Photovoltaic systems for improved domestic energy services in off-grid communities of developing countries

A techno-economic analysis of various photovoltaic systems for decentralized electrification in Sierra Leone

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ABBREVIATIONS & ACRONYMS

AC	alternating current
ADB	Asian Development Bank
ALCC	annualized life cycle cost
CAD	cost of autonomy days
CFL	compact fluorescent lamp
CRF	capital recovery factor
D	autonomy of days
DC	direct current
DPR	detailed project report
EFA	Environmental Foundation for Africa
ESL	energy service level
GHI	global horizontal irradiation
HDI	Human Development Index
HOMER	Hybrid Optimization Model for Renewables
IIC	initial investment cost
kW	kilowatt
kWh	kilowatt hour
LDC	Least Developed Country
LED	light emitting diode
Li-ion	lithium ion
LV	low voltage
MACS	maximum annual capacity shortage
MDG	Millennium Development Goal
MGRID	micro-grid
MUS	multi-user system
NASA	National Aeronautics and Space Administration
PbA	lead-acid
PCU	power conditioning unit
PDN	power distribution network
PV	photovoltaic
PVGIS	Photovoltaic Geographic Information System
Re-ch	re-chargeable
RMS	root mean square
SCS	solar charging station
SEE	substitutable energetic expense
SEI	Solar Energy International
SHS	solar home system
SoDa	solar radiation database
SSE	Surface Meteorology and Solar Energy
TCM	terrain cost multiplier
UNDP	United Nations Development Programme
ViPOR	Village Power Optimization Model for Renewables
WMO	World Meteorological Organization
W_p	watt peak

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SUMMARY

The access to reliable and affordable energy services needs to be improved for many of the developing countries to facilitate the alleviation of poverty. Photovoltaic (PV) systems can play a useful role in realizing that, since they are clean, safe, require little maintenance and have low recurring cost. This in contrast to its predominantly used alternatives: kerosene, dry cell batteries and home generators. The alternative of grid extension to peri-urban and rural areas is often financially unviable due to the areas' remoteness and low load densities. The characteristics of a PV system make it a promising technology for decentralized electrification, although different barriers hinder its large-scale use.

The barriers of high up-front cost, poor technical performance and unsuitability to the user needs are addressed in this study by designing the PV project according to the actual needs of the user and focusing on cost-effective technology. First, the relevant techno-economic assessments for PV project design are discussed through a literature study. Thereafter, these assessments are applied to a case study in Sierra Leone. A techno-economic analysis of various PV systems is performed to find the most cost-effective solution for a peri-urban community and two rural communities.

Assessments concerning the solar resource, user energy demand and optimized system design are discussed. The resource assessment concerns satellite-based irradiation data, optimal inclination and an estimation of the system's reliability. Energy demand is assessed through questionnaire based household surveys focused on energy use, expenditure, and service priorities. The energy use is relevant to grasp the picture of PV project impacts on consumption patterns. The energy expenditure concerns the user's ability to pay for a PV system and is needed to approximate its affordability. In order to establish a PV system that is reliable on the long-term, the expected present and future load is calculated. Further, an optimized system design on the basis of cost-effectiveness is desirable to increase the project's viability.

A well-founded decision on technology selection is crucial in the PV project planning. The evaluated systems for the rural communities are the Pico PV system (1 – 10 W_p), solar home system (SHS) and solar charging station (SCS). These technologies are sized using analytical equations with a yearly average irradiation, and they are evaluated on their initial investment costs, annualized life cycle costs and cost of useful light output. A SHS and hybrid PV-diesel micro-grid are studied for the peri-urban community. These systems are both sized using a simulation-based *Optimization Model for Distributed Power* (HOMER) that produces hourly simulations of solar power supply and demand. The least-cost configuration of a power distribution system is computed using a *Village Power Optimization Model for Renewables* (ViPOR). Both systems are compared on their initial investment costs and annualized life cycle costs.

For the rural communities, it was shown that the relative weight of up-front cost, reliability and lighting quality of the PV system determine the most desirable system in the project design. The SCS showed the most potential to supply reliable and affordable improved energy services to the rural communities. It demonstrated to have the lowest initial investment costs, while the Pico PV system showed the lowest annualized life cycle costs, with a limited reliability. The SHS and SCS can increase their reliability against limited incremental costs. The user is able to pay for all evaluated systems, except the SHS with reliability above 93% of the annual load coverage. The clear benefit of the SHS is the low cost of useful light output for the user. The system is costly, but supplies lighting of a higher quality.

For the peri-urban community, the hybrid PV-diesel micro-grid showed lower annualized life cycle costs compared to the SHS. However, reliable data on installation costs for both systems are important for further improvement of the analysis. The spread of the village, its terrain, the number of service connections and the daily load determine the cost-competitiveness of the hybrid micro-grid compared to the SHS. For a hybrid micro-grid, the break-even point of user fee and incremental cost for each service connection is important. The user's ability to pay is relevant to estimate the feasibility of such connection fees. Besides, the use of optimization software for the distribution network increases the viability of the micro-grid. The micro-grid becomes more cost-competitive with increasing loads, because the power distribution network cost stays constant for an equal number of service connections. Once the scale benefits and a reduced system capacity for the micro-grid surpass the additional cost for the distribution system, an increase in load leads to a more cost-effective micro-grid compared to the SHS. The households classified as *low* are able to contribute fully to the annualized cost of both systems, for the present daily load. The *middle* and *upper* households would need to spend more than their substitutable energetic expenses in order to cover the annualized costs for both systems. Their willingness to pay more for a PV system will determine the interest in changing their energy supply system. An increase in capacity shortage for a SHS substantially reduces its system costs and makes them more affordable by the user. A desirable reliability level is ideally chosen based on people's willingness to pay for reduced capacity shortage.

