OPERATIONAL COSTS AND RELIABILITY IN A LARGE RURAL ELECTRIFICATION PROGRAMME BASED ON SOLAR HOME SYSTEMS

L.M. Carrasco*, L. Narvarte
Instituto de Energía Solar (IES) – Universidad Politécnica de Madrid (UPM)
Carretera de Valencia km 7, EUIT Telecomunicación, Despacho 16101, 28031, Madrid, Spain
*Phone: +34 91 336 55 31, Fax: +34 91 336 78 29
*e-mail address: luismiguel.carrasco@ies-def.upm.es

ABSTRACT: Experiences in decentralized rural electrification programmes using solar home systems have suffered difficulties during the operation and maintenance phase, due in many cases, to the underestimation of the maintenance cost, because of the decentralized character of the activity, and also because the reliability of the solar home system components is frequently unknown. This paper reports on the reliability study and cost characterization achieved in a large photovoltaic rural electrification programme carried out in Morocco. The paper aims to determinate the reliability features of the solar systems, focusing in the in-field testing for batteries and photovoltaic modules. The degradation rates for batteries and PV modules have been extracted from the in-field experiments. On the other hand, the main costs related to the operation and maintenance activity have been identified with the aim of establishing the main factors that lead to the failure of the quality sustainability in many rural electrification programmes.
Keywords: Rural electrification, solar home systems, cost reduction, reliability

1 INTRODUCTION

Decentralized rural electrification using solar home systems (SHS) has been a widely extended solution for electricity access in many developing countries. During the last 3 decades more than 5 millions of SHSs have been installed all over the World throughout a great deal of different electrification programmes [1-3]. Despite the great development of quality standards and accuracy sizing methods, there are still great gaps in the quality sustainability of the SHSs. On the one hand, the lack of reported experiences about the SHS failures does not allow to know the reliability parameters of the photovoltaic systems in the rural electrification (PVRE) programmes. On the other hand, the costs involved in the operation and maintenance (O&M) activity have been usually underestimated due to the lack of knowledge related with the design of adapted maintenance structures. These two issues have led to the failure of many programmes, because of both, the unawareness of the solar systems components reliability, and the inappropriate design of the maintenance structures, what dramatically have soared the O&M costs.

This paper reports on the reliability study and the characterization of the maintenance costs based in a real and large PVRE programme carried out in Morocco within the so-called PERG programme (*Programme d'Electrification Rurale Global*).

The reliability study has already been reported in a previous paper [7] in which the failure rates ($\lambda(t)$), the mean time to failure (MTTF) and the failure functions ($F(t)$) have been extracted from the real failures recorded in the maintenance database of the energy service company (ESCO) during a period of 5 years. Figures in Table I show the reliability results for lamps, charge controllers and batteries. PV modules does not appear in the reliability assessment due to the low failure rate found in the database: 20 failures over more than 13,000 SHSs.

Table I: Reliability study results. Note that battery MTTF is very low regarding the other components figures.

	Charge controller	Lamps	Battery
Failure rate λ (% / year)	3.7 %	6.0 %	-
Mean Time To Failure (Years)	27.2 ± 9%	16.5 ± 4%	5.5 ± 3%

Two in-field assessments have been carried out in Morocco to determine both, the deterioration of the capacity in batteries and the power degradation rate of the PV modules when operate under real conditions in a sample of SHSs.

Moreover, it has been achieved a cost characterization of the programme based on the real ESCO accounting recorded for a period of 5 years. Taking into account that the PERG involves 10 years of O&M, and considering the SHS's reliability assessment results, it has been achieved the overall programme cost characterization focusing in the main issues involved in the O&M phase, such as the spare-parts costs, the fees collection activity, the indirect costs related to decentralization, etc.

This study tries to contribute with real data to the lack of knowledge in the O&M phase of the PVRE programmes through the obtained results. The goal of this study aims to contribute to the optimization of the design of maintenance structures in decentralized rural electrification.

2 PERG PROGRAMME

The photovoltaic PERG programme has been promoted and designed by the Moroccan utility ONE (*Office National de l'Electricité*) to provide access to electricity in the most remote and inaccessible rural areas of the country. It was articulated in a *fee for service* model in which the ESCO is responsible for commercializing, installing and maintaining the SHSs for a period of 10 years. The ESCO must guarantee the systems during this period and must repair or replace damaged components. It is also responsible for collecting the monthly fees that the users pay for the maintenance service. These fees are established by the utility ONE in 5 €/month/SHS (excluding VAT), that it is equivalent to 60 €/year/SHS.

