Electrical, mechanical and optical analysis of Pico PV systems after use in rural areas of Peru

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Abstract: The objective of this study was to analyse parameters of performance of Pico PV systems in a proper scientific way in order to deliver information regarding technical factors. In addition, a field research was used as a tool to analyse the performance of different Pico PV systems order to observe the current state of the electrical and electronic components after use under real conditions. This was done by visiting households and using survey forms to be filled by end-users living in three different locations of rural areas of Peru. Further, laboratory tests were implemented in order to investigate the current state of Pico PV lamps. Three different types of Pico PV systems were analysed in a case study. The three types of lamps were evaluated under the same conditions and testing protocol. The Pico PV lamps considered for the study had been used for more than 20 months in rural areas. The current state of these Pico PV products under detailed analysis was determined to identify the causes and reasons for their deterioration. Suggestions and recommendations to prevent failures, to prolong the lifetime of these products and information related to their warranty were also described. The causes of failures of the systems before the nominal warranty time expired were determined bearing in mind that the devices typically had an appropriate performance considering the time of use. From the total sample number, the devices had a 55% failure rate concerning end-user intervention, a 33% failure rate due to technical failure and 12% of the systems did not report failures. The batteries have to be charged and discharged in a proper way in other to get better operational results, e.g. longer lifetime and low capacity degradation. It was determined that in order to reach the minimum 2 years of use, PV panels should be able to operate for at least the same lifetime as the lamp. End-users should charge the lamp, ideally with a daily sun charge of 8 hours per day, keeping in mind that only one function at a time should be made, e.g. lighting or cell phone charging. With the research portion of the study, it was possible to show that for an overall evaluation of Pico PV lamps after use in real conditions, is necessary to implement the technical evaluation of the components of the Pico PV systems but also to consider the influence of end-users behaviour.

1 Introduction

A broad variety of Pico PV products are available in local markets of developing countries. However, large quantities of these products are considered of low performance (Brüderle and Mayer-Tasch 2011) and as a result, final users are not prepared to buy these products. In addition, end-users cannot always distinguish among high and low quality products; therefore, it is most probable that they will not be satisfied with the investment in these products because they do not satisfy their needs. Therefore, in order to help the customer to get value for money, different technical parameters could be analysed to establish the performance of these Pico PV products. These analyses include the examination of: robustness, quality of switches, degradation of luminous flux and energy supply. Furthermore, other factors can be included, such as: awareness campaigns and training; information supply for end-users and introduction of voluntary or forced parameters of security. The warranty of the products could also be analysed (Hellpap, Raabe, and Pfisterer 2011).

Since 2006, EnDev has developed field researches in several countries such as: Bolivia, Tanzania, Ethiopia, Uganda and Peru. The Pico PV models evaluated in these countries include: Mighty Light, Aishwarya, Solux 100, Solux 50, Phocos, Fosera, Sundaya, Sun King Pro and Solar 2007-1. A field research may be a complement of laboratory test regarding Pico PV products which have been previously evaluated (Attigah et al. 2011).

However, to obtain a better understanding of the performance of Pico PV products that were used under real conditions, other laboratory evaluations are required and recommended for establishing the conditions of performance after the use of the Pico PV systems based on a defined time interval.

From previous experience, Energising Development (EnDev) Peru Programme, developed laboratory tests to analyse some of the electrical characteristics (e.g. battery charging) and luminous flux of the LED of the Pico PV systems. The models Ulitium 200, Fosera 7000, Pico LED and Sun King Pro were evaluated taking into account a minimum period of 8 months of use. Yet, a laboratory test for a longer time period is recommended (Brüderle and Mayer-Tasch 2011) so as to describe the current state of the electrical-optical and mechanical characteristics of the Pico PV systems that families in rural communities use daily for a period of at least 20 months and to obtain a better understanding of the performance of the devices.

1.1 Pico PV as alternative for rural electrification

The sun can provided around 7kWh/m^2/day of irradiation in Sunbelt countries (Reiche et al. 2010). This amount of energy can be used to activate energy consumption of electrical or electronic devices (e.g. lanterns/lamps, cell phone chargers and radios) by means of photovoltaic panels. These devices can be used for the benefit of end-users that request lighting and communication services such as radio and cell phones. Table 1 shows the energy demand of a Pico PV system.

Table 1. Minimum energy demand of a Pico PV system.

