Global Cumulative Installed Photovoltaic Capacity, Solar Home Systems and Mini-grids

Internship at the Reiner Lemoine Institut, Berlin, Germany. September-December 2011

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REINER LEMOINE INSTITUT

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Introduction

The Internship was carried out in the Reiner Lemoine Institut, located in Berlin, Germany. It is a relatively new institute dedicated to the research of the Renewable Energy Sources, their aim is to support the processes for long-term conversion of the energy supply to 100% renewable energy sources.

Among the researches carried out by them there is one about cumulative installed photovoltaic capacity. They have been the first in the world who have compiled an estimation of the cumulative installed PV capacity by end of 2010 for all countries in the world and therefore they have a good estimate of the cumulative installations per country, nevertheless there are still some countries from which there is not enough data and they would like to improve their data base, after gathering all these data the finalized numbers of the research will then be published.

In this way the first objective of the internship was to obtain new data for some specific countries with few or no source of data available, the second objective was to make a comparison between photovoltaic solar home systems and mini-grids.

In the first part of this report the description of the methodology and results of the database are presented. After that the complete comparison between solar home systems and mini-grids is presented, this was a literature research with several sources (papers, conference proceedings, presentations, posters) provided by the institute and also a web search for new insights in literature. The characteristics of the solar home systems, economics, results of some experiences and some issues found are presented in the report, for the case of the mini-grids a similar approach is done.

Cumulative PV installed capacity in the world

The first task was to read documentation supplied by the institute about different topics such as rural electrification, market potential of PV, installed capacity of PV, conferences documents, etc. Some presentations in power point about off grid systems were also provided. The objective was to obtain a better understanding of the topic.

The basic source of information of the database is the international customs database, monitored by the 'Market Analysis and Research' section of the International Trade Centre (ITC), which is an agency of UN's World Trade Organization. The database contains the customs data of all countries worldwide since the year 2001; the particular national customs authorities give this data. The database provides the opportunity to evaluate the total value of imported and exported products for each country per year. Additionally, a possibility of evaluating bilateral trades for a specific product is given. Products are classified in several specific product numbers, so-called HS Codes, being obligated by more than 200 countries, customs and economic unions, representing more than 98% of world's trade. HS Code group 854140 represents 'photosensitive semiconductors devices, photovoltaic cells and light emitting diodes'. More specific descriptions with detailed determination in codes between light emitting diodes and PV are available for approximately 95% of the data. Otherwise an experienced ratio of 80% PV and 20% light emitting diodes was used. Data have been assigned for 193 countries in a period from the year 2001 until 2010. Basis of the calculation of PV capacities per country is the following assumption: 'import A' – 'exports A' + 'production A' = 'market A'. The production volumes refer to the publications of the magazine 'Photon' on the production output of the years 2001 until 2010. Regarding this, attention is paid to the fact that approximately 25% of annual productions are installed in the following year. Since data are including monetary value of the products, a conversion to PV capacities is necessary. For this purpose a reliable estimation of PV prices per Wp for every country is needed. These price data refer to a worldwide annual average PV price per Wp. (Taken from C. Werner, A. Gerlach, P. Adelmann, Ch. Breyer, Global cumulative installed photovoltaic capacity and respective international trade flows, 26th European Photovoltaic Solar Energy Conference, 5–9 September 2011, Hamburg, Germany)

Using the data obtained with the methodology above mentioned together with some other numbers published by other sources (EPIA, German GTZ, Photon magazine) and also the opinions of experts the preliminary estimation of the installed PV capacity was done.

The first task was to identify the target countries for a deepest research of data; the countries were categorized according with the following criteria:

- By the number of sources available at the moment
- The size of the installed capacity from the highest to the lowest.
- The deviation between the different sources in the cases that there were two or more. Big differences between the numbers provided by the sources might be a problem

After this process it was defined to focus in 33 countries from all regions in the world mainly from Africa and Asia.

Nigeria	AFR	Lithuania	EUR
Angola	AFR	Romania	EUR
Rep. Congo	AFR	Guyana	LA
Madagascar	AFR	Colombia	LA
Djibouti	AFR	Iran	MENA
Zambia	AFR	Kuwait	MENA
Mauritius	AFR	Qatar	MENA
Botswana	AFR	Israel	MENA
Uganda	AFR	Morocco	MENA
Cuba	CA	New Zealand	OCE
Honduras	CA	New Caledonia	OCE
Dominican Republic	CA	Pakistan	Rest-ASIA
Nicaragua	CA	Singapore	Rest-ASIA
Russia	CIS	DPR Korea	Rest-ASIA
Belarus	CIS	Afghanistan	Rest-ASIA
Estonia	EUR	Papua New Guinea	Rest-ASIA
Ireland	EUR		

Table 1 Countries of focus for the data search.

The way of obtaining data was mainly a web search for information with the help of search engines such as Google, Yahoo and Exalead. In the case of scientific papers the search was done with Google scholar and Scopus. Not all the papers were available with my account of the University of Twente.

There was not much information regarding the PV installations for most of the countries in the list, among the websites consulted there are websites of the ministry of energy for such countries, companies that supply electricity, organizations or universities doing research or projects in solar energy, solar energy associations of the countries, development banks, rural electrification agencies, some examples are the World Bank, Asian Development Bank, USAID, REN21, World Energy Council, British Petroleum. Most of the sites mentioned above had data only for the biggest markets and leaders in the field. The magazine Photon was checked due to they provided with new data for new markets in every edition.

After finding almost no data available in the web, different organizations around the world were contacted by means of an e-mail asking for information about the topic, the preliminary paper was attached to the e-mail and they were asked to comment whether our data was close to reality or not. Reminder e-mail was sent in case of no reply. In the case of a phone number in the webpage the organizations were reached by phone, sometimes the phone numbers were wrong.

After contacting the organizations only few numbers were obtained. This new data was added to the database in order to improve the estimations.

New Data obtained from e-mails to the organizations and Photon magazine:

Benin 0.5 MWp
Estonia
Photon Magazine11/2011: 0.02MWp
Sustainable Energy Division of Energy Department of Estonia: 0 MW (detailed information in the mail received)
Photovoltaic Barometer-Eurobserv'er, April 2011: 0.08 MWp
Romania
Photon Magazine11/2011: 1.3 MWp
ISES Romania: 1.5 MW (detailed information in the mail received)
Photovoltaic Barometer-Eurobserv'er, April 2011: 1.94 MWp
Israel
Solar Research Unit of The Weizmann Inst. of Science: 52 MWp (detailed information in the mail received)
Statistical review of world energy full report 2011, British Petroleum: 61 MWp
Colombia
Photon magazine 09/2011: 9 MWp
El Salvador
Photon Magazine 08/2011: 0.3 MWp
Uruguay
Photon Magazine 05/2011- <1 MWp
Lithuania
Photovoltaic Barometer-Eurobserver, April 2011: 0.1 MWp
Photon Magazine 11/2011: 0.02 MWp

The countries and institutions contacted for the request are listed In the Annex 3

The second part of the internship was carried out while waiting for the reply of the e-mails sent for obtaining new data of the PV capacity.

For this part the institute provided literature: papers, proceedings of conferences of the 4th European PV-Hybrid and Mini-Grid Conference 2008, the 5th EU PV-Hybrid Mini-Grid Conference, 2010 and the 1st and 2nd Symposium Small PV Application in Ulm in 2009 and 2011.

The comparison is presented below.