The installed SHS consists of a 80 Wp mono-crystalline silicon cells photovoltaic module, a 150 Ah C_{20} lead-acid SLI battery made in Morocco, a 15 A series charge controller with PWM regulation (non MPPT function), 4 compact fluorescent lamps (CFL), and a DC plug for small devices (less than 50 W).

In all, 13,600 SHSs were installed during the installation phase (the 3 first years of the programme), covering a vast area of around 200,000 km^2. This fact leads to an extremely low geographical density of systems (0.068 $SHSs/km^2$), characterized by difficult access and remote locations.

3 RELIABILITY

In the reported reliability study, the failure distribution of every SHS's component was evaluated in order to obtain the reliability parameters. The results achieved showed that battery was the main limiting factor as regards the reliability of the system, since its reliability figures are much lower than those of the PV modules, lamps or charge controller (Figure 1). These parameters were calculated from the database of the O&M companies. In the case of batteries, they were replaced when a catastrophic failure occurs, that's to say, when they capacity was almost zero.

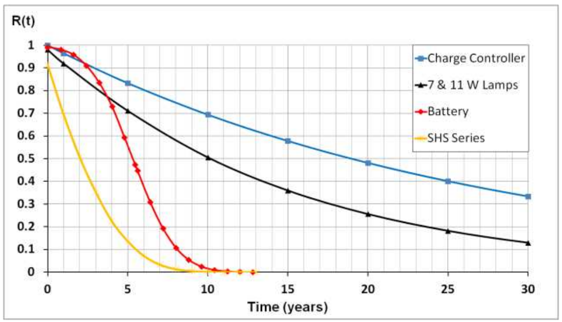

Figure 1: Reliability functions for the different SHS components. The yellow line indicates the system reliability function considering as a series system.

In the other side, the data regarding the reliability of PV modules was very scarce. This led us to carry out two in-field tests of both, batteries and PV modules with the aim of studying their reliability when working in real conditions.

The in-field assessment has been based on the selection of a sample of SHSs installed in different regions of the PERG programme. In all, 40 new batteries and 41 PV modules have been tested. In addition, 32 dataloggers have also been installed to record the operating parameters of the SHSs.

3.1 Battery in-field assessment

The set of batteries, similar to the PERG programme ones, have been installed in 40 different dwellings equipped with SHSs. In all, five capacity tests have been achieved: the first one was carried out after the batteries acquisition in order to check the SOC of batteries delivered directly from the manufacturer (Test 1.1); the second one after the initial full charge of batteries (Test 1.2), before installing them in the households; and the remainder tests, after 6 (Test 2), 12 (Test 3) and 18 (Test 4) months of starting to work in the SHSs.

The results of the different capacity tests are summarized in Figure 2. Note that the ensemble capacity of batteries when delivered from the manufacturer shows a SOC of 93% on average (Test 1.1).

The Tests 2, 3 and 4 show the degradation rate of the batteries under real operating conditions. It must be underlined that after one year of operation (Test 3) the remaining average capacity is lower than 80% regarding the initial full capacity, what means that according to the international quality standards [11-12], these batteries have already exceeded their lifetime. However, for rural electrification, they are still in operation.

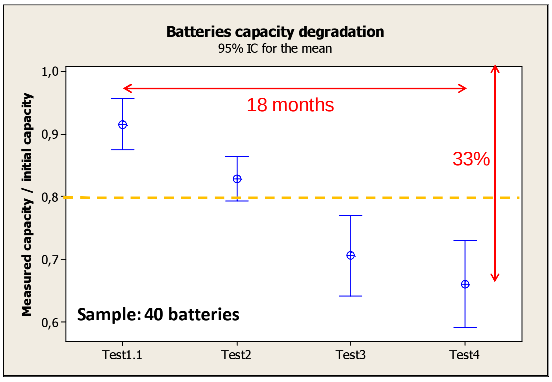

Figure 2: Capacity representation of the whole batteries sample on the Tests number 1.1, 2, 3 and 4. Note that from the Test 3, the ensemble capacity is situated below 80% regarding the initial capacity.