Load	Service	Nr.	Watt	hours/day	Wh/day
Ambient light	50 lux	1	0.5	3	1.5
Study light	200 lux	1	2	2	4
Night light	10 lux	1	0.1	8	0.8
Cellphone	Charge at 50% SOC	1	2	1	2
Radio	Sound	1	0.5	2	1
TOTAL					9.3

Source: Lysen, 2013

On the other hand, in Peru, the yearly solar irradiation (G) on average for the region of San Martin[1] is around: 4.37kWh/m^2/day. With this amount of radiation incident over a photovoltaic panel of 5Wp (21.5cmx16.2cm) with a surface area (S) equal to 0.035m^2, one can calculate the average amount of available energy for a Pico PV system over the day. This calculation is possible assuming that Pico PV systems have an efficiency (η) of 7% (Gauna 2012):

$$E_{picopv} = Panel\_Surface_{picopv} * \eta_{picopv} * G$$

$$E_{picopv} = 0.035m^2 * 0.07 * 4{,}370 \frac{Wh}{m^2 * day}$$

$$E_{picopv} = 10.07 \frac{Wh}{day}$$

Available energy for a Pico PV system is in table 1. This energy is high enough to activate one low consumption lighting point (e.g. 1W LED) around 8 hours; equally, 2 lighting points can be activated for around 4 hours if the same energy is consumed.

Besides, if all the energy generated is not consumed for illumination in its totality, it is possible even to charge cell phones and listen to the radio.

For the case of rural area communities in Peru, it was estimated that one family living in rural areas will need to use only 2 incandescent lamps of 50W for 3.5 hours at night and also a small radio of 10W for 5 hours per day, having an average consumption of about 400Wh/day. Using incandescent lamps with an efficacy of 11lm/W; 350Wh/day will be needed for lighting. In total, 4klmh/day will be obtained, which is equal to 120klmh/month. The energy consumed can be converted to luminous consumption, but LEDs of high

[1] NASA web page https://eosweb.larc.nasa.gov

efficiency obtain this luminous efficacy with values approximate to 120lm/W (Horn 2011).

2 Methodology

The selection of the Pico PV models that are participating in this research is based on the potential market in the area of study and models used in previous field studies as well. These lamps are used by families in different rural communities and they also have different characteristics among them. Therefore, the study evaluates the different characteristics of the main components of the three models under analysis. From each model, 6 samples were considered for the respective analysis bearing in mind the suggestion of the Quality Test Method (QTM) of "Lighting Global" (an initiative of the International Finance Corporation – World Bank).

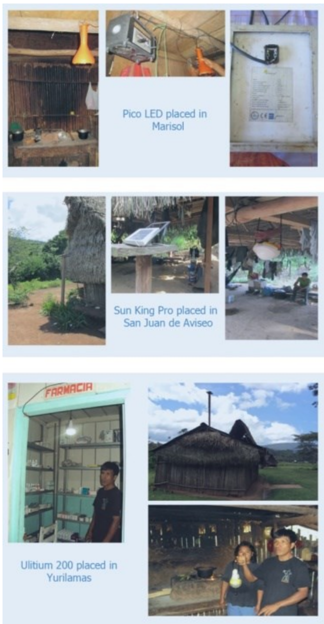

Figure 1: Field visit in Marisol, San Juan de Aviseo and Yurilamas

Source: Author, 2014

By using the QTM as a testing method, one has an overall evaluation. The analysis results are quick and not require sophisticate equipment as in other methods such as PV GAP (Global Approval Program for Photovoltaic) or ISE

Fraunhofer (Institute für Solar Energie). In addition, the QTM is described in the International Electrotechnical Commission through the document IEC/TS62257-9-5 (Lighting Global/IFC 2013) and it is performed in programmes such as Lighting Africa and lately, Lighting Asia as well. For the present analysis, it is important to consider the testing protocol, developed for the Photometry laboratory of the Physics department of the Faculty of Science at the UNI (Universidad Nacional de Ingeniería) in Lima. IEC60529 (International Electrotechnical Commission 2001) and IEC62262 (International Electrotechnical Commission 2002) tests protocols for the mechanical analysis are considered. To get the determination of the technical parameters, the evaluation of the Pico PV systems will be estimated throughout two complementary methods: the non-evaluative method for examination and the performance qualification method considered in test protocols of Lighting Africa, PV GAP and ISE Fraunfoher.

