place commonly because of low capacity (reduced daily energy supply) more than sudden and complete failures. In those situations, the battery is substituted by a new one and the system down time is very short. Supply shortages due to low battery capacity affect the LLP side more than the failure-repairing one. In this way is dealt with in the present publication.

4.2.6. Consumption patterns

The great importance of users' behaviour on PV system performance is widely accepted, but it has not been in accordance with the efforts (and funding) dedicated to research on this topic. However, some valuable works have been done in the field of rural electrification during the last years, for domestic systems,[23] mini-grids[34] and water pumping.[35] The interesting point is that similar patterns seem to be followed even at very different places and applications. A gamma function describes common consumption patterns within a community, with many people consuming small amounts of energy and some people consuming big quantities. Besides, the consumption profile during the year depends on the specific characteristics of the community (geographical, socio-economical, cultural and religious).

4.3. System dependability modelling and evaluation

The first step of the analysis (Subsection 4·3·1) tries to predict the technical reliability of stand-alone PV systems based on field data collected (failures and maintenance). Two options, failed or not failed are considered in this first stage since partial operation states are dealt with in a following one (Subsection 4·3·2) dedicated to the energy balance evolution with time. Finally, both parts are put together through the availability estimations in the dependability analysis.

The strong dependency of the dependability analysis on solar radiation and energy consumption profiles, characterized by their high uncertainty, and the influence of local factors, calls for the realization of comparative studies more than absolute dependability evaluations.

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4.3.1. Technical reliability of PV components and systems

As it was mentioned, PV component field lifetime data is not commonly published or even registered, with some exceptions. Some trends outcome from the collected data, which allows a first approach by modelling the associated distribution functions.

PV module sudden failures are a more probable cause of replacement than deep power loss, although this is not inconsiderable for certain models and technologies. On the contrary, battery end-of-life in the field is normally associated to low capacities and a reduction of the number of hours of use, more than a sudden breakage. For other components like charge controllers or inverters, although the causes of failure can be diverse, usually they come as a sudden breakage and a complete interruption of their function. These failures are commonly non time dependant, and in this way are shown in literature. An example representative of field data is shown in Table VI. Non time-dependent failures are modelled by exponential distribution functions, with the proper scale parameter, λ. Besides, the effects of component degradation on time-to-failure are better represented, as a first approach, by growing linear Weibull distribution, with a scale and shape parameters, λ and α, respectively.

By improving failure data registration and dissemination, models can be modified for a better adjustment to specific cases or to general behaviours.

Reliability values of PV components and systems are obtained from the specified distribution functions and represented in Figure 11. From this graphic, lower quality equipment or harder operative conditions are shown as a translation to the left. It is clear that, nowadays, the battery operation leads the whole system performance.

From this first graphic, further comparative studies can be done. If no spare parts are available (which is sometimes found in the field) and wiring by-pass is strictly forbidden (which is not commonly followed), the effects of fuse blown on system reliability (lack of supply) are remarkable. An example is shown in Figure 12, with data taken from field collection already presented. For safety reasons, the presence of fuses is mandatory, but spare parts have to be always planned in order to maintain the energy supply and to avoid manual substitution with an incorrect wire. In practice, blown fuses will be 'repaired' with that wire by-pass, although this practice can affect safety and early failures of other components.

A similar behaviour occurs for lamp failure if the stock of spare lamps is not well predicted.

4.3.2. PV system energy balance (without technical failures)

The influence of real PV generator peak power and battery capacity, for a determined radiation database and consumption profiles, is reflected in the loss of load probability parameter (LLP). The use of the proposed time-dependent C_{At} and C_{St}, instead of ideal C_A and C_S indices allows a closer approach to the reality, where PV components experience a progressive loss of their characteristics from their initial real values. The application of these linear models to an ideal LLP analysis, show the effects of time in the energy balance at non-failed states. A comparative example is represented in Figure 13, with data of Table VII. As time goes on, PV module power and battery capacity decrease (at different rates), and the loss of load probability increases from the designed value.

The loss-of-load probability is lower in the second case. The increase in LLP due to ageing is strongest in case I, which is mainly due to the higher rate of battery loss of capacity. If battery replacement is delayed from optimum time, the system energy supply is strongly affected, as it can be seen in Figure 13. The effects of the performance ratio, has not been considered in these graphics, in order to analyse component effects (PV module, battery and charge controller) independently.