Photovoltaic Solar Home Systems and Mini-Grids

Introduction to Solar Home Systems and Mini-grids

Electricity is a key factor in the modern life, and it is perhaps the most functional type of energy nowadays. Nevertheless today around 1.3 billion people do not have access to electricity and also 2.7 billion people still rely on the traditional use of biomass for cooking. [1]

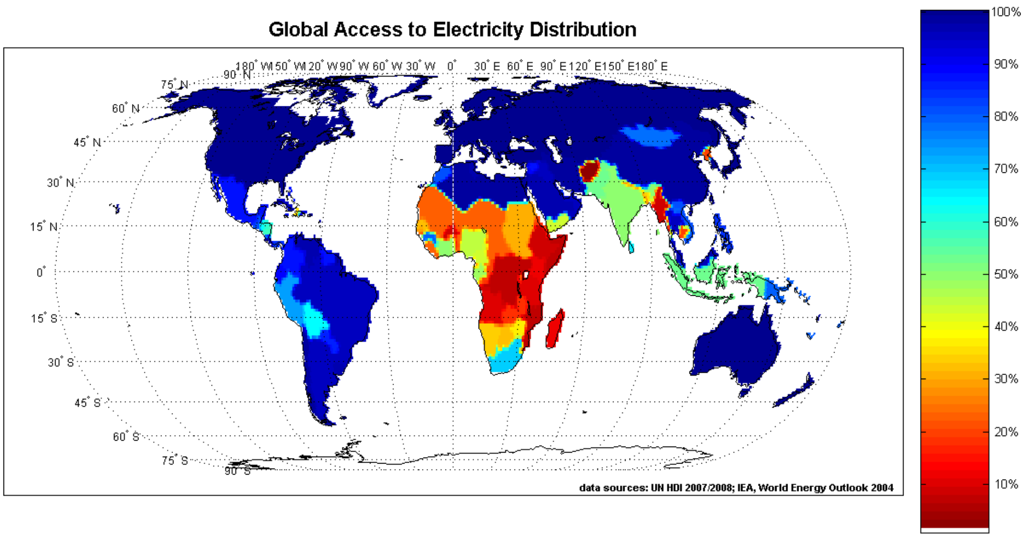

Fig. 1 Electrification Rate in the world. [3]

Most of these people live in rural areas in developing countries with a gross domestic product (GDP) per capita of less than 2,500 USD [2] and as shown in the picture above mainly in sub-Saharan Africa and South East Asia.

At the moment the communities without access to electricity satisfy their energy needs with kerosene lamps, candles and also with dry cell batteries for electrical appliances such as torches, tape recorders, radios and charging mobile phones. [4] These types of energy sources are harmful for the human health and for the environment as well as costly for users.

Among the possibilities for bringing electricity to people one might think that a grid extension could be the easiest way to do it, but in the case of rural areas where complex terrain and big distances are present most of the times this scenario does not seem financially viable due to the fact that a grid extension requires a minimum demand of electricity as well as established load densities which rural communities most of the time do not have.

Therefore the decision of which would be the best and least costing option to bring electricity to these people is not easy; it has to take into account several factors such as distance from grid, resources availability, equipment availability, community organization, income level, household service level, total number of households to be served, load density, productive loads and load growth, also we cannot underestimate factors such as different geographical, social and cultural characteristics which may have influence on the way of meeting electricity needs.

During years rural electrification projects were based on diesel engines generators, but in the long term these type of systems lead to a high operation cost (mainly fuel, spare parts, etc.) and high maintenance. Environmental and noise pollution also cannot be ignored. The limited availability (natural and political) of fossil fuel resources together with the previous lead us to the need to adopt different energy sources in order to minimize the impact on the environment, making in this way renewable energy sources (RES) a good solution for rural electrification. Solar energy for example hits the surface of the earth everyday; it is free, clean and available in considerable amounts in the regions where most of the people without electricity live. [2]

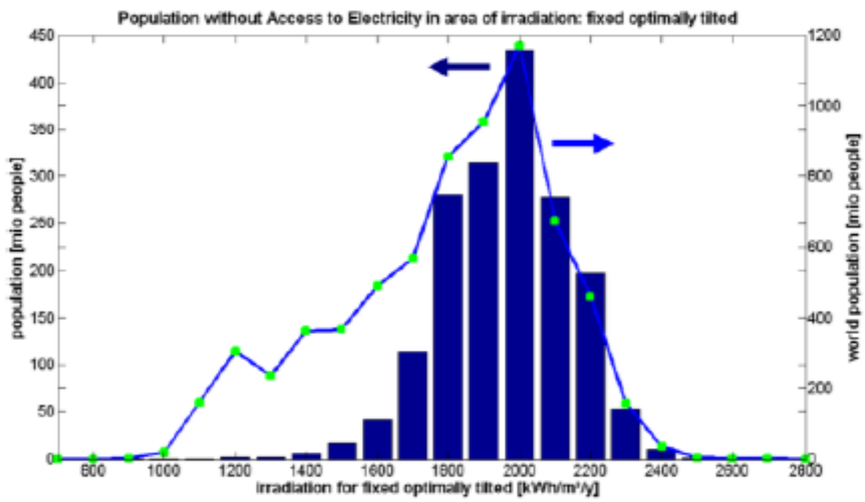

Fig. 2 Solar resource available in the world

"The line refers to the right axis and represents the distribution of total world population. The bars refer to the left axis and represent population without access to electricity" [2]

One of the viable options to deal with the problem are the utilization of the off grid systems. These consist of low capacity power generation equipment, from tens to hundreds of watts, capable of provide electricity for the basic needs of the people. In recent years there have been several projects using different technologies for this purpose, for example small hydro turbines, small wind turbines and PV systems.

The most of the PV systems fall in three categories: PV Pico systems (PS), solar home systems (SHS) and PV mini-grid systems.

Moreover these systems can help to improve local standards of living of the rural communities making a considerable impact in areas such as education, health, communications and economy. Better education conditions due to the use of lighting for schools, electronic teaching resources and information systems, health centres using electrical medical equipment and cooling devices for vaccines, improvement in communications due to the possibility to charge a mobile phone or use a radio and also an increase in the income of the households by means of the establishment of small enterprises could be listed as part of the benefits of the use of PV systems. [5]

A question raises then: which type of system to choose? And in which condition one system would be more adequate than the other. This is not an easy decision and involves different aspects that should be analyzed.

SOLAR HOME SYSTEMS (SHS)

SHS are decentralized systems located in every home. Typically they comprise a PV module that charges a battery (or battery bank) supplying DC electricity to DC appliances such as lamps (generally CFL, although LED lighting could be a good solution as well), fan, TV and other low power consuming devices. A charge controller is needed to regulate the energy flow that goes through the battery. In order to use AC loads (almost all the commercial appliances) an inverter from DC to AC is needed.

Fig. 3 Solar home system commercialized by Solar Electricity Co in Nepal. [17]

Characteristics

SHS are most of the times designed for domestic lightning and small power applications and to provide a regular electricity service to a single household. Normally the battery size incorporates 2 or 3 days of autonomy in case that they cannot be charged due to a low level of radiation and also to prevent any capacity shortage or loss of peak load at any time of the year.