Table 2: Parameters for the evaluation of solar lamps

N°	Procedure of the test	Evaluated parameters	Category	Type of criteria
		Non-evaluative method / fast test		
1	Visual Screening	Workman quality, Environment impact	Performance	Basic – Robust
2	Visual perception: light output	Lighting distribution and diffusion	Lighting	Basic – Intense
3	Inspection and description of the charge controller	Overcharge/deep discharge protection	Performance	Excluded – Ideal
		Qualification performance tests / Prolonged test protocol		
1	State of the battery	Capacity, Autonomous Run Time, Luminous flux, Depth of discharge, Efficiency.	Performance / Use	Degradation – Strong
2	Lighting characteristics, lifetime of the lighting source	Luminous flux performance	Lighting / Performance	Degradation – Strong
3	Characteristics of the charge controller	Battery protection NiMH / Li-ion (LiFePO4), Charge/discharge fraction, Solar fraction simplified	Performance / Use	Excluded – Strong
4	Mechanical inspection	Mechanical endurance, connector and switch robustness, Ingress protection, Impact strength	Performance	Degradation – Strong

Source: Bopp, 2009

2.1 Technical tests performed by the Pico PV lamps

To find the sampling number, the suggestions from QTM protocol (Lighting Africa Programme) to choose 6 random samples for each Pico PV model to be tested is adopted in the study because with this number it is possible to find manufacturing characteristic with accurate estimation. The following tests were accomplished in this study.

2.1.1 Electric tests

a) Charge with own circuit, so as to determine the operation of the charging circuit.
b) Discharge at shorter operating level with own circuit, so as to determine the operation of the discharge circuit.
c) Measurement of capacity and energy delivered to/from the battery, thus calculating efficiency.
d) Depth of discharge measurement, to determine the battery charge remaining before the charge controller turns off the light source.

2.1.2 Optical tests

a) Measurement of luminous flux through an Ulbrich integrating sphere, to determine characteristics of the light source such as luminous flux, color rendering index and color temperature of each lamp to describe their current value after two years of use.
b) Determination of luminous flux over time, in order to indicate the running time available at the maximum level (shorter operating level/high energy consumption) and quality of lighting service.

2.1.3 Electronic inspection

a) Evaluation of charging/discharging circuit to determine which elements of the electronic circuit could suffer permanent damage or degradation.
b) Thermal analysis of electronic circuit at charging and discharging stages by means of thermo-graphic images.

2.1.4 Mechanical tests

a) Tests to check protection index degree: Ingress Protection - IP (Ingress Protection against liquids and solids). Tests take into account the IEC 60529 standard (International Electrotechnical Commission 2001).
b) Tests for determining impact protection degree: Impact Test - IK (on impact resistance). Tests take into account the IEC 62262 standard (International Electrotechnical Commission 2002).

2.2 Instruments

2.2.1 Load measurement and battery power

1) Power supply for battery charge GW Instek - GPR1810 OHD.
2) Data acquisition system with PC communication RS- 232 serial interface and software LabView8.0.
3) Multimeters: Fluke 45 Dual Display (± 0.03%) with RS- 232 PC interface, to measure current through shunt resistor. Tech TM 145 (± 0.1%) with RS - 232 PC interfaces for measuring voltages.
4) Shunt Resistance, Blatter 50 [mΩ] (± 1.0%) for voltage drop measurement.
5) Banana and crocodile connectors.

2.2.2 Runtime measurement and light output degradation over time

1) Fluxmeter Luxtron LX- 1108 (± 0.1%) with RS-232 PC interface for luminous flux measurement as a function of time.
2) Square box covered black cloth (52.5cmx41.5cmx24.5cm) with a 5cm diameter for Fluxmeter measurement.

2.2.3 Measurement of luminous flux

1) Integrating sphere: Labsphere LMS 400 / 1m diameter (± 0.4 %).
2) Labsphere CDS 1100 Spectrometer (350-850 nm).
3) Power Source LPS- Lamp Pattern: Labsphere 105-0268.
4) Lamp pattern Labsphere Gilway SCL- 050 187-1 (1,538 lm ± 0.7%).

2.2.4 Measurement of thermal graphic images

1) Camera: Fluke Ti55 Thermal Imager IR Flexcam, clamps and braces.

2.2.5 Measurement of ingress protection IP and IK index

1) Instrumentation according to IEC60529 standard.
2) Instrumentation according to IEC62262 standard (Hammer Pendant with 1.14kg load).