Table VI. Reliability scenario, Example

Components	Hypothesis (Distribution Function)	Scale and shape parameters
Generator	Exponential (G1) + increasing	$\lambda_{G1} = 0{\cdot}002$; $\alpha_{G1} = 1$
	Weibull (G2)	$\lambda_{G2} = 0{\cdot}01$; $\alpha_{G2} = 2$
Battery	Increasing Weibull	$\lambda_{B2} = 0{\cdot}2$; $\alpha_{B2} = 2$
Charge controller	Exponential	$\lambda_{R2} = 0{\cdot}05$; $\alpha_{R2} = 1$
Wiring	Exponential	$\lambda_{C2} = 0{\cdot}002$; $\alpha_{C2} = 1$

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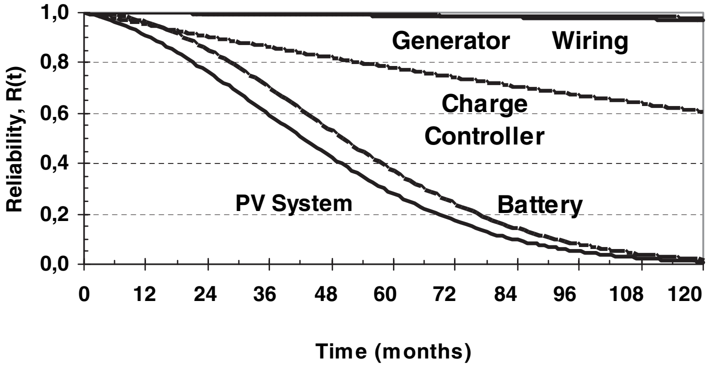

Figure 11. Reliability scenario, Example

4.3.3. Dependability estimations in the long-term

The availability of a PV system for supplying energy on demand is based on the two main influencing factors considered up to now: component failure and subsequent stop for repairing, on one hand, and energy shortage at non-failed states, on the other hand. Both factors are related. Costs need to be also considered in a global dependability analysis.

A comparative study is presented here in order to show the effects of the different factors that determine the system performance in the long-term. A typical PV system is used in this example, where two different battery replacement times are considered: 4 and 6 years. The extension of battery usage is a common practice, for money saving or because real consumption is lower than design estimations.

Main system data is presented in Table VIII.

In this example, PV modules have a 0·2% of sudden failures per year and a yearly peak power decrease of 0·5%. In the case of batteries, sudden failures take place at a 4% yearly rate (first 2 years of Puno data[21]). Together, low capacities are considered as the other cause of replacement. In this exercise, battery replacement takes place when a new one is available, although its operation has worsened during time, with a 10% of yearly capacity loss. Besides, charge controllers are supposed to have sudden failures at a 5% yearly rate.

Failure associated reliability is expressed as the product of component reliability, in a series configuration:

$$R_{\mathrm{S}}(t) = R_{\mathrm{G}}(t) \cdot R_{\mathrm{B}}(t) \cdot R_{\mathrm{CC}}(t)$$

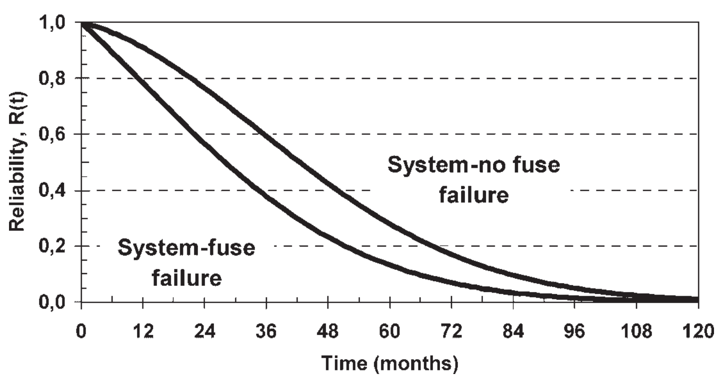

Figure 12. Effect on reliability of no-replaced blown fuses (0·15 failures per year)