1. Introduction

In September 2000, at the United Nations Millennium Summit, world leaders set commitments to halve extreme poverty, hunger, illiteracy and disease by 2015. These commitments and targets are called the Millennium Development Goals (MDGs). The MDGs do not explicitly refer to improving access to energy services, although these services are acknowledged as one of the prerequisites for meeting each MDG. Energy services are defined as the benefits that energy carriers produce for human well-being. Access to at least three types of energy services is required to meet each MDG: *"(1) Energy for cooking, (2) electricity for illumination, ICT, and appliances to support household and commercial activities and the provision of social services, and (3) mechanical power to operate agricultural and food processing equipment, to carry out supplementary irrigation, to support enterprises and other productive use, and to transport goods and people.*" (Modi *et al.*, 2005).

Rural electricity use progresses up a ladder. "*The bottom rung is lighting, the basic purpose to which rural electrification is put in all homes"* (World Bank IEG, 2008). This statement is supported by the fact that the share of electricity use for lighting is higher for the poor, among households connected to the grid (Miller, 2009). A publication of the Asian Development Bank in 2007 shows the strong correlation between the Human Development Index (HDI) and the annual electricity consumption per capita of 171 countries (ADB, 2007). It suggests that only a marginal increase in consumption for lighting results in a strong momentum of human development. Illumination of homes and small businesses is thus one of the most appealing energy services for human well-being. The use of low-efficiency energy carriers, such as dung, crop residues or firewood, has negative environmental and health effects. Therefore, it is said that they are at the bottom of the energy ladder (World Bank IEG, 2008). Climbing the energy ladder means the use of more efficient energy carriers, with less pollution and harmful health effects. Electricity is at the top of the energy ladder and can be generated from many different primary sources. However, the user in a developing country is more concerned about the reliability, affordability and accessibility of the energy service instead of the primary source. In the meantime, the rising human induced greenhouse gas emissions and its subsequent effect on the global climate induces a shift from the use of fossil fuels to renewable energy sources. Therefore, an improved access to reliable and affordable energy services is preferably provided from renewable sources. Unfortunately, the progress in renewable energy use in off-grid areas of developing countries is hard to map, since statistics are not systematically collected by any international organization (REN21, 2010). However, fact is that still 1.5 billion people lack access to electricity in developing countries. One third of these people are to be found in rural areas of the Least Developed Countries (LDCs). Grid extension to rural areas is often unviable due to their remoteness and low load factors (Jones *et al.*, 1996). The densely populated urban areas are usually within closer reach to an electricity grid. That increases the viability of grid extension and the chance of future connection. The unprecedented low electricity access rates in peri-urban and rural areas and their lacking prospects to future access gives them a priority in this study. Photovoltaic (PV) systems can play a useful role in realizing access to reliable and affordable energy services for rural households (Van der Vleuten *et al.*, 2007). PV technology is already adopted globally for meeting basic electricity needs in rural areas (Chaurey *et al.*, 2010b). PV is clean, safe and scalable, which makes it highly suitable for household energy use. For lighting, the most important improvement in switching to PV is the convenience and lighting quality (UNDP & GEF, 2004). These qualities are in contrast to the predominantly used alternatives for lighting: kerosene, dry cell batteries and candles (Purohit, 2009). They are expensive due to recurring costs and have poor lighting qualities. Besides, kerosene and candles produce fumes, bring about fire risks, and make a country dependent on fossil fuels. For appliances PV could provide a more continuous service when replacing dry cell batteries and home generators.

Research Question

The characteristics of PV make it a promising technology for rural electrification. However, different barriers hinder its large-scale use for decentralized rural electrification purposes. Many studies have been carried out to identify these barriers. They can be categorized into financial, technical, institutional and regulatory barriers (Kumar *et al.*, 2009). Barrier removal strategies are also formulated in literature. For example, the high up-front capital costs of PV are often disputed as a key barrier, due to the limited purchasing power of the poor. Although the up-front costs are usually higher in comparison with fossil fuel alternatives, the recurring costs are considerably lower (Miller, 2009). Micro-credit schemes, removal of taxes and levies, capital and tariff subsidies and fee-to-service delivery models are suggested to lift this financial barrier (Wamukonya, 2007). The appropriate finance activities depend on a country's PV market state (UNDP & GEF, 2004).

In the period 1980-2000, development assistance for renewable energy was focused on technical demonstrations and non-replicable projects. "*Many projects were considered failures because of poor technical performance, and poor suitability to user needs and local conditions"* (Martinot *et al.*, 2002). This observation is explained by the tendency of development assistance to rely on the *technology-push* approach. Technology-push is explained by the support for PV solutions in a specific market without properly considering the local user demand. When the PV system is designed according the actual needs of the user, one speaks of a *demand-pull* approach (Martin *et al.*, 1994). The objective of this study is to gain insight in how a demand-pull approach for PV project design could improve energy services in developing countries. In order to achieve this objective, the following main question is raised:

How to improve domestic energy services in off-grid communities of developing countries by decentralized photovoltaic solutions, using a demand-pull approach?