3 Results

After collection of random samples, labelling and testing; the results of the overall evaluation were achieved for each model. The technical evaluation included a comparison with results of previous evaluations made at the Universidad Nacional de Ingeniería in order to have some trends or perceptions of performances. Also matching of data from end-users and registered in the field poll was made. Figure 2 shows examples of visual screening of the three different solar lamps.

Figure 2: Examples of visual screening of three different solar lamps

Source: Author, 2014

Charging and discharging processes were measured and graphically registered as shown in figure 3.

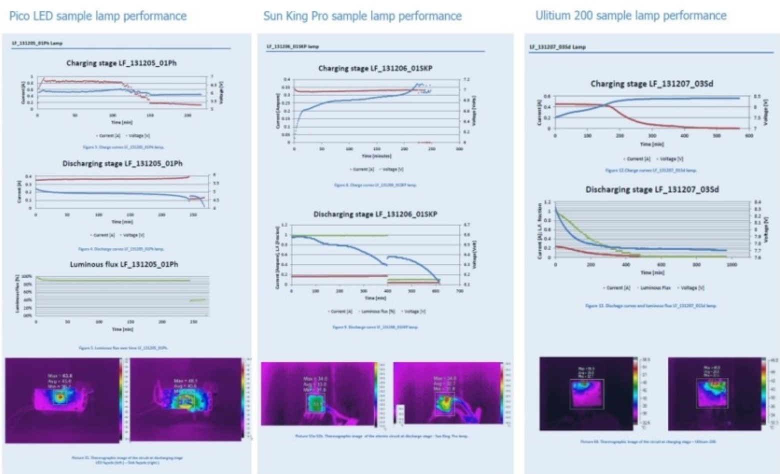

Figure 1: Electrical and thermal tests on three different solar lamps

Source: Author, 2014

Additionally, since the systems were randomly collected, in case of internal failures that are not possible to identify in the field; refurbishment was considered and required according to available resources among the existing samples in better conditions or samples with a normal performance, e.g. batteries with higher capacity, charging connectors less damaged. After evaluation, a table with results was made. An average value per model for each of the functional samples was recorded for the analysis. Table 3 shows the results delivered from each model.

Table 3: Average values of the electric-optical evaluation of solar lamps

		TEST	Ulitium 200	Sun King Pro	Pico LED
		Date	**January 2014**	**January 2014**	**December 2013**
		State of the lamp	**Post-use 36 moths**	**Post-use 21 months**	**Post-use 30 months**
		Samples amount	6	6	**6**
Electrical test (average)	**Discharge**	**Capacity [Ah]**	0.25	1.30	1.47
		Energy [Wh]	1.98	8.37	6.99
	Charge	**Capacity [Ah]**	0.73	1.35	1.80
		Energy [Wh]	6.10	9.25	10.83
	Efficiency	**Coulomb [%]**	0.21	0.95	0.81
		Energy [%]	0.20	0.90	0.65
		DOD	-	0.97	0.97
Optical test (average)		**Luminous flux [lumen]**	210.83	98.50	104.76
		Color temperature [K]	6,378	4,411	4,226
		IRC [%]	60	62	68
		Power [W]	1.93	1.10	1.83
		Efficacy [lm/W]	109.85	88.96	57.25
		Running time [h]	0.21[2]	10.19	4.00
		Luminous flux [%]	-	100-20	100 -20

Source: Author, 2014

As the Pico PV lamps have different type of batteries, LEDs and electronics; the results show a variation on battery efficiencies, luminous flux and running

[2] If the lamp with the best performance is considered, the LF_131207_03Sd lamp has a running time of about 5 hours with a luminous flux variation from 100% to 20%.

time. Running time of two of the models is acceptable for use at night time. End-users reported an average lighting use of about 3.5 hours.