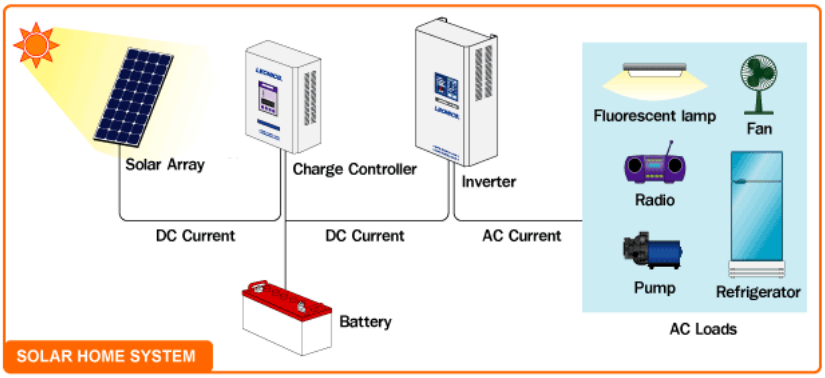

Fig. 4 Diagram of a SHS with inverter. [19]

Due to the fact that the PV panel and the battery work with DC the ideal scenario would be to have only DC appliances, however most of the commercial appliances run on AC making in this way necessary, in most of the cases, the use of an inverter, nevertheless both type of systems can be found on the market. In fact more and more appliances are offered for DC. For example there are DC compact fluorescent lamps or LED lamps, which in case of a SHS only for lighting will avoid the use of an inverter.

The size of the solar panel is in most cases below 100Wp (although systems of 3Wp can be found in the market) and the voltage can vary between 12V, 24 or 48V.

When related to generate income for households they are limited in certain aspects and also not all the systems are capable of perform community development tasks like street lighting, safe drinking water and vaccine refrigeration.

Economics

Cost and amortization of the systems vary from country to country and financial analysis can be performed in different ways; comparing the benefits of a SHS against the use of fossil fuels is one of the most common approaches done. [4] Nevertheless analysis can be difficult due to the fact that the cost and benefits of the system have to be distributed over long periods of time (10-20 years).

Another way to do the economical analysis is to compare the cost per kWh of the SHS against other type of electricity sources. Basically this cost can be obtained by dividing the total cost of the SHS with the annual production of electricity of the system. The levelised unit cost of electricity (LUCE) is a tool that helps us to estimate the cost per kilowatt-hour that the SHS delivers to the user. [7]

For calculating the LUCE it is necessary to calculate first the annualised life cycle cost (ALCC), which is obtained by considering the costs of all components of the SHS (PV module, battery, charge controller and appliances) multiplied by the respective capital recovery factor (CRF). The CRF is calculated with the following expression.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

The n stands for the life of the particular component and "i" stands for the chosen discount rate.

Then the ALCC can be estimated with:

$$\mathrm{ALCC_{SHS}} = C_{\mathrm{0pvSHS}} \times \mathrm{CRF_{pv}} + C_{\mathrm{0battSHS}} \times \mathrm{CRF_{batt}} + C_{\mathrm{0cc}} \times \mathrm{CRF_{cc}} + C_{\mathrm{0appl}} \times \mathrm{CRF_{appl}} + C_{O\&M-\mathrm{SHS}}$$

And the LUCE as

$$\mathrm{LUCE_{SHS}} = \frac{\mathrm{ALCC_{SHS}}}{W_{\mathrm{p}} \times \mathrm{EHFS} \times 365 \times \mathrm{CUF}}$$

For obtaining the annual generation of the system it is necessary to know the level of irradiation received by the sun, in this formula this value is given in equivalent hours of full sun (EHFS), and the capacity utilization factor (CUF), which also takes into account outages, and non-utilization of the system due to several reasons.

Considering a Solar Home System with 4 CFL lamps and a very good solar resource (5 EHFS) the ALCC resulted to be €228.11, with a LUCE of 0.21€/kWh. (See Annex1)

The LUCE of the solar home system was also calculated for different solar conditions. The results are presented in the graph below. As can be observed the LUCE decreases with the increasing amount of EHFS.

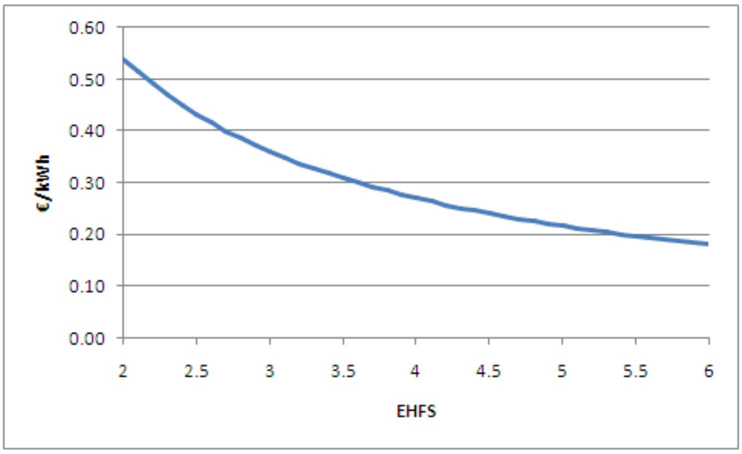

Fig. 5 Levelised Unit Cost of Electricity depending on the Equivalent Hours of Full Sun.

In the case of the addition of one plug for a radio cassette recorder or charging a cell phone, for the same conditions of 5 EHFS the ALCC resulted to be €246.77, with a LUCE of 0.16€/kWh (See Annex 1).

The cost per kWh seems to be reasonable considering the benefits of the system, nevertheless an initial investment of €1129.78 for the system with only CFL and €1229.88 for the system with a plug for other appliance, is very high for people living in the countries with no access to electricity. This is the main reason why PV systems are perceived as the most expensive option.

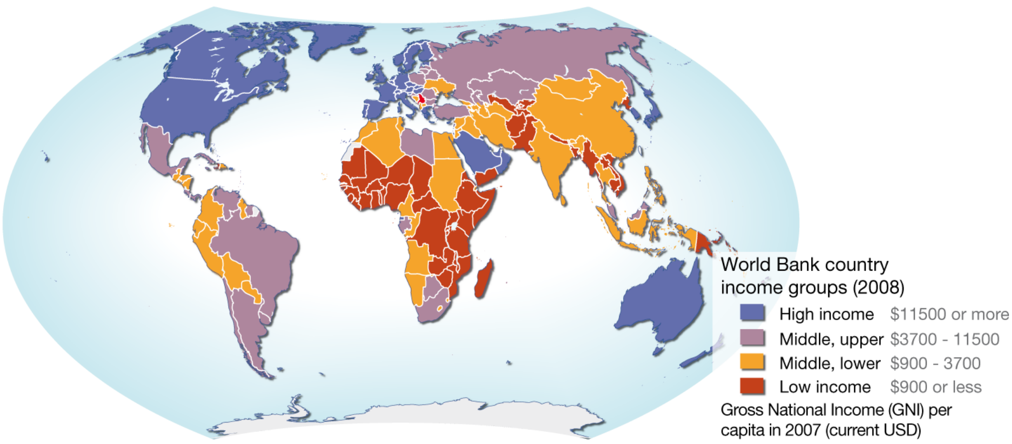

Fig. 6 Country income groups (World Bank classification), 2008 [15]

Therefore it is necessary to develop distribution mechanisms such as credit, leasing, subsidies, etc. The predominant current financing instruments are not well suited for renewable energy technologies. New models, based in the proven ones, should be developed by governments and multilateral institutions, this with the purpose of attracting investors, compensate the high capital cost and guarantee at the same time a sustainable way of providing electricity. End consumers in some cases will be willing to spend a considerable amount of their income in electricity, as in Ethiopia [4] A convenient model would be one allowing the consumer to afford the initial investment and the subsequent payments.

Experiences with the systems

In the following section some study cases from some countries will be presented, some of them give a more detailed approach than others.