Using a demand-pull approach and focusing on cost-effective technology for PV project design addresses the barriers of high up-front cost, poor technical performance and unsuitability to the user needs. Two sub-questions are raised to answer the main question:

1. *Which techno-economic assessments are relevant for the design of decentralized PV electrification projects, using a demand-pull approach?*

2. *Which decentralized PV solution is most cost-effective for improving domestic energy services in peri-urban and rural communities?*

The first sub-question is answered in Chapter 2 by means of a literature study. Thereafter, the relevant assessments are applied to a case study in Sierra Leone in Chapter 3 by answering sub-question two. The purpose of the case study is to collect and analyse all necessary information that leads to the implementation of a PV project. A techno-economic analysis of various PV systems is performed to find the most cost-effective solution for peri-urban and rural communities. A cost-effective match in electricity demand and supply increases the project's viability, which positively affects its sustainability (Kumar*, et al.*, 2009). A PV system should be designed in such a way that it best meets the needs of the user and ability to pay for that system. The larger the discrepancy between system costs and user's ability to pay, the less user financed a project becomes. A cost-effective technology choice diminishes such discrepancy.

Case Study

The West-African country of Sierra Leone belongs to one of the Least Developed Countries, ranked 158th out of 169 countries in 2010 for the HDI (UNDP, 2010). An unprecedented low share of 0.1% and 12.7% of its respective rural and urban population has access to electricity (UNDP & WHO, 2009). The rural population in Sierra Leone represents 64.2% of its total population (SSL & ICF Macro, 2009). Since the declaration of Sierra Leone as an independent nation in 1961, there are only two national Population and Housing Censuses conducted. One before and one after the rebel war: in 1985 and 2004 (SLL, 2004). Statistics state that kerosene is the primary source for lighting in 86% of the households. Merely 1 – 5% of the households use electricity for lighting, depending on the region (SLL, 2004).

The capital Freetown is located in the Western Area of the country, shown in Figure 1. Just a few kilometres South of Freetown the head office of the Environmental Foundation for Africa (EFA) is based. This NGO operates in Sierra Leone and Liberia on protecting and restoring the environment. In 2007 the EFA started the Renewable Energy Programme (REP) focused on solar electrification projects for development agencies, e.g. UNICEF and GTZ. In order to broaden the REP activities to off-grid communities for improved energy services, a scientific research based pilot project is performed which functions as the case study of this report. The project includes three target communities: peri-urban community *Sussex* and rural communities *Mapuma* and *Jene*, indicated by the left and right arrow in Figure 1, respectively. They are the selected communities, due to the prior activities of EFA in these communities, which increase the cooperative attitude of the inhabitants.

Sussex is called a peri-urban community, since it is located between the suburbs of Freetown and the countryside. It constitutes 500-600 inhabitants and is divided into two sub-communities: Kingtown and Sharbro. Sussex is not incorporated in the urban planning of Freetown; therefore it lacks access to the electrical grid. Up to 1996 it was connected to the grid, but broke down during the rebel war. While the war already stopped more than 10 years ago, the community is still not connected to the grid. Besides, it still remains unclear when the government is planning to connect it. The inhabitants of Sussex are already familiar with PV from the system installed on their local health centre. Rural communities up country are in an even more dead-end situation in respect to electricity access. Their remote location and negligible load demands make connection to the grid far from cost-effective and therefore very unlikely. Solar power is also evaluated as an option for improved energy services in such communities. Mapuma is located at the river Moa south of the Kenema district, near the Liberian border. It has roughly 250 inhabitants distributed over 38 households, mainly located in the middle of the village. Storage and kitchen huts, made from mud and thatched roofs, surround the households. Jene is located in the Southern province in the North of district Pujehun, also at the river Moa near Tiwai Island. Jene constitutes 19 households, housing roughly 120 people. The satellite-based map of Sussex, Mapuma and Jene are shown in Appendix E.

Figure 1. Country map of Sierra Leone

Scope

Ideally, the selected renewable energy resource for a cost-effective electrification project is based on least-cost power delivery. A preliminary assessment on the availability of renewable energy sources, carried out by EFA, revealed the potential of solar power in the target communities. Therefore, the scope of the Sierra Leone case study is limited to solar power generation. The planning of decentralized PV projects is categorized into three stages with sub-activities, shown in Figure 2. In this study the scope is limited to the thick lined box in Stage II: a detailed project report (DPR). It is defined as a report that contains all necessary information that leads to the implementation of projects (Kumar, *et al.*, 2009). This delineation is based on the necessity of a detailed techno-economic analysis prior to project implementation.

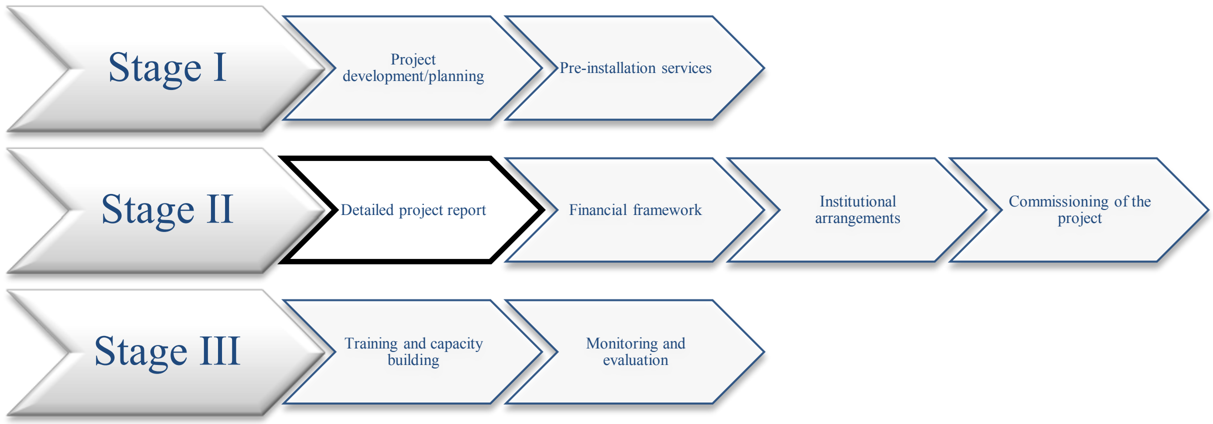

Figure 2. Three stages for planning decentralized electrification projects (Kumar, et al., 2009)