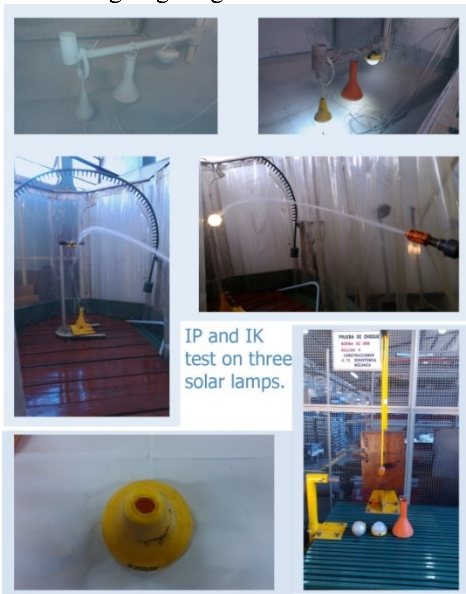

Figure 4: Mechanical tests on three different solar lamps

(IP-IEC60598 and IK-IEC62262 test protocols)

Source: Author, 2014

Results of IP-IEC60598 and IK-IEC62262 test protocols are shown in table 4.

Table 4: Values of the mechanical evaluation of solar lamps

Protection degree				
Pico PV Lamp	**Code**	**IP adjusted conditions (less protected lamp)**	**IP ideal conditions (protected lamp)**	**IK**
Ulitium 200 (Indoor model)	**LF_131207_03Sd**		43	07 (energy up to 5J)
Sun King Pro (Indoor/outdoor model)	**LF_131206_06SKP**	43		
	LF_131206_01SKP		54	07 (energy up to 5J)
Pico LED (Indoor/outdoor model)	**LF_131205_02Ph**	20		
	LF_131205_04Ph		64	09 (energy up to 10J)

Source: Author, 2014

For the mechanical analysis of the samples, two scenarios were suggested, one scenario refers to IP adjusted conditions, meaning that the lamps under analysis did not have all the protection components and the other scenario refers to IP ideal conditions (lamps with more protection included).

4 Conclusions and recommendations

4.1 Conclusions

With the resources of the study, the determination of the current state of the Pico PV lamps was possible. Three different types of lamps were evaluated and their condition after extensive use was determined. Electrical, optical and mechanical parameters were measured under suggestions of protocols that are considered by different institutions. These protocols determine the main factors of Pico PV technology in order to apply it in rural electrification programmes. The evaluation reported different results since the electric and mechanic design of these technologies are different: charge regulator with or without Maximum Power Point Tracker, Li-ion or NiMH batteries, single or arrays of LEDs, indoor or outdoor use. With 6 samples, it was possible to analyse which are the main factors degrading the performance of Pico PV lamps in real conditions. The complement of electrical-optical and mechanical analysis gives a global evaluation of the lamp being tested. The causes of failures of the systems before the nominal warranty time expired were determined, the devices had an appropriate performance considering the time of use. From the total sample number (18 lamps), the devices had: 55% failure rate concerning end-user intervention due to lack of knowledge for proper use, long periods without charge, wrong replacement of batteries or another pieces and wrong PV panels' placement.

33% failure rate due to technical failure such as: batteries with low Coulomb's efficiency use of non-certified PV panels and disconnections of components on Printed Circuit Board (PCB); the first failure was reported after 12 months of use due to PV panel deterioration and consequently lack of energy harvesting.

And 12% of the systems did not report failures.

The high rate of failures concerning end-user intervention shows that there is a relation among end-user behaviour and the rendering of the system, some of the end-users opened the lamps in order to repair it if light output was not working, even if the lamps were not damaged. As the batteries are electrochemical components, they have to be charged and discharged in a proper way in other to get better operational results, e.g. longer lifetime and low capacity degradation. At the same time, it was determined that in order to reach the minimum 2 years of use, PV panels should be able to operate for at least the same lifetime as the lamp. End-users should charge the lamp, ideally with a daily sun charge of 8 hours per day, keeping in mind that only one

function at a time should be made, e.g. lighting or cell phone charging. As the Pico PV lamps have different type of batteries, LEDs and electronics; the results show an acceptable variation on battery efficiencies, luminous flux and running time compared to a new lamp. Running time of two models is acceptable for use at night time as end-users reported an average lighting use of about 3 hours and 30 minutes.
Ingress Protection index has decreased only for outdoor lamps. For the case of indoor design, it remained constant.
IK index tests were determined over different points and surfaces of impact. The three evaluated models are able to resist energy impacts equals to accidental drop from a height of 2.0 meters over flat surfaces.
Non Surface Mounting Device (SMD) components of the electronic circuit that are not fastened to the PCB have a risk of disconnection.
The methodologies of IP and IK index for Pico PV lamps have been adapted for the current analysis without varying from the conditions described by IEC 60598 and IEC 62262 standards.
Concerning local institutions for technical evaluations in Peru: the Universidad Nacional de Ingeniería and José Feliu Bosch (JFB) laboratories have the protocols and instruments for high precision measurements and, necessary to elaborate lamp evaluation (new and post-use).