After analyzing the Voltage - Time (V-t) discharge curves extracted from the capacity tests, some other results have been obtained:

A) The charge controllers installed in the PERG are programmed to protect the battery against deep discharge cutting the consume load when the battery reaches 11.4 V (25°C), as required by the technical specifications imposed by the programme promoter (ONE). It has been determined from the discharging test that the average capacity extracted when batteries reach 11.4 V is practically 100% (see Figure 3). Thus, the battery SOC when the charge controller disconnects the load is next to 0%.

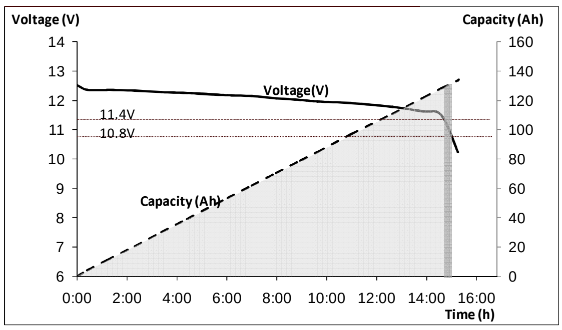

Figure 3: Voltage and capacity curves of one of the battery discharging tests. The dashed line over the light grey area represents the hypothetic capacity extracted from the battery if the charge controller disconnects the battery at 11.4V. The dashed line over the thin and darker

area shows the remaining capacity of the battery after the CC disconnection.

B) According to the quality international standards, floated lead-acid batteries with flat plates must not be discharged more than 50% of their full capacity (compulsory) or 30% (recommended). The discharging curve of all the tests have been analyzed, and it has been obtained that, in average, the charge controller should disconnect the battery at 12.1 V (DOD = 50%) or 12.3 V (DOD = 30%), and not at 11.4 V.

C) The average density of the electrolyte when batteries are fully charged, measured for the ensemble of the tests, is 1261 mg/cm^3, and for SOC = 0% (final voltage = 10.8V) is 1166 mg/cm^3. Densities higher than 1.26 g/cm^3 are not recommended due to the high corrosion degree that it produces in the plates. Most of the tested batteries have presented, at least once, density values higher than 1.26, what means that they could have suffered high levels of acid corrosion.

On the other hand, based on the capacity test results, the degradation tendency on time of the batteries has been studied. The distribution function of batteries when they reach 80%, 70%, 60% and 50% of their initial capacity has been fitted by a Normal distribution. For example, Figure 4 shows the distribution function F(t) of batteries when they are degraded till 80% of their initial capacity, taking into account failures (batteries degraded till 80%) an survivors (batteries that have not reach 80% during the test period).

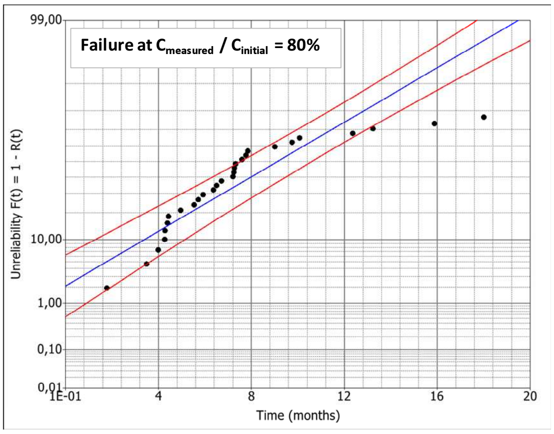

Figure 4: Normal fit of the batteries ditribution when they reach 80% of their initial capacity. The center line represents the Normal fit of the distribution and the side lines are the 95% confidence bounds.

The MTTF of each fit has been calculated as well as the 95% confidence bounds of the fit. From the MTTF results, it has been deducted the experimental degradation function of the batteries, represented in Figure 5. Then, the battery MTTF extracted from the previous reliability study, showed in Table I, has been plotted in the chart in order to characterized the capacity degradation state of the batteries when the users perceive that they have reached the end of their lifetime and have to be replaced by a new one. This point is situated in 18% of the initial capacity and it could be considered as the possible definition of death of batteries in decentralized rural electrification.