This study fits into the broader standardized framework for detailed designing of off-grid electrification projects from Kumar *et al.* (2009) and provides a focus on PV solutions. First, it proposes a DPR methodology by means of a literature study, including a resource, demand, and optimization assessment. Secondly, the methodology is applied in a case study Sierra Leone in collaboration with EFA by means of two months fieldwork. The fieldwork involves three communities: peri-urban community *Sussex* and rural communities *Mapuma* and *Jene*. The data for the case study is collected from primary and secondary sources, shown in Table 1.

Table 1. Structure of data collection for resource, demand and optimization assessment

Type of assessment	Data collection	Primary/Secondary	Source
Resource	Insolation	Secondary	PVGIS (JRC EC, 2011)
	Optimal inclination	Secondary	PVGIS (JRC EC, 2011)
	Number of cloudy days	Secondary	NASA (NASA, 2011)
	Spread of village	Primary	Interview chief, ViPOR
Demand	Appliance availability	Primary	Market survey
	Energy use/expenditure	Primary	Household surveys
	Daily load	Primary	Household surveys
	Energy priorities	Primary	Household surveys
	Load growth	Secondary	Global energy model (Daioglou, 2010)
Optimization	Technology choice	Secondary	(Hankins, 2010); (ARE & USAID, 2011)
	Optimized design	Secondary	Optimization models HOMER, ViPOR
	System costs	Primary	Wholesale PV supplier EFA

The resource assessment entails collecting insolation data, the optimal inclination and the number of cloudy days in a row that might occur, since these parameters serve as inputs for the system design optimization. The demand can be categorized into domestic, community, commercial and agricultural (Kumar*, et al.*, 2009). The scope is limited to domestic demand for two reasons: its applicability for PV systems and the importance of domestic illumination for human development, described in the introduction section. The demand is assessed through questionnaire based household surveys. The optimization assessment concerns (1) the technology choice, (2) its optimized design and (3) the system costs.

(1) For the technology choice a distinction is made between peri-urban and rural communities, because of the differences in loads, accessibility and the user's ability to pay for improved energy services. The PV systems evaluated are a Pico PV system, solar home system (SHS) and solar charging station (SCS) for the rural communities. While a SHS and hybrid PV-diesel micro-grid are studied for the peri-urban community. This choice is explained by knowing that Pico PV and SCS are considered technologies for low income communities, since they provide basic energy services and require smaller investments for the user (World Bank, 2008). Basic energy services include lighting, listening to radio and mobile phone use. SHSs are scalable and therefore used for both community types. More fortunate households can afford to buy a SHS that is able to provide more energy services. A hybrid micro-grid is not suitable for low power demand and limited accessibility. The low power demand make the high investments for a micro-grid hard to justify and not economically viable. Besides, limited road connectivity requires minimized transport and O&M activities, while a micro-grid needs both activities for system set-up and maintenance.

(2) The methods for sizing PV systems are categorized into analytical and simulation-based approaches (Chaurey *et al.*, 2010a). Both types are used in this study: (1) analytical sizing with a yearly average irradiation and (2) simulation-based sizing using modelling software HOMER[1] that produces hourly simulations of the solar power supply. Method (1) is used for PV system sizing for the rural communities, while (2) is used for the peri-urban community. This distinction is made, because analytical sizing is typically used for small size systems, while simulation-based sizing is more appropriate for a hybrid micro-grid (Hankins, 2010), due to the variable use of the generator.

(3) Assessed project costs include the initial investment costs (IIC), the total net present cost (NPC), annualized life cycle costs (ALCC) and cost of useful light output. HOMER ranks systems on their total NPC. Besides, it provides the IIC and O&M cost. The ALCC is calculated by multiplying the total NPC by the capital recovery factor (CRF).

[1] HOMER is used for designing and analysing hybrid renewable energy systems. The user provides data on resource availability, capital cost curves, technical parameters, economic conditions and system constraints. Thereafter, HOMER inter- and extrapolates the capital costs based on a 'sizes to consider' table defined by the user. The power systems are ranked by their total net present cost (NPC), which represents the life cycle costs at present value. Costs include investment capital; replacement, O&M and fuel costs and revenues include salvage value and grid sales revenue.

2. METHODOLOGY

In this chapter the relevant assessments for a decentralized PV electrification project are discussed, focused on domestic energy services. It is divided into three sections: resource (section 2.1), demand (section 2.2) and optimization assessment (section 2.3). All accompanying equations are given in Appendix B, C and D.