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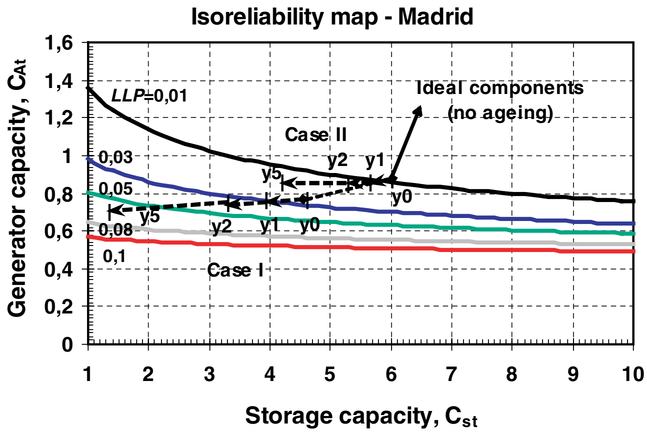

Figure 13. Isoreliability curves with real components, Constant consumption

Table VII. Real characteristics of PV modules. Comparative examples: Case I: average values (not worst case); case II: ideal/design values

	Case I	Case II
PV module		
P/P_{nom}	0,9	1
$\Delta P/P_{nom}$ (per year)	0·02	0·005
Battery		
C/C_{nom}	0·85	1
$\Delta C/C_{nom}$ (per year)	0·12	0·06
Charge controller		
$DOD_{max,r}/DOD_{max}$	0·9	1

Table VIII. Failure rate and characteristic losses, Example

	Failure rate	Maintenance times	Mean yearly degradation rates
PV generator	0·2%	1 day/1 week/1 month	0·5%
Battery	4%	Available for replacement	10%
Charge controller (DOD = 70%)	5%	1 day/1 week/1 month	—

All failure rates are considered constant with time, so the MTTF is:

$$\mathrm{MTTF} = \frac{1}{\lambda_G + \lambda_B + \lambda_{CC}} = \frac{1}{0{\cdot}002 + 0{\cdot}05 + 0{\cdot}04} = 10{\cdot}9 = \mathrm{MUT}\ (\text{mean up time})$$

It should be remarked that these mean-time parameters are often misunderstood and made equivalent to lifetime, but their statistical meaning is different.[9] They depend on the distribution function (i.e. 36% of failed/not failed systems for exponential distributions) which are only a simplified approach to field data that should be limited to a certain range. For this reasons, we recommend the use of failure rates and reliability values much more than mean-time ones.

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Table IX. MDT and technical availability for three maintenance scenarios in rural electrification

Maintenance Scenario	MDT	A_{failures}
1 day	1/365	0·9997
1 week	7/365	0·998
1 month	30/365	0·993

The energy supply is interrupted after each failure until repairing is done. This maintenance time differ from some minutes to even months. Three scenarios are proposed: 1 day, 1 week and 1 month. The associated MDT (mean down time) caused by such failures is 1/365, 7/365 and 30/365 respectively.

The availability associated to sudden failures and maintenance is:

$$A_{\text{failures}} = \left(1 - \frac{\text{MDT}}{\text{MUT} + \text{MDT}}\right)$$

If lamps and fuses are considered, regarding their high failure rates (easily 15% failures per year, for each), the new MTTF can decrease down to 2·5 years. If spare parts are available, the maintenance time is very short and the effect on energy supply is not considerable. However, spare parts are not always available in rural electrification environments, they are expensive and transportation is complicated. If there is only a 1-week delay, system availability could decay to 0·992 and 0·968 for 30-day delay.

These values could seem to be very optimistic compared with what is said about the field. However, it should be realised that PV system end commonly come from the absolute lack of maintenance and component reposition (a 30-day delay is, in fact, the optimistic data in many rural electrification cases). So, few and simple technical failures are the beginning of the system end if maintenance is not considered. This point, which is not very important in developed countries and even less in experimental PV systems, turns to be crucial in large-scale PV rural electrification programmes.

But also at non-failed states it is necessary to study what happens with the PV system and with its energy supply to the users. No sudden failures are considered in this second part of the study. The initial LLP_o value predicted, is modified by component degradation, mainly the battery. For the 10% capacity loss (of the total capacity, not the useful) per year taken for the example, the battery capacity factor varies with $C_{St} = C_s \cdot\ (1 - (0{\cdot}1/0{\cdot}7)t)$, with time t in years. From the isoreliability curves used in Figure 13, for Madrid, the annual LLP parameter increases with time until battery replacement takes place, as it is shown in Table X.

In the field, users adapt (by reducing) their consumption to system conditions, although certainly the energy service provided is not what it was initially stated.