Ethiopia [4]

Solar Irradiation: 5.34- 7.12 kWh/m²/d

GDP per capita (2010): 1220 USD [16]

Characteristics of the system: 10 Wp module, charge and remote controller, 18 Ah gel lead acid battery, two 50lm/W LED lamps, one plug for radio or tape recorder.

Sources of energy replaced by the SHS: Kerosene and dry cell batteries.

Cost in Ethiopian Birrs (ETB), 14 ETB/€: complete 10 Wp PV system (3,200 ETB), fuel cost for one kerosene lamp (45 ETB/month), dry cell batteries for one radio (24 ETB/month), dry cell batteries for one tape recorder (48 ETB/month), new PV battery (440 ETB/every 4 years), new charge and remote controller (600 ETB/every 10 years), 4 new LED lamps (400 ETB/every 7 years), inflation 10% p.a.

Financial tool used: Payback Periods

Result:

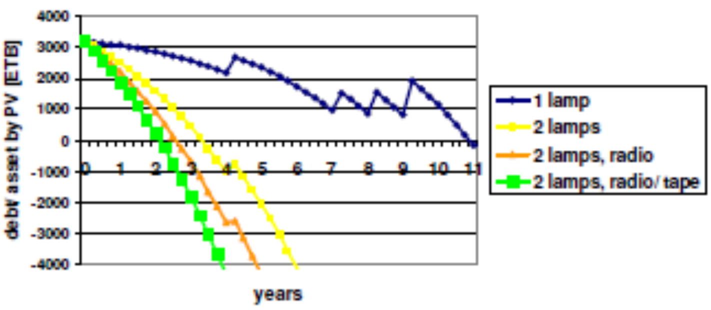

Fig. 7 Payback period for SHS, The discontinuous line is due to replacements (battery, charge controller and lamps) [4]

According to the authors of the study the payback period of such system could be between 2-4 years, consumption habits are of big impact in the amount of time, users with a larger consume of energy reach this even in 2,2 years. A monthly reduction of the energy cost between 80%-90% in the energy is presented.

Tanzania, Kondoa district [8]

Solar Irradiation: average 4- 4.5kWh/m^2/d

GDP per capita (2010): 1423 USD [16]

Characteristics of the system: size of 14Wp, 40Wp and 80Wp

Sources of energy replaced by the SHS: Kerosene, Diesel, disposable dry batteries.

Cost in local currency, Tanzanian Shilling (Tshs) 1USD=1500Tshs: Liter of diesel 1620 Tshs, Liter of Kerosene 1200 Tshs, Disposable dry batteries 500 Tshs per battery, maintenance cost can be neglected. Inflation rate 10.3%, Interest rate 13%, for petrol, kerosene and other equipment.

Financial tool used: Life Cycle of PV (10 years)

The households were categorized in low (A), medium (B) and high income(C). The houses in Kondoa have a low load energy demand (as low as 8kWh per month), small and scattered households. Annual operating cost was considered as the annual cost of the fuels and batteries.

Results:

	PV		*Diesel Generator Set*		*Kerosene and Battery*	
	Initial +Annual Cost	*LCC*	*Initial +Annual Cost*	*LCC*	*Initial +Annual Cost*	*LCC*
A	516.000 + 0	720.600	130.000 +487.200	4.065.700	0 + 55.200	434.100
B	1.081.500 + 0	2.060.800	160.000+681.600	11.717.900	0+131.350	2.143.900
C	1.892.500	3.989.000	160.000+973.200	16.477.400	0 + 340.800	5.562.500

Results in the analysis showed that the people with the lowest income cannot afford even the smallest SHS; conversely people with higher budgets can get any of the alternatives and the SHS shows to be cheaper in the life span of the systems.

Bangladesh [9]

Solar Irradiation (average) [11]: 4 - 5 kWh/m²/d

GDP per capita (2010)[16]: 1,643 USD

Characteristics of the system: 25Wp, 47Ah Battery 12V 1x6W CFL lamp or 30Wp, 47Ah deep cycle battery 12V,2 x 6W CFL lamps or 40Wp, 71 Ah deep cycle battery 12V, 2 x6W CFL lamps.

Sources of energy replaced by the SHS: Car battery, Kerosene

Financial tool used: Net Present Value (NPV), Simple Payback Period and Internal Rate of Return (IRR).

Six different cases were analyzed, going from SHS for lighting and entertainment purposes to SHS for income generation purposes (grocery shop, mobile phone services, tailoring).

Results:

The results of the reference paper can be summarized as follows

Type of System	Sources replaced by the SHS	Simple Payback period (years)	Net Present Value (12%) Taka, local currency	Internal rate of return (%)
40W, 71Ah 12V Battery, 2x 6W CFL lamps	2 kerosene lamps and B&W TV	6,34	2 845	15,6
40W, 71Ah 12V Battery, 2x 6W CFL lamps	Micro-utility and own grocery shop	2,13	41 973	47,5
30W, 47Ah 12V Battery, 2x2x 6W CFL lamps	2 kerosene lamps	41	-8 422	-
30W, 47Ah 12V Battery, 2x2x 6W CFL lamps	Lighting, entertainment and tailoring	2,45	46 351	45,7
30W, 47Ah 12V Battery, 2x2x 6W CFL lamps	Kerosene pressure lamp	2,79	18 253	39
25Wp, 47Ah Battery 12V 1x6W CFL lamp	Mobile phone service	2	162 181	51

Systems resulted to being economically feasible and with short payback periods in the cases where it was used for income generation activities, when the system was used exclusively for lighting it turned to be not viable. In the case of adding another appliance such as TV, the system presented acceptable numbers.

When comparing the SHS with fossil fuel energy the following pros and cons can be highlighted:

Pros and cons of SHS

Pros

- Energy provided by a SHS is cleaner, more comfortable, safer and not polluting as kerosene.
- SHS can be used as a very good initial experience with electricity for the people living in rural areas. In this way they can know the benefits and familiarize with this type of energy.
- It is easy to expand due to its modular nature.
- Fast amortization period depending on the energy consumption of the users.
- In some cases it can be used as a promoter of income generation activities.
- Highly cost competitive on a life cycle basis for rural electrification, even without internalizing environmental costs.

Cons

- Relative high upfront investment.
- Credit and financial support are needed in most of the cases.
- The need of a storage device (battery) implies a considerable number of issues related to it.
- Personal skilled is needed for maintenance and installation of the systems.
- Systems can be victims of vandalism.
- Limited amount of loads can be connected to the system.

Issues related to the performance of the systems

Some experiences in the past have shown similarities in the problems presented by the systems. It is necessary to provide the users with basic knowledge about the systems in order to make them understand the technology, some users can think that the system is able to support as much loads as they want, leading with this to an overload and later into a failure of the system. For instance it is very important to educate the people with the use of the systems. [8,10]

Inaccurate assumptions, misevaluations or ignoring of safety principles can lead to wrong sizing of the systems, bad quality equipment, wrong size of cables or batteries. [11]

Maintenance of the systems is also another point that should be noticed. Lack of technicians, insufficient education and training of users represent a threat to the performance of the SHS. Moreover maintenance and repair by the user should be avoided although the remoteness of the area or bad conditions of the roads make this task complicated in most of the cases.

PV MINI-GRIDS

Definition

Mini-grids refer to relative small electric networks providing electricity to a community (village or neighbourhood); the voltage of operation is normally below 11kV. The energy can be produced in different ways by means of small generators; these can use either fossil fuels (diesel) or renewable energy sources (PV, wind, small hydro, biomass, etc.). Usually it utilizes also a battery bank for energy storage.