2.1. RESOURCE ASSESSMENT

Once an electrification project location and its terrain are identified and grid extension is not feasible or cost-effective, the locally available renewable sources need to be assessed. Electricity supply from renewable sources can be ranked with priority in terms of its least-cost delivery. For example, if wind or micro-hydro resources are perennial, it might be the least-cost option for electricity generation. Consultations with the community of interest generate more information on local resource availability. Further, measurements on site are necessary to estimate the resource potential for power generation. Solar energy has two important advantages over other renewable sources: it is more evenly distributed over the world and its availability is known with greater certainty (Inversin, 2000). Usually, information on wind, hydro and biomass resources is scarce. For example, reliable data on micro-hydro resource availability requires discharge rate measurements for at least two years on site (Kumar, *et al.*, 2009). Similar requirements hold for wind resources, where for example annual average wind speeds need to be known. Although PV might not be the least-cost option in a specific location, it has resource data readily available, discussed in section 2.1.1. However, power generation could be hindered due to shading. Shadow on part of a PV array results in substantially lower power generation, since small modules are connected in series to increase the system voltage. Choosing shade-free sites for the PV array is thus important.

2.1.1. MONTHLY AVERAGED IRRADIATION

Reliable solar resource information is important for sizing a PV system. There are two ways to acquire such information: using either measurements from (1) radiometric stations or (2) satellite images.

1. The number of radiometric stations is limited and their uneven distribution around the world make it difficult to obtain representative solar resource data for most regions (Huld *et al.*, 2005; IES, 2007). Interpolation techniques are applied to estimate the solar resource at sites in between different stations. The data accuracy decreases with the distance between radiometric station and location of interest. A dataset of ground level irradiance was established for 62 sites in Africa. The data originates from different sources and is measured over different time periods, representing accuracies of 5 – 20% (Diabaté *et al.*, 2004). Thereafter, monthly mean clearness indices were calculated, serving as a guideline for establishing solar climate zones for Africa.

2. Satellites make use of the linear relationship between atmospheric transmittance and planetary albedo measured by them. The satellite image pixels are normalized using the optical air mass. Thereafter, the satellite-derived irradiance at ground level is related to the brightness of each pixel. It forms a fraction of the clear sky irradiance. The brightest pixels correspond to heavy cloud cover, while the darkest correspond to clear sky conditions. The atmospheric transmittance induces the random behavior of irradiance at ground level (Graham *et al.*, 1990). It is defined by the monthly mean of the daily clearness index (

atmospheric turbidity (Diabaté*, et al.*, 2004), which is expressed by the Linke turbidity factor (T_L). It is a dimensionless parameter that indicates the transparency of the cloudless atmosphere and typically varies between 3 and 7, where 1 denotes a clear and dry sky. Worldwide T_L-maps were produced in the SoDa project financed by the European Commission.

A detailed structure of the solar resource availability for Africa cannot be provided by the radiometric ground network (Huld*, et al.*, 2005). Therefore, the monthly averaged irradiation data for the case study are gathered from satellites-derived measurements. They are taken from the Photovoltaic Geographical Information System[1] (PVGIS), developed by the Joint Research Centre of the European Commission. PVGIS provides the irradiation on a horizontal surface including both direct and diffuse radiation, referred to as the average daily global horizontal irradiance (GHI). It provides a map-integrated interface and utilizes the radiation database HelioClim-1[2]. The steps in constructing the HelioClim-1 database are shown in Figure 3.

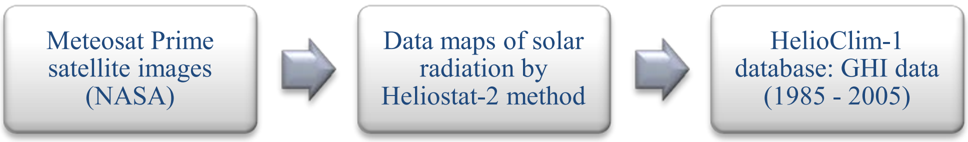

Figure 3. Construction of the HelioClim-1 database (Huld, et al., 2005)

Solar radiation maps are derived from Meteosat satellite images by applying the Heliostat-2 method, developed by Mines ParisTech in November 2002. This method incorporates sun, earth and satellite geometry and clear-sky models. The GHI data serve as an input for the optimization in HOMER, which synthesizes hourly data from the monthly averaged data provided. The known monthly mean clearness indices for each month are converted into daily values by using the frequency distributions of the occurring daily values. These distributions show a universal nature for each particular month (Graham *et al.*, 1988). The daily values are converted into hourly values using two parameters: k_{tm} and α. The k_{tm} represents the atmospheric transmittance if cloudiness was uniformly distributed over the day. The random behavior of varying cloud cover is reflected by α. Models for both parameters are developed with help of hourly historical data (Graham*, et al.*, 1990).

Besides GHI data, PVGIS also provide the optimum inclination for a PV array at a specific location, called the *optimal inclination angle* (I_{opt}). It provides the angle at which the monthly averaged irradiation is at its maximum. Ideally, the optimal inclination for each month is used to maximize production. However, for the sake of simplicity and maintenance free technologies, tracking systems are neglected and a fixed optimum inclination for the entire year is assumed. As a rule of thumb, the map from Appendix A is consulted if only a rough estimate of the optimum inclination is required for an African country.

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[1] Website: http://re.jrc.ec.europa.eu/pvgis

[2] Website: http://www.helioclim.net

2.1.2. DAYS OF AUTONOMY

The number of cloudy days in a row that might occur and for which you intend to store energy represents the *days of autonomy* (D). This variable is of profound importance to the PV system's reliability and battery costs. There exists a trade-off between these two. More days of autonomy result in a more reliable system, but also lead to higher battery costs. Reliability requirements are depending on its application and vary from country to country (Hankins, 2010).