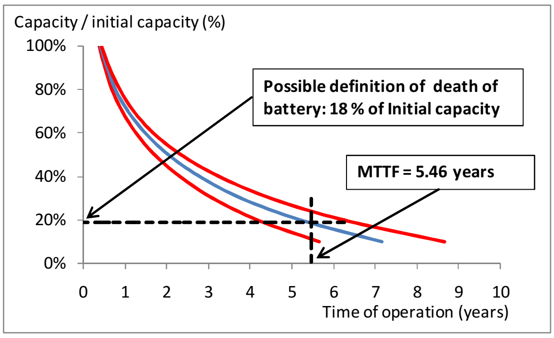

Figure 5: Battery experimental degradation function. The two side lines indicate the 95% confidence bounds. When plotting the MTTF from Table I, the capacity degradation reaches 18%. This point could be defined as the death of batteries in decentraliced PV rural electrification.

3.2 PV modules in-field assessment

The set of 41 PV modules were tested after have been working for a period of 6.15 years on average.

The testing method consisted of measuring the I-V curve of the PV modules from the sample in field-testing conditions. Afterwards, this I-V curve has been extrapolated to STC and compared with the data flash reported by the manufacturer**.** The measurement of the I-V curve has been done using a twin capacity load, [8], which allows to measure two I-V characteristic simultaneously of both, one PV module from the sample and a reference PV module (previously stabilized and calibrated).

The I-V curve from the reference PV module has been measured to get G_{eff} (from I_{sc}) and T_C (from V_{oc}) simultaneously to the I-V characteristic capture, as well as to check the extrapolation to STC [9-10].

The statistics of the STC results are summarized in Table II. Note that the most relevant parameters, in terms of difference between the two measures, are the maximum current (I_m*) and the maximum power (P_m*).

Table II: Statistics of the PV modules degradation of parameters from the sample in STC conditions.

	ΔI_{sc}*	ΔV_{oc}*	**ΔI_m***	ΔV_m*	**ΔP_m***	ΔFF*
θ (%)	-2,76	-1,97	**-4,77**	-2,04	**-6,70**	-2,10
σ (%)	-1,42	-1,26	**-1,57**	-1,84	**-2,05**	-2,23

The test shows a reduction of P_m* in 6.7%, in average, and the standard deviation σ = 2.05%. The P_m* annual average degradation corresponds thus to 1.1 %. However, PV modules can experiment a premature degradation after the first hours of solar radiation exposure. The possible early degradation has been included in this yearly rate. Taken into account an early degradation in terms of maximum power P_m* between 0 % and 4 % [13], we can conclude that the mean yearly degradation of the sample goes from 0.4% to 1.1%, which is consequent with other reported experiences [13-14].

Besides the power test, a visual inspection of the modules have shown a PV module with a hotspot in one of the silicon cells and other that presents cells with browning effect, due to the degradation of the EVA layer over the cells. Nevertheless, these defects cannot be considered as a threat for the reliability of PV modules and they only could lead to a decrease of the electrical performance.

4 PROGRAMME COST CHARACTERIZATION

In assessing the overall cost of the PERG programme, three main activities have been identified: the installation, the O&M and the general management. The installation refers all the works and activities required to install the SHSs, as well as the purchase of equipments and the marketing. The operation and maintenance of the systems requires the technical maintenance of the SHSs (including spare parts) and the collection of user's fees.

The general management refers to the ESCO management staff and headquarter, as well as other issues related to the management of the project.

Other indirect costs as taxes, banking fees, assurances, staff training, office supplies, contingences fees, financial expenses, transports, customs, etc, are included in these three main activities.

The costs of the first five years of the PERG programme, extracted from the accounting of the ESCO, are shown in Figure 6: from 2006 to 2008 the activity was mainly devoted to the installation of the SHSs, and 2009 - 2010 to the operation and maintenance service. Obviously, O&M was also carried out from 2006 to 2008 for already SHSs installed.

The total expenses in these five years reached the amount of 12.5 MM€, distributed as shown in Figure 6. Note that every expense involved in the development of the programme has been considered, taking into account all operative and financial costs before amortizations.

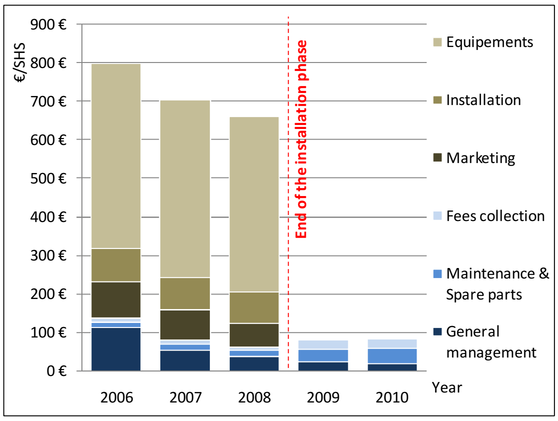

Figure 6: Distribution of actual costs in the first 5 years of programme.