Characteristics

Typically mini-grids are arrangements that are able to provide electricity (AC) for several applications, households or establishments, distributed in a specific area. Commonly they supply 220V 50 Hz (three-phases or single phase) AC. [7] Additionally to commercial and home applications they also can provide the community with services such as drinking water supply, street lighting and vaccine refrigeration. Making them in this way an interesting approach also for increasing the life quality of communities. Final consumer wants reliable electricity and available when he needs it, considering the intermittent nature of the renewable energy sources the only way to achieve this availability is including a storage system such as a lead acid battery bank (a cheap way to store electricity). [4]

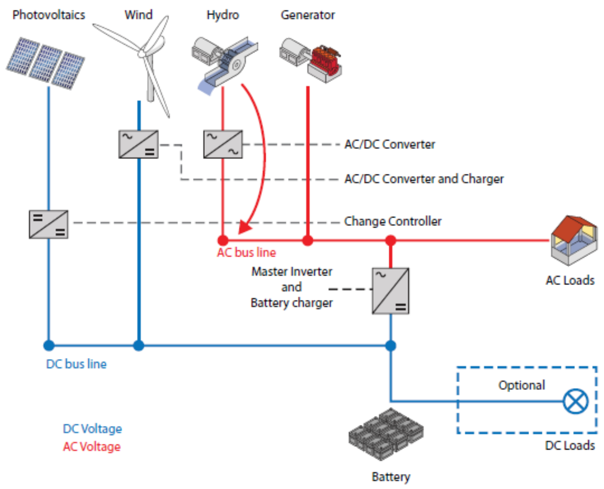

Fig. 8 Example of an arrangement of a Mini-Grid [12]

As shown in the figure above typical components of the mini-grid can be listed as follows:

- Centralized single power generation station (e.g. micro-hydro power plant, wind turbine, combustion engine running on biogas or a PV array)
- Battery bank for energy storage.
- Power conditioning unit (junction boxes, charge controllers, inverters, distribution boards, wiring, etc.), all this into an appropriate building.
- Power Distribution Network (PDN), poles conductors, insulators, wiring, service lines, appliances to users.

For the specific case of this report the focus is related to solar PV mini-grids, which means that the electricity generation source is an arrangement of solar panels.

When correctly designed PV micro-grids can supply power up to 24 h combined with other systems such as biomass gasifier, diesel generator set or wind electric generator (which is called a hybrid mini-grid).

The battery bank is calculated for meet the average load most of the times in the year. An important assumption for this is that not all users will turn on all the appliances at once and not all users will be connected at the same time. Similar to a SHS normally the bank allows for a 2 or 3 days of autonomy. This is related to another design parameter: the so-called diversity factor (DF), which is the ratio of the sum of all individual peak loads to the average load. This value is always greater than unity.

Due to the high capital cost of the mini-grid, contrary to SHS the owner of the mini-grid could be an electricity company or the community itself.

Economics

The cost of a mini grid in a literature study like this is difficult to estimate accurately; due to it depends very much on the location of the project. Also there are not many studies about mini-grids using only PV power, most of the studies include a second power source (hybrid mini-grid). For this reason the cost will be estimated in Euros based in some studies that have calculated the proportional value of the components of the mini-grid.

The cost of the mini-grid can be assumed as fixed for certain parts of the arrangement: generation unit, battery bank and power conditioning equipment. In the case of the power distribution network, the cost will be variable depending on the distance, terrain characteristics and also the number of households involved in the electrification project.

As mentioned in the beginning of the report during years the most common approach for supplying electricity to isolated/rural areas was to install a diesel generator per village and simply connect the houses. This was at first instance a cheap model to delivery electricity; the initial cost of a diesel power system is low compared to a PV arrangement, especially when the fossil fuel prices are "artificially" lowered with public subsidies. Nevertheless a drastic rising in the prices of crude oil or the depletion of it, can translate into an abandon of the system due to the affordability and availability of the resource. [13]

As with SHS the LUCE of the mini-grid can be calculated in a similar way, although more factors should be taken into account. The ALCC of the mini-grid can be obtained with:

$$ALCC_{MGRID} = [C_{0pvMGRID} xCRF_{pv} + C_{0battMGRID} xCRF_{batt} + C_{0pcu} xCRF_{pcu}]$$
$$+[PV_{MGRID} xR]^{b} + [(C_{0dn} xL) + (C_{0SC} xN)] xCRF_{pdn} + C_{O\&M-MGRID}$$

Capital costs and capital recovery factor of all the components is considered, PV array, battery bank, Power Conditioning Unit, Power Distribution Network. In the case of the later the cost is split in two taking into account the length of the network (L, in km) and also the cost of service connection per household (C0sc, N). The operation and maintenance costs are considered to be the salary of one skilled and one semi-skilled operator)
Some additional factor are added to the formula:

- PVMGRID: the capacity of the mini-grid in kWp.
- R: the benchmark unit cost of the mini-grid (€/kWp)
- b a scale factor that includes cost reduction in overall cost of the mini-grid (excluding the PDN) because of the larger capacity of components used in the mini-grid.[7]

In a very similar way like with SHS the LUCE for the mini-grid can be calculated with:

$$LUCE_{MGRID} = \frac{ALCC_{MGRID}}{PV \times EHFS \times 365 \times CUF}$$

Based in the above mentioned the LUCE assuming different costs for the PV modules was calculated. (See Annex2)

For a load of 36W, 4 CFL lamps, 4 hours of operation and a solar resource of 5EHFS the LUCE can be observed in the graph below, with 500 households is around 0.25 €/kWh.

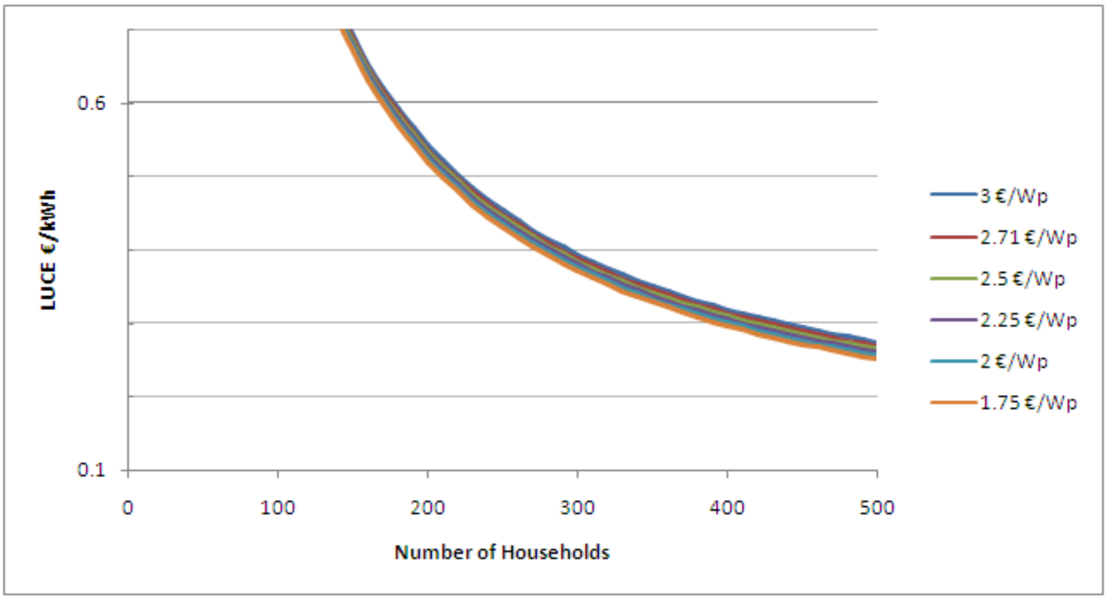

Fig. 9 LUCE for a load of 36W and different prices of PV modules.