A typical SHS incorporates 2 to 3 days of autonomy in its battery size (Chaurey*, et al.*, 2010b). In the case study, 3 days of autonomy is used for the SHS in rural communities, using analytical sizing. However, a HOMER simulation of the sized systems is performed to estimate the actual reliability in the field. The simulation-based sizing method is able to calculate an optimized system design for a pre-defined minimum reliability. The reliability of a system is varied through adjusting the maximum annual capacity shortage (MACS). The MACS is the maximum allowable value of the capacity shortage fraction (f_{SC}), which is the total capacity shortage (E_{SC}) divided by the total annual electric load (E_{tot}) (NREL, 2004). HOMER computes the cost versus reliability curves by a sensitivity analysis on the annual capacity shortage. The resulting capacity shortage is an indicator for the reliability of the SHS. Costs include capital, replacement and O&M of required PV system components. The salvage value of capital investments after the project lifetime is considered revenue.

2.2. Demand assessment

The demand assessment is divided into multiple sections: energy use (section 2.2.1) and expenditure (section 2.2.2), load assessment (section 2.2.3) and energy service priorities (section 2.2.4). The energy use is relevant for understanding the potential impact of a PV project on people's consumption patterns. The energy expenditure is assessed to determine the user's ability to pay for a PV system. The load assessment is performed in order to size the PV system and energy priorities are mapped to classify households into different energy service levels. The equations used for the demand assessment are presented in Appendix B.

2.2.1. Energy use

Domestic energy use is assessed using questionnaire based household surveys. The survey includes a comprehensive list of available energy carriers, their common household use and typical units for purchasing or collecting. The list is country specific and composed prior to the actual field survey. It functions as a guideline of possible interviewee responses to avoid misunderstanding by the interviewer. If seasonal variations in fuel consumption are substantial, the energy use is disaggregated for each season. The mass or volume of the typical units is determined by sample measurements to avoid time loss and undesirable pauses during the interview. For every energy carrier from this list, interviewees are inquired about its household use and service it provides. The question how many units of fuel are used over a substantial period is difficult to answer for most people. Instead, interviewees are inquired how long one typical unit of fuel is used before they decide to collect or buy a new unit. In this way, respondents are able to tell their accurate fuel consumption rate. The question is repeated for every fuel separately, since different fuels tend to have distinct time cycles of consumption. The time cycle for consumption is not equal to that of purchase. People tend to have a fluctuating income and only make purchases when their financial situation allows them to purchase new fuel. This may not apply to essential fuels for cooking, since people need to eat every day, but it may apply to kerosene, candle and battery use for lighting or radio use. The time lag in purchasing new fuel is called the consumption time lag factor. This factor is calculated by dividing the daily load for radio use inquired in the *appliance* module questionnaire (Appendix K) by the energy content of the batteries consumed for radio use from the *fuel and electricity* module questionnaire (Appendix J).

2.2.2. Energy expenditure

Payment schemes are established on the basis of the user's ability to pay for a PV system. It is expected that projects where users pay for the annualized costs, result in more user involvement. The ability to pay for households is assessed by calculating the total domestic energy expenditure for all existing energy services. However, PV cannot replace all energy services in a cost-effective way. As a general rule, energy services that require resistive heating are not supplied cost-effectively by a PV system (Hankins, 2010; Solar Energy International, 2007). Therefore, a distinction is made between substitutable and non-substitutable energy services. In the case a fuel provides both services, a fuel allocation factor is used. The substitutable energy services for PV are lighting and appliance use. People's ability to pay for these services is determined by calculating its Substitutable Energetic Expense (SEE). It is defined as the amount of money that households would save if they were provided with solar power to provide the energy services otherwise made possible by fuel consumption (Camblong *et al.*, 2009). The energy carrier price is not assumed the same for every household, since people experience differences in accessibility. For example, somebody that is able to travel to the petrol station to purchase kerosene and petrol spends less on its fuels than somebody who purchases it in the village from a salesman, as the salesman marks up the fuel station price.

2.2.3. Load assessment

The term load is defined as the demand for electrical energy. Load is subdivided into load for running presently owned lights and appliances and for fuel substitution. Finally, the daily load profile and load growth is discussed, since the PV system should supply future loads as well.

Present load

The demand for electrical items depends on the availability at the local market. The largest markets are usually based in the capital or other large cities. From there the items are transported to smaller local markets and end up in the households. The average power rating of the most abundantly available light bulbs, radios, televisions, DVD players, stereo sets and freezers are obtained through a market study at dealers of electrical items in the nearest large city (Appendix H). A duty cycle of 55% for freezers is assumed, since they do not continuously draw power (Solar Energy International, 2007). The average power rating of the electrical items is assumed equal for all households. Interviewees are asked which electrical items they own in the house, how many of them and their duration of daily use. For the mobile phone is asked after how many days it needs to be charged again on average. At this point, the present load for an average household is calculated. The load is assessed by the questionnaire based household surveys (Appendix K). The number of households in a community is determined by using an up-to-date map and counting houses during a field survey.

Load for fuel and battery substitution

Substituting the lighting hours from kerosene lamps or candles by light from an efficient light bulb for an equal luminous flux yields the load for fuel substitution, which is calculated using Equation 1. The daily domestic use is inquired in the questionnaire based household survey. The consumption rate and luminous flux of light sources are given in Table 2. The luminous flux is defined as the visible light produced by a light source. Table 2 also gives the luminous efficacy, which indicates the produced luminous flux per watt consumed. It is desirable to have a high efficacy for lamps in PV systems, in order to obtain maximum light output from a minimum system size. Efficacies for fuel-based light sources are calculated using the fuel energy content from Table 20.