4.2 Recommendations

The lamps should be protected against end-user intervention (e.g. changing batteries, disconnection of cabling) so as to decrease its high failure rate. Suggested improvement to the design of the Pico PV lamps are: use of protective film cover (e.g. paralyne) on the electronic circuit; use of slots if cabling is part of the design with the aim to avoid tin welding with high risk of disconnections; lighting and electric compartments should be isolated from water and humidity effects; LEDs using heat sinks are recommended as it was identified that LEDs' last longer if operative temperature is decreased ; the use of less quantities of storage cells to avoid mismatches of internal resistance among the cells. However, not only lamps should be considered for improvements, but panels as well.
Manufacturer may use of hot-melt adhesive to add the non SMD components and high frequency vibrations may cause the devices to separate from the PCB.
A characteristic of Pico PV systems is that they are designed to be "plug-play" technology. However, it will still be necessary to install cables inside and outside the households. Cable gutters are an option to protect cables from rodents and domestic animals.
The thermal analysis is ideal for the determination of failures of components during the charge and discharge stage. Possible failures of the electronic circuit are avoided if thermal analysis is made at the design stage. Nevertheless, the

thermal analysis post-use will determine acceptable temperature range of different components.
In the case of fuses, these should be easily replaced, keeping in mind that SMD components are difficult to replace in rural areas. If a fuse is part of a design, then it should not use SMD technology and should be locally accessible.
Textile cloths present in design should be avoided in order to prevent capillary absorption and water ingress as a result of suction effects.
It is also advisable to avoid usage of the lamps for a very long time without the lamps being charged; if possible, not more than 1 week.
IEC standards give consideration to optimize the performance of solar panels. If the panel fails before the lamp fails, then the whole system will be considered to fail due to loss of the energy harvesting system, in that manner its failure rate could also be decreased.
The mechanical tests of Ingress Protection IP and Mechanical Impact Resistance IK showed that the protection index tends to decrease in function of the placement of all the pieces. Protection should remain in the same position as a new product e.g. the electrical connectors should be continuously protected, only when charge is provided the covers are not necessary. IEC norms for IP and IK test protocols allow analysis of electric devices with a 72,5kV voltage rate. However, a proposal for an IP and IK index determination for specific analysis to Pico PV lamps is suggested in future studies.
After the evaluation of the samples and obtaining the results, it was recommended to analyse the most vulnerable components of the lamps e.g. batteries with high degradation.
Concerning informative topics; user's manuals and training could include instructions regarding optimal charge conditions e.g. if the lamp is charging, then external devices should not be running.
Training should have an emphasis on the state of charge determination, especially if SOC (State of Charge) indicators do not have a bi-color or LCD design.
Emphasis on periodic cleaning of the lamp and components is ideal.
In local villages or communities where availability of post-sales services are present, local retailers are able to answer end-users' requests regarding warranty claims.
Telephone numbers of local retailers could be included in manuals. End-users could know and remember the use and care of the lamps and panels: a poster or manual with most relevant use and care considerations is an option.
In addition, measurement devices such as multimeters (to measure voltage and current) should be available in local retail stores in order to identify basic failures.
As a register for controlling lamps distributed in rural areas, an inventory will help manufactures to identify the most frequent failures in order to improve lamp designs.

There are hardware stores where technical services and repairing of electronic devices is possible. These stores are ideal for repairing connection boxes, cable connectors and plugs, panel cables, battery replacement, cleaning of inside cavities in case of water and insect presence.

It is recommended the creation of a “Pico PV Committee” to promote good care practices is possible in local communities it could also be a local contact to retailers.

Also, recycling of batteries, lamps and PV panels should be considered in local communities.

If components are locally available, then it is possible to replace defective parts of the circuits or even the batteries and fuses. In the framework of this study, visits to electronic components stores were done. Jr. Paruro is a local marketplace in Lima with a high variety of PV products. Local retailers can approach electronics hardware stores to investigate local market and distribution channels.

Visits to local communities must be coordinated with local and regional authorities in order to have a successful field research.

Before surveys and focus group are held, a bond with end-users gives a friendly environment in order to ask questions without receiving unconcerned replies.

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