Given the failure rate of the SHS components in this programme, and taken into account that the total number of SHSs installed in at the end of the installation phase remains practically fixed, it is reasonable to suppose that the O&M costs in 2010 are representative of the following years. Therefore, we can establish the whole cost of the programme after the 10 years period of O&M.

Thereby the PERG programme, whose completion year would be in 2018, will have a global cost of **21.2 MM€**, which expressed in euro per installed peak power means **21 €/Wp**, and referred to the whole installed systems would be **1,574 €/SHS.**

It can be appreciated in Figure 7 that the installation costs are similar to the O&M costs for the whole programme period. The major costs are the initial equipment (29.4%) in the installation phase, and the maintenance activity including spare parts (26.5%).

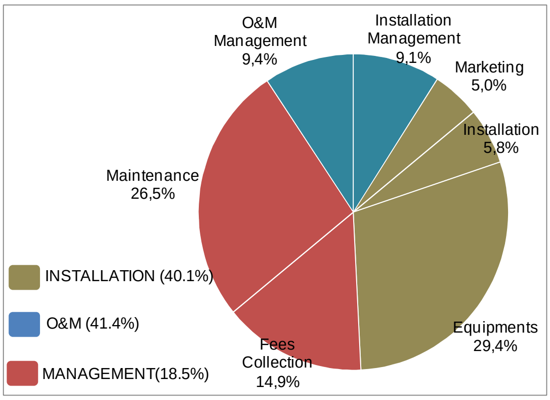

Figure 7: Global cost distribution of the PERG programme. Percentage distribution of costs for each group of activities.

Other of the main costs of the programme is the *fees collection* activity (14.9% of the total cost). The method to carry out this activity is based on the daily presence of the ESCO staff in the main rural communities from each region, coinciding with the days in which the local markets (*souks*) are organized, and it demands a great effort in human capital and mobility, which justifies this elevated cost.

Considering all of the O&M costs over the whole duration of the project (2006 – 2018), we can get the average yearly cost of the O&M as 76 €/year·SHS, being the yearly user fees just 60 €/year·SHS. Making a cash-flow balance for a 5% constant annual discount rate, and given an ideal fees collection rate of 100%, we will reach a total deficit of -3.4 MM€ for the O&M activity over the whole project duration.

This deficit reflects the lack of knowledge that exists about the O&M costs when designing a PVRE programme. That is the case of many other programmes carried out before [15-17] where the ESCOs incurred in important economic losses because low user fees were established. Therefore, we can conclude that the O&M is, in general, an activity more expensive than expected; moreover, the fees paid by the users for the maintenance service are generally lower than necessary. These two facts lead to an unsustainable financial situation of many PVRE programmes.

When evaluating the accumulative costs of the main SHS components during the whole duration of the programme, it can be proved that the most important cost is not the PV module, but the battery and the general management (both 18.5%). The PV module cost, of course, is significant, but it means just 15.5% on the global cost. Considering 2013 PV market prices, the PV module would mean only 4.36%.

It must be underlined the relevance of the general management activity within the cost structure (18.5% over the global cost). The ESCO had designed the management structure for a 34,500 SHSs programme, as initially planned. The lack of potential customers and the electric grid expansion achieved by the ONE, limited dramatically the number of SHSs installed despite the commercial efforts carried out by the ESCO. This fact suggests that the size of the PVRE programmes must be big enough to support the high cost of the decentralized management structures.

5 CONCLUSIONS

Both, the reliability study and the cost characterization have been achieved in the photovoltaic rural electrification programme in Morocco. The reliability assessment was already reported in a previous paper in which the reliability functions, the failure rates and the MTTF were calculated for lamps, charge controllers and batteries, based on real failures reported on the maintenance database of the ESCO. After that, two in-field testing have been carried out in the Moroccan programme to study more deeply the batteries and PV modules reliability.

In the case of batteries, several capacity tests have been achieved along 18 months when the batteries were operating in real conditions. The capacity tests demonstrate that batteries capacity decreases quickly, dropping to 67% of the initial capacity, in average, after 18 months of operation.