Equation 1. Daily load for community with kerosene and candle use substitution

Table 2. Performance parameters for conventional lighting sources in developing countries

Type of lamp	Fuel consumption g *or mL / hour*	Power rating *Watt (W)*	Luminous flux *lumen (lm)*	Luminous efficacy *lm / W*	Lifetime *hours*
Candle	15.7 g / h	200	10	0.05	2.5 [I]
Simple wick lamp	9.6 mL / h	97.5	7.8	0.08	200
Hurricane lamp	35.8 mL / h	364	40	0.11	400
Pressurized lamp	100.9 mL / h	1,026	400	0.39	1,000
Flashlight (incand.)	-	0.74	3.8	5.14	15
Incandescent lamp	-	40	410	10	1,000
CFL [II]	-	11	650	59	10,000
WLED – ST2 [III]	-	1.19	73.9	62.1	30,000

Source: (Mills, 2005), (Mahapatra *et al.*, 2009) CFL = compact fluorescent lamp; WLED = white light emitting diode. Luminous efficacy

2.2.4. Energy service priorities

The local demand for appliances that are potentially powered by PV, determines the demand for PV. If a PV project is focused on meeting domestic needs in a community, it is necessary to find out what the local consumer really wants. The willingness of consumers to choose for PV strongly depends on their aspirations to own appliances that can be powered by PV and their current ownership. Thus, knowing local appliance priorities are important to gauze the PV market potential.

Electrical item priorities

The assessment of energy service priorities is performed in a few consecutive steps, shown in Figure 4. In *step 1* all commonly available electrical items are listed in a so-called *priority matrix* (Appendix K, column A3). In the survey, interviewees are asked what they consider more important to own in their life, item *X* or *Y*. To avoid repetition of the same answer without thinking the question over, items are alternated in the questionnaire. In this way, each household yields a priority list for all items, ranging from one to eight. An eight denotes the highest priority and a one the lowest. The priority score or index is calculated for each item and averaged for the whole community (*step 2*). Thus, the mean priority index reflects how many times each item is considered more important relative to the other items in a community. *Step 3* defines the categories *Essential* (E), *Useful* (U) and *Non-Essential* (NE) to classify the items from step 1. To allocate them to these categories, value ranges for each category are defined in *step 4*. The ranges are set arbitrarily by taking: (1) the lower quartile or 25th percentile (≤ classified as E), (2) the upper quartile or 75th percentile (≥ classified as NE), and (3) the interquartile range (classified as U) of the averaged mean priority indexes for all items. According to the community preference index and their value ranges, each item is categorized as essential, useful or non-essential in *step 5*.

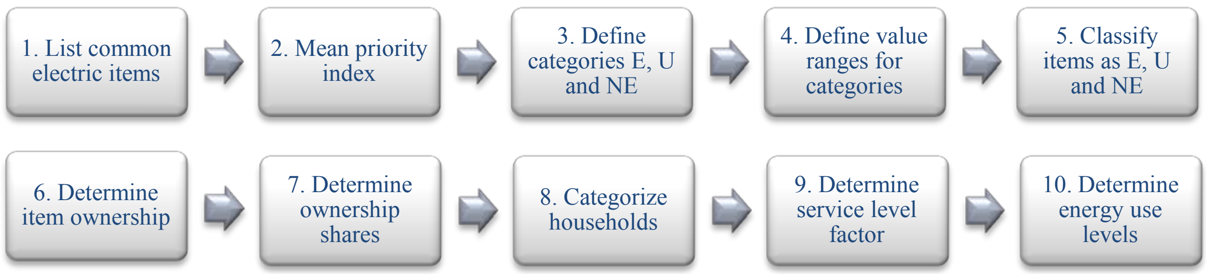

Figure 4. Steps for energy service level definition, based on (Patel et al., 2007)

Energy service levels

Once all items are categorized, the current domestic ownership is mapped in *step 6*. Ownership shares (*step 7*) of the item categories are calculated to classify households to a low, middle or upper energy service level (ESL) in *step 8*. In *step 9* the share of households that classify as low, middle or upper ESL is calculated for the community, referred to as *service level factor*. The service level factors function in *step 10* as percentiles of the sample households to determine the energy use ranges for the defined ESLs. For example, if *X*% of the households classify as a low ESL, the *X*th percentile of the electricity demand is taken: *Y* kWh/day. That means *X*% of the sampled households is to be found below the daily energy use of *Y* kWh.

2.3. Optimization assessment

The three components of the optimization are: technology choice (section 2.3.1), optimized system design (section 2.3.2) and the system cost (section 2.3.3). Critical preconditions of a successful system design include proper sizing, technical and economical efficiency, modularity, simplicity and safety (Alzola *et al.*, 2009). Proper sizing means to configure a PV system in such a way that it supplies the demand for energy services. The system needs a techno-economic optimized design to provide reliable and affordable energy services. In order to size an optimized design, either an analytical or simulation-based sizing method (HOMER) is used. The analytical sizing method is discussed in section 2.3.2.

2.3.1. Technology choice

The systems under study are discussed in this section. A decentralized PV system is classified according to the number of users and its power capacity, shown in Table 3.

Table 3. Classification of decentralized PV systems

PV system option	Abbreviation	System voltage	Approximate size
Pico PV System	Pico PV	6 / 12 V	1 – 10 W_p
Solar Home System	SHS	12 / 24 V	10 – 200 W_p
Multi-user PV System	MUS	12 / 24 / 48 V	200 – 5,000 W_p
Micro-grid System	MGRID	24 / 48 V	< 4,000 W_p

Source: (GTZ, 2010), (Chaurey*, et al.*, 2010b).