In the case of a load of 51W meaning 4 CFL lamps and a plug for radio/cassette player/cell phone, 4 hours of daily operation. The results were the followings, the LUCE for 500 households was around 0.19 €/kWh.

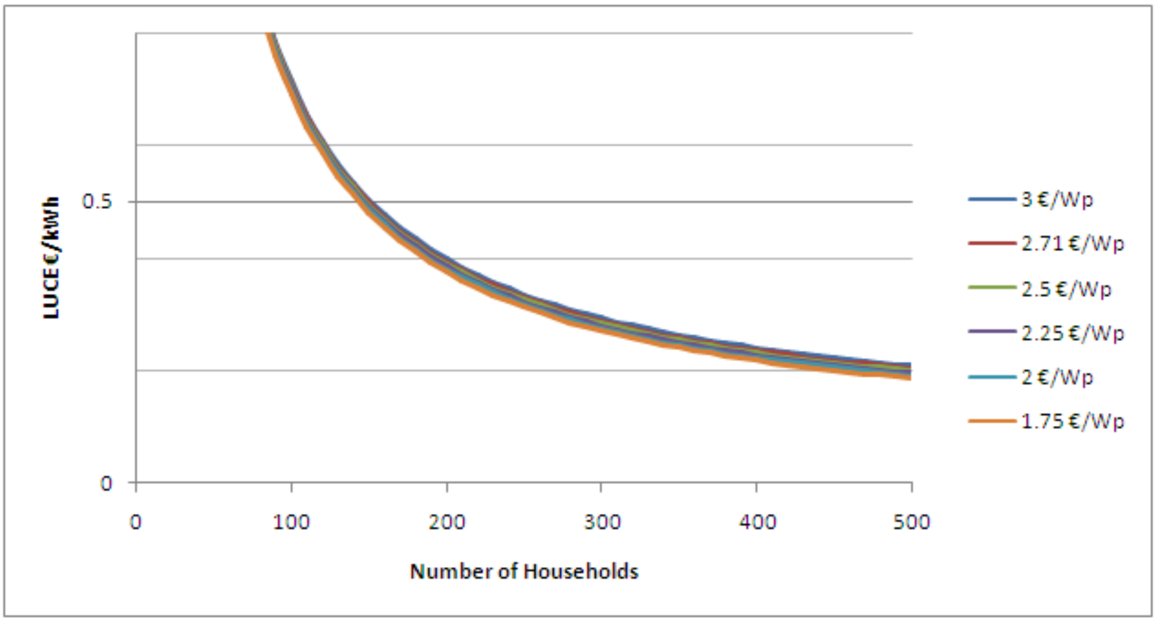

Fig. 10 LUCE for a load of 51W and different prices of PV modules

Another economic approach can be comparing the PV system with a diesel generator. The main assumption for this is that the system will have a size of at least 1kWp. Also as the PDN is needed for both systems the cost of it is neglected. [4] The tool used is the levelised cost of electricity (LCOE), which basically is the same as the LUCE used in the other study. All the costs (capital cost, investment, operation, maintenance, fuel) should be annualised and then divided by the annual energy output, the LCOE is also given in €/kWh.

In the case of diesel 90% of the cost is in the fuel and in the case of PV almost 100% of the cost goes in the initial investment.

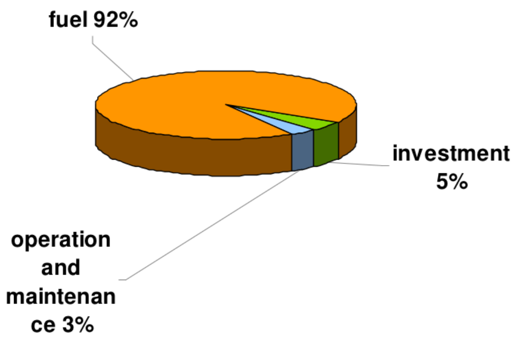

Fig. 11 LCOE breakdown of diesel generator.
[4¡Error!No se encuentra el origen de la referencia.**]**

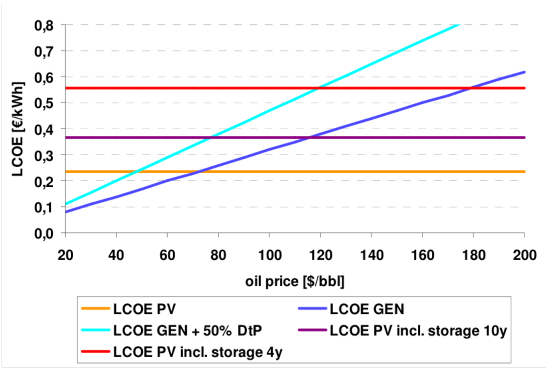

Fig. 12 LCOE comparison of PV and diesel generators depending on different oil prices. [4]

Experiences

The first experiences with mini-grids were carried out on Greek islands, Indian islands also were equipped with wind and solar energy in the 1990s and in China townships have been equipped with PV systems. Most of the systems failed over the years due to overloading or failure in the maintenance. [5]

Pros and cons of mini-grids

Pros

- Easy to expand due to its modular nature.
- The fact that the generation unit is centralized makes it possible to have maintenance and operation in one specific point.
- Can provide social benefits such as pumping water and street lighting.
- Easy to connect to the national grid if it is necessary.

Cons

- High initial investment.
- The intermittency of the solar resource makes the use of a power backup technology necessary such as wind, diesel, biogas or a bigger battery bank.
- High commitment of the community is needed.
- Skilled personal should take care of the maintenance.

Issues related to the performance

As presented with SHS an overload of the system caused by the addition of loads that were not considered in the design can lead to a failure in the mini-grid. So it is necessary to make the power supply powerful and large enough to fulfil future demands and also to educate the people in the functioning of the mini-grid and the understanding of the technology. [5]

When to choose which? Conclusion

Solar Home Systems (SHS) for basic lighting needs in some cases might be the right first step to familiarize rural citizens with the new conditions and new requirements. As soon as the village community takes the initiative and organizes itself demanding more electricity, mini-grids are more favourable providing more power and energy, which can also be used for productive purposes.

Other authors mention that due to the cost of mini-grids, these can perform well in isolated communities without any prospect of grid connection in 15-20 years. A community with households not too scattered. [1] If the community is too scattered and/or the terrain conditions are difficult then the investment necessary for the PDN can increase the cost of the mini grid in a considerable way. [7]

European educated engineers typically advice the construction of mini-grids due to their scalability to higher loads and AC voltage design. Typical PV based mini-grids are designed for an annual electricity consumption of 100 kWh – 500 kWh per user which is equivalent to LCOE of about 0.40 – 0.80 €/kWh [14]

The income of the community is another important factor that should be taken into account. When the income level of the community is low, it would be better to provide electricity with a SHS, because it is easier for the user to pay small amount of money and there are systems in the market with only a few Wp. As we saw in the graphs, mini-grids seem better suited for a “high” amount of households and bigger loads.

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Conclusions of the Internship

The first part of the internship was not as successful as expected. Only few new data was obtained besides the time spent in contacting the people and the web search, maybe a different approach to the people is needed. Other difficulty found is the lack of communication forms with some countries in Africa, no existing websites at all, wrong phone numbers or even no websites of the government. Also there were people that agreed to comment the data and never replied. There might be somebody who knows the numbers but most of the time this people are not reachable due to they work in the field

I found the comparison of Solar Home Systems and Mini-grids very interesting and also I could understand more about the economics and how to calculate the electricity production cost in order to compare which solution is better, which does the program of SET not cover.