Regarding the PV modules, a set of 41 monocrystalline modules have been tested in the field to estimate the power P_m* degradation rate and to analyze their potential visual defects.

The results indicate a mean power degradation rate of 6.7% after an operation period of 6.15 years. This ratio matches with others experiences reported in bibliography.

Concerning the cost characterization, the PERG programme has been analyzed based on the real data costs of the first 5 years. The overall cost for 10 years of maintenance has been obtained as 21 €/Wp (or 1,574 €/SHS), where 40% of this cost corresponds to the installation phase; 41.4% to the O&M activity and 18.5% to the general management.

The O&M of the systems (maintenance, spare parts and fees collection) reaches 76 €/SHS·year. This figure is further higher than usually considered in photovoltaic maintenance and it is not covered by user's fees, causing unsustainable financial balances.

PV module represents just 15.5% in the global cost, versus 18.5% of the battery and general management (18.5%), so battery and decentralization have to be considered as the most expensive components in decentralized PV rural electrification.

4 REFERENCES

[1] E. Lorenzo, Photovoltaic rural electrification, Progress in Photovoltaics Research and Applications. 5 (1997) 3-27

[2] E. Martinot, A. Cabraal, S. Mathur, World Bank/GEF solar home system projects: experiences and lessons learned 1993–2000, Renewable and Sustainable Energy Reviews. 5 (1) (2001) 39-57

[3] J.M. Huacruz, J. Agredano, L. Gunaratne, Photovoltaics and Development, in: A. Luque, S. Hegedus, Handbook of Photovoltaic, Science and Engineering, 2nd edition, Wiley, Chichester, 2011, pp. 1078-1105.

[4] X. Lemaire, Off-grid electrification with solar home systems: The experience of a fee-for-service concession in South Africa, Energy for Sustainable Development. 15 (3) (2011) 277-283

[5] X. Lemaire, Fee-for-service companies for rural electrification with photovoltaic systems: The case of Zambia, Energy for Sustainable Development.13 (1) (2009) 18-23

[6] A. Zomers, The challenge of rural electrification, Energy for Sustainable Development. VII (1) (2003) 69-76

[7] L.M. Carrasco, L. Narvarte, A. Peral, M. Vázquez, Reliability of a 13 000-SHS photovoltaic rural electrification programme. Prog. Photovolt: Res. (2013)Appl., 21: 1136–1145. doi: 10.1002/pip.2218

[8] J. Muñoz, E. Lorenzo, Capacitive load based on IGBTs for on-site characterization of PV arrays, Solar Energy, Volume 80, Issue 11, November 2006, Pages 1489-1497, ISSN 0038-092X, 10.1016/j.solener.2005.09.013.

[9] International standard IEC 60891. Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics. International Electrotechnical Commission, 2009.

[10] R. Moreton Viungra, E. Lorenzo, F. Martinez-Moreno, Field Performance of PV Modules Quality Control Process, 23rd European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain (2008), DOI 10.4229/23rdEUPVSEC2008-4AV.3.33

[11] IEC standard 60896-11. Stationary lead-acid batteries – Part 11: Vented types – General requirements and methods of tests. 2002

[12] IEC standard 61427-1. Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application. Edition 1.0 (2013-04-23)

[13] M.A. Muñoz-García, J.P. Silva, F. Chenlo, Influence of Initial Power Stabilization over PV Modules Maximum Power, 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany, DOI: 10.4229/24thEUPVSEC2009-4AV.3.50

[14] M.A. Munoz, M.C. Alonso-García, Nieves Vela, F. Chenlo, Early degradation of silicon PV modules and guaranty conditions, Solar Energy, Volume 85, Issue 9, September 2011, Pages 2264-2274

[15] F.D.J. Nieuwenhout, A.L. van Dijk, P.E. Lasschuit, G.M. van Roekel, V.A.P. van Dijk, D. Hirsch, H. Arriaza, M. Hankins, B. d. Sharma, H. Wade, Experience with solar home systems in developing countries: a review, Progress in Photovoltaics Research and Applications. 9 (2001) 455-474.

[16] A. Cabraal, Best practices for photovoltaic household electrification programs: lessons from experiences in selected countries, World Bank Technical Paper number 324, Asia Technical Department Series. 1996

[17] M.J. Horn, Solar photovoltaics for sustainable rural electrification in developing countries; the experiences in Peru, ISES Solar World Congress. Göteborg, 2003