Furthermore, up to now all LLP values have been expressed in annual reference. However, the energy cuts are mainly concentrated during the winter months, for constant consumption profiles. As an example, monthly ideal LLP distribution for Madrid under specific conditions is shown in Figure 14. It is important to remark that the LLP value is five times greater during certain (winter) months than the annual mean value. So, ageing effects would be even more crucial during those months.

Table X. Annual LLP evolution (case of battery replacement delay). Ten per cent annual battery capacity loss

Time from battery installation (in years)	1	2	4	6
LLP	0·02	0·03	0·05	0·1

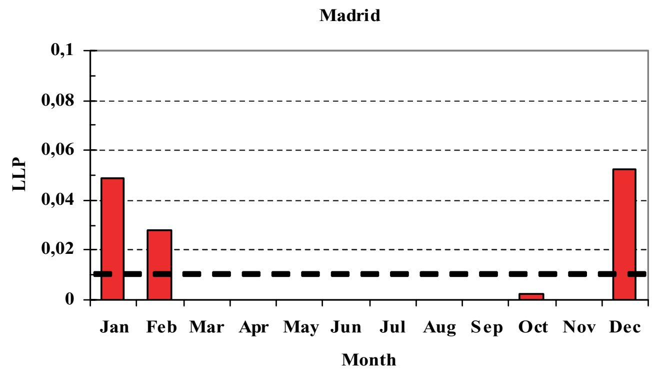

Figure 14. Monhtly LLP values for Madrid. $Cs = 4$, annual LLP $= 0{\cdot}01$

Finally, the mean availability can be expressed by the product of both availability variables, considered independently as a first approach:

$$A = A_{\text{failures}} \cdot A_{\text{LLP}} = \left(1 - \frac{\text{MDT}}{\text{MUT} + \text{MDT}}\right)(1 - \text{LLP})$$

There would be some cases were the appearance of technical failures and the lack of repairing will determine the system operation but others were, with no sudden failures, the system would decay in its energy service to the users.

5. CONCLUSIONS

The application of dependability methods to stand-alone PV applications can contribute to their quality improvement and performance understanding. Only the failure mode identification and the registration of data on failures and maintenance times is a valuable help by their own. However, more efforts need to be dedicated to reliability data registration, mainly on projects with a high number of systems with similar characteristics.

A long-term analysis of PV systems should consider the effects on energy supply of component ageing together with the influence of system faults and usual repairing times in the field. The application of the presented dependability methods to some field cases show that, depending on the circumstances, failure/maintenance and energy deficit aspects influence in a similar magnitude the energy service provided by a stand-alone PV system. Factors like PV component quality, spare-parts availability or maintenance resources are crucial in the long-term performance of systems.

Laboratory and field data collection shows that PV system quality and operation, and maintenance tasks have to be strictly monitored. Underrated PV modules (less than 90% of nominal power) can be found in rural electrification applications if quality control actions are not performed. Besides, the use of SLI and 'solar modified' batteries is a reality in all developing countries, where the availability and cost of tubular stationary batteries, reduce their implementation in small PV systems. Low initial battery capacities (sometimes below 80% of nominal value) and further losses (6–12% per year) reduces the daily available energy, until their replacement takes places. The number of energy shortages could increase up to five times during the first 4 years (or the available energy substantially reduced) from design expectations. In this sense, real capacity values must be in accordance with specifications. Besides, an acceptable range around the nominal one should be included in manufacturers technical documentation, as it is done in other components like PV modules.

The influence of charge controller thresholds is not sufficiently valuated. Differences of 0·1 V in the load disconnection set-point varies the useful energy storable in the battery about a 10%, apart from their influence on its lifetime.

Apparently minor events like blown fuses or bad quality lamps are, in fact, a crucial issue in rural areas of developing countries, where spare-parts are commonly not available or too expensive. Values around 15% failures per year are not rare, especially in the first and most critical stages of a project. Large-scale PV programmes need to assure the quality and the availability of this components in the local or regional markets.

In all autonomous systems the external dependency on radiation and consumption profiles is essential. However, due to their uncertainty, they can conceal other important factors and results. For this reason, all the studies here presented correspond to systems operating at certain external conditions. In this sense, relative values are obtained more than absolute ones. The extension of researching on real consumption patterns would enrich the application of these dependability methods and, widely, would improve PV system performance in rural applications.

As a final conclusion, the implementation of large-scale PV programmes in rural areas should include reliability (failures and component degradation) and maintenance registration activities. For that, more resources need to be dedicated to field monitoring of installed PV systems.

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