With the two topics covered during the internship it was nice to realize the potential of development of solar energy in Sub-Saharan and South-East Asia regions, nevertheless the economics of PV systems is still an issue that should be solved in the near future.

And finally as a personal experience it was very educative to live in a different country, know a different way of working and a different culture, even more in a country where not many people speak English, which I found complicated in the beginning.

Annex 1

Calculation of the Solar Home System (7)

Case 1, Solar Home System with 4 CFL 9W bulbs, 4 hours of daily operation.

Assumptions for the calculation of the SHS	
Load (L)	36 W
Hours of use (h)	4 h
Operating voltage of the Battery (V)	12 V
Days of Autonomy (D)	3 days
Efficiency of the inverter for the CFL (η_{invSHS})	0.9
Maximum deep of discharge (MDoD)	0.7
Charge/discharge efficiency of the battery ($\eta_{battSHS}$)	0.85
Efficiency of the charge controller (η_{CC})	0.85
Loss by Temperature (f_{temp})	0.1
Loss by dust (f_{dust})	0.1
Loss by mismatch of the modules due to shadow or other factors ($f_{mismatch}$)	0.15
Equivalent hours of full shine (EHFS)	5
Capacity Utilization factor (CUF)	0.9

The size of the battery was calculated with
$\text{SHS\_Batt(Ah)} = \left[\frac{L \times h}{\eta_{\text{invSHS}} \times V \times \text{MDoD} \times \eta_{\text{battSHS}}}\right] \times D$
$SHS_{\_Batt}$= 67.23 AH

The size of the PV module was calculated with

$$\text{SHS\_PV}(W_p) = \left[\frac{L \times h}{\eta_{\text{invSHS}} \times \eta_{\text{battSHS}} \times \eta_{cc} \times (1-f_{\text{temp}}) \times (1-f_{\text{dust}}) \times (1-f_{\text{mismatch}}) \times \text{EHFS}}\right]$$
$SHS_{\_PV}$= 64.33 Wp

For the cost of the system the following values were considered:

Element	Price (€) [18]	Life (Years)
Capital cost panel (C_{0pvSHS}), Solar panel BlueSolar 80Wp 12V.	379.90	20
Capital cost battery ($C_{0battSHS}$) AGM battery 90Ah 12V Victron Energy.	239.90	5
Capital cost charge controller (C_{0CC}) Solar charge controller 10A PHOCOS	39.99	5
Capital cost appliances (C_{0appl}) CFL Lamps 9W and inverter.	419.99	10
Operation and Maintenance costs 5% of the cost of the system ($C_{0\&M\text{-}SHS}$) annualised	11.5	
Total cost of the system	€1129.78	
Discount rate i	0.12	

Case 2, Solar Home System with 4 CFL 9W bulbs and a plug for radio/cassette player/cell phone, 4 hours of daily operation.

The load was estimated as 51W and the other assumptions remained the same as in case 1.

$SHS_{\_Batt}$= 95.24 AH, $SHS_{\_PV}$= 91.13 Wp

The costs were assumed as follows

Element	Price (€) (15)	Life (years)
Capital cost panel (C_{0pvSHS}), Monocristalline 100Wp, 12V.	449.90	20
Capital cost battery (C0battSHS) 100 Ah AGM Gel Battery 12 Volts.	239.90	5
Capital cost charge controller (C_{0CC}) Solar charge controller 10A PHOCOS	39.99	5
Capital cost appliances (C_{0appl}) CFL Lamps 9W and inverter.	419.99	10
Operation and Maintenance costs 5% of the cost of the system ($C_{0\&M\text{-}SHS}$) annualised	12.4	
Total cost of the system	€1229.88	
Discount rate i	0.12	

The graph for LUCE depending on the EHFS is shown below:

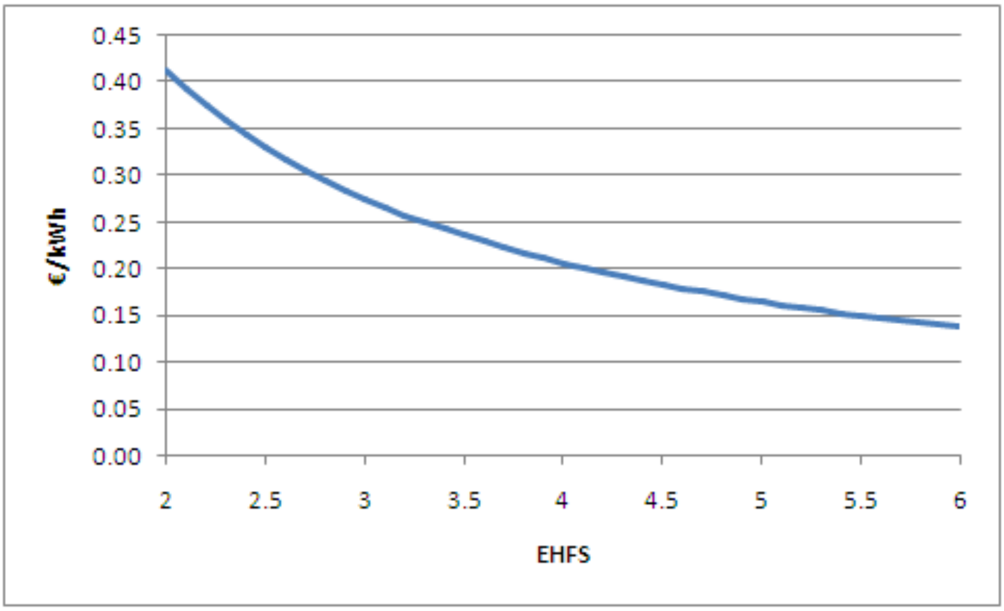

Fig. 13 LUCE of a 51w SHS depending on the solar resource.

Annex 2

Calculation of the cost of a PV mini-grid.[7]

Assumptions for the calculation of the mini-grid	
Load (L)	36 W / 51 W
Hours of use (h)	4 h
Operating voltage of the Battery (V)	48 V
Days of Autonomy (D)	3 days
Efficiency of the inverter for the CFL (η_{invSHS})	0.95
Maximum deep of discharge (MDoD)	0.7
Charge/discharge efficiency of the battery ($\eta_{battSHS}$)	0.9
Efficiency of the charge controller (η_{CC})	0.85
Diversity Factor	1.1
Loss by Temperature (f_{temp})	0.1
Loss by dust (f_{dust})	0.1
Loss by mismatch of the modules due to shadow or other factors ($f_{mismatch}$)	0.15
Equivalent hours of full shine (EHFS)	5
Capacity Utilization factor (CUF)	0.9

The size of the battery was calculated with
$\mathrm{MGRID\_Batt(Ah)} = N \times \left[\frac{L \times h}{\eta_{\mathrm{invMGRID}} \times V \times \mathrm{MDoD} \times \eta_{\mathrm{battMGRID}} \times \mathrm{DF}}\right] \times D$

The size of the PV module was calculated with
$\mathrm{MGRID\_PV}(W_{\mathrm{p}}) = \left[\frac{L \times h}{\eta_{\mathrm{invMGRID}} \times \eta_{\mathrm{battMGRID}} \times \eta_{\mathrm{cc}} \times (1-f_{\mathrm{temp}}) \times (1-f_{\mathrm{dust}}) \times (1-f_{\mathrm{mismatch}}) \times \mathrm{DF} \times \mathrm{EHFS}}\right]$

Assumptions for the calculation of the cost:

- The capital cost of the mini grid was considered in percentages regarding the PV array as follows: PV array (53%), battery bank (11%), PCU (20%) and PDN (16%). [7]
- Factor b=0.05.
- Discount rate i=0.12
- Cost of the connexion for one household was considered as 8 hours of a worker in a manufacturing sector earning 22.7 €/h (the average in the EU) [20].
- M&O costs were considering the salary of one full time worker and one part time worker. Full time worker 1,987 hours per year 22.7€/h, Part time worker 1,030 hours per year 22.7€/h
- No additional cost for PDN regarding the distance was considered.

Annex 3

Institutions contacted for Information

Afghanistan

Form filled at the webpage of the Kabul University and e-mail sent to USAID, No reply. In the folder there is a paper about rural electrification but it is from 2008.

Angola

E-mail sent to the Ministry of Energy and Mines, No reply

Belarus

E-mail sent to Belaya Rus Ecological Initiative Belarus, Center of Environmental Solutions and Minsk Division of International Academy of Ecology. The Center of Environmental Solutions was contacted by phone and replied that they would check with their colleagues and give a reply. No reply yet.

Benin

Maliky Djamiyou Siaka from DG/SOLARISS-ING commented that the number 0.5 MWp is near the reality of 2010 indeed.

Botswana

E-mail sent to Centre of Study in Renewable and Sustainable Energy, University of Botswana. No Reply

Congo

E-mail sent to African Development Bank group DRC field office. No Reply

Cuba

E-mail sent to Cubasolar.com and to the Center for Information Management and Energy Development (Centro de Gestión de la Información y Desarrollo de la Energía, CUBAENERGÍA). Both replied that they will respond in an appropriate way as soon as possible.

Djibouti

E-mail sent to the African Development Bank group Djibouti. The e-mail was forwarded to another person. No reply yet but I sent a reminder.

Dominican Republic

I found a report on internet about “Consulting for the evaluation and identification of sustainable rural electrification projects in Dominican Republic” and sent an e-mail to the person who elaborated the report (Humberto Rodriguez), He replied that he might help us but he is traveling at the moment. The report is in the folder Dominican Republic.

Estonia

E-mail sent to Ministry of Environment; Annika Päsik, Head Officer of Sustainable Energy Division of the Energy Department Ministry of Economic Affairs and Communications, replied. Data obtained from the Photon Magazine.

Guyana

E-mail sent to the Guyana Energy Agency, Dr. Mahender Sharma, Chief Executive Officer of the agency replied that he will work with our Customs authority to verify the information and will let us know as soon as he has confirmation. He sent us the information of the importing of PV modules in 2010.

Iran

E-mail sent to the Renewable Energy Organization of Iran. No Reply

Ireland

E-mail sent to the Solar Energy Society of Ireland. No Reply. In the report “Renewable Energy in Ireland 2010 Update”, published by the Sustainable Energy Authority of Ireland in the Section 5.4.1 Solar PV It is presented that the installed capacity at the end of November

2009 was 33.9 kW. While there are also some existing standalone commercial and domestic installations, statistics are not available for these installations. An e-mail was sent to them. No reply yet.

Israel

E-mail sent to Israel Sustainable Energy Society, Michael Epstein, Director of the Solar Research Unit of The Weizmann Inst. of Science, replied the mail.

Kuwait

E-mail sent to Kuwait Institute for Scientific Research. They replied that KISR recently launched a new program for Renewable Energy. We are currently conducting studies and working with international consultants for the suitability of Solar Energy for Kuwait. We are preparing an outdoor testing facility for Solar PV. Therefore, Kuwait doesn't really have any large installations of Solar PV. The use of solar PV is very limited to small applications here and there for road signs and emergency lights. A presentation about renewables in Kuwait can be found in the folder.

Lithuania

E-mail sent to the Ministry of Energy of Lithuania. Reminder e-mail sent. No reply yet. Data found in

Photovoltaic Barometer-Eurobserv'er, April 2011

Madagascar

E-mail sent to Groupe de la Banque Africaine de développement Bureau National de Madagascar, Replied that they will check the data and will let us know.

Mauritius

E-mail sent to African Development Bank Group Temporary Relocation Agency (TRA). No reply.

Morocco

E-mail sent to M. Mustapha Enzili from Resources & Engineering Department Morocco. No Reply

New Caledonia

E-mail sent to Direction de l´industrie des Mines et de l´Energie, Reminder sent and also contacted by phone, they told me to send again the e-mail. No Reply

New Zealand

E-mail and reminder mail sent to the "Energy Efficiency and Conservation Authority New Zealand" Phone number in the webpage does not work. There was no reply to both e-mails. An Email was sent to the "Sustainable Electricity Association New Zealand" also they were reached by phone, they are at the moment doing a survey in their own country, they agreed to provide a reply at the end of the week of December 9th.

Nicaragua

E-mail sent to the "Ministery of Energy and Mines". A request of information was sent to the Minister of Energy and Mines, they said they would reply with data but they have not replied yet.

Nigeria

E-mail sent to the "Solar Energy Society of Nigeria". Contact by phone was made but the contact person is out of the office. A second e-mail to another contact was sent and they replied that will check the data. An e-mail was sent also to the Sokoto Energy Research Center of Nigeria but the webpage is not valid anymore.

North Korea

E-mail sent to the National Comitee on North Korea, and they forward the e-mail to the Nautilus Institute. A first reply was received, then nothing. A reminder e-mail was sent, with no response until the moment.

Pakistan

E-mail sent to the Ministry of Water and Power in Pakistan and also to the Pakistan Council of Renewable Energy Technologies, Contact by phone was made and they agreed on reply the e-mail.

Qatar

E-mail sent to the “Qatar General Electricity and Water Corporation”, No reply

Romania

E-mail sent to Romanian Solar Energy Society (SRES) to Prof. Laurentiu Fara. Replied with data.

Russia

E-mail sent to ISES Russia, no reply. I found an article on Internet about “Renewables in Russia” and I contacted him (Anton Galenovic) he was not able to provide further data. Also an e-mail was sent to the Association of Solar Energy of Russia and contact by phone could not be made due to a wrong number in the contact web page. No Reply.

Singapore

E-mail sent to the “Energy Market Authority”, they were not able to provide information. Another e-mail was sent to the “Sustainable Energy Association of Singapore”, e-mail not replied.

Uganda

E-mail sent to the “Rural Electrification Agency Uganda”, the first mail was not received. Contact by phone was made and another e-mail address was obtained. No reply yet.

Zambia

E-mail sent to the “African Development Bank Group Zambia Country Office”, they replied that they would read the paper and come back to us. E-mail sent also to the “Rural Electrification Authority”, later phone contact was made and the e-mail of the responsible person was obtained. An e-mail was sent but there is no reply yet. The rural electrification master plan of Zambia can be found in the folder.

Other organizations were contacted for request of information:

Asian Development Bank. An e-mail was sent to three different people and one of them replied that would reply later because he was traveling.

Delft Energy Initiative, Contact were made with the University of Delft, they suggested another people who contact, no reply at the moment.

International Renewable Energy Agency, Contact was made and they asked for a detailed cooperation plan between the institute and them.

ISES Arab Section, an e-mail was sent to the Arab section of ISES, also phone contact were tried, no reply.

Southern Africa Power pool. E mail Sent, no reply

Southern Africa Alternative Energy Association. E-mail sent, no reply

Sustainable Energy Society Southern Africa. E mail sent and contact made by phone and another e-mail was sent. No reply yet.

West African Power Pool, Email sent no reply.

OLADE, enquiry form sent, they replied that they are still working in a data base.