Pico PV System

A Pico PV system is an independently operating appliance that provides lighting and additional electrical services (GTZ, 2010). It is an emerging low cost technology, characterized as a downsized SHS that supplies low-cost energy services with less reliability. Pico PV systems vary greatly in technical specifications and quality (GTZ, 2010). Quality standards and norms are being developed to favour well performing Pico PV systems in developing and emerging markets by *Lighting Africa*. The *Lighting Africa 2010 Award* winners from Table 4 are subjected to strict quality tests and serve as a reference for high quality Pico PV systems. Therefore, they receive support in dissemination practices for the African market. They show a wide variety in useful light output and capacity sizes: 110 – 1273 lm-h/day, PV modules sizes of 1.5 – 5 W_p, and battery sizes of 0.68 – 4.5 Ah. Also different battery types are used: lead-acid (PbA), re-chargeable NiMH and NiCd. The extended version of the SunTransfer 2, called Power Box Domestic Solution, is the reference system in this study. The reason is twofold: it is able to supply the energy services under study and the technical specifications and market prices for its product components are available for January 2011.

Table 4. Technical specifications of Lighting Africa 2010 Awards winners

Brand	Product name	Luminous Flux [I] (lm)	Light h/day	Useful Light Output (lm-h/d)	Capacity (PV module; Battery)
Barefoot Power	Firefly 12 Mobile	25	4.4	110	3.6V, 0.68 Ah, Re-ch NiCd
Barefoot Power	PowaPack 5W	190	6.7	1273	5 W_p; 12V, 4.2 Ah, Sealed Re-ch PbA
d.Light Design	Nova S250	60	4.0	240	3.6V, 1.5 Ah, Re-ch NiMH
Greenlight Planet	Sun King	32	4.0	128	3.7V, 0.78 Ah, Re-ch Li-ion
Philips	Uday Mini	120	4.1	492	5 W_p; 6V, 4.4 Ah, Sealed Re-ch PbA
Solux	Solux LED-50	68	3.1	211	1.5 W_p; 3.6V, 1.8Ah, Re-ch NiMH
SunTranfer	SunTranfer 2 [II]	73	4.1	299	2 W_p; 6 V, 4.5 Ah, PbA gel

Source: (Lighting Africa, 2010), website: http://www.lightingafrica.org. [I] Solar charge provided by 1000 W/m^2, IEC 60904-9. [II] Equipped with Cree XP-C LED, the LED has a CRI of 75 and produces about 73 lm (Lighting Africa, 2011), which corresponds to a neutral white P3 group LED (1.19W for a light output of 73.9 lm; Cree Product Characterization Tool; website: http://pct.cree.com).

Solar Home System

The most dominant decentralized PV system used and promoted in developing countries on the justification of cost-effectiveness is the Solar Home System (Wamukonya, 2007). A typical SHS that provides AC electricity consists of the components shown in Figure 5 and is used for the peri-urban community. All components are sized according to solar resource availability, load demand and reliability requirements. Components are purchased separately, leaving the design to the PV project planner. The DC configuration does not require an inverter and is used for the rural communities.

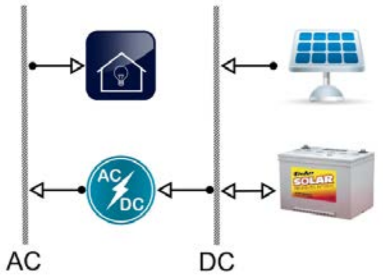

Figure 5. SHS configuration

Solar Charging Station

A Solar Charging Station (SCS) or often called 'energy kiosk' is a MUS, with a typical size range of 0.2 – 5 kW_p (Table 3). The SCS is centrally located in the village and generates solar power for multiple users. Figure 6 shows that the DC power is used to charge multiple Pico PV systems. When charged, the systems are distributed with a fee-for-service delivery model. In this way, people only use the service when they can afford to and a regular payment commitment is avoided. The replacement costs of system components are included in the fee-for-service. A SCS is able to provide many energy services, such as lighting, mobile phone charging, cooling, etc.

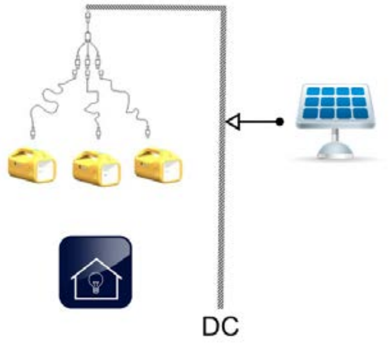

Figure 6. SCS configuration

Hybrid PV Micro-grid

A PV system that is part of a small-scale low voltage distribution grid where the distributed energy resources are placed closed to the electrical loads is called a micro-grid (Chowdhury *et al.*, 2009). Micro-grids usually consist of hybrid electric systems, combining for example photovoltaic, wind, hydro and generators. An AC configuration is most preferable for small village grids, since it is more efficient (distribution-wise), flexible and expandable than a DC configuration (ARE & USAID, 2011). From Figure 7 becomes clear that PV modules and batteries run on DC voltage, while electro-mechanic technologies that convert kinetic into electrical energy run on AC voltage. The generated DC power from the array and is stored in a battery bank. If a load is applied, DC power is converted into AC power and distributed along a low voltage, single-phase grid to all the households. A diesel generator is connected to the AC bus to supply the peak loads of the system, in order to reduce the PV system cost. A single-phase distribution line is preferred when there are no power loads for productive purposes in the village. The advantages are grid simplicity, reduced costs due to less conductor lines, no load balancing requirement and larger surge capacities (ARE & USAID, 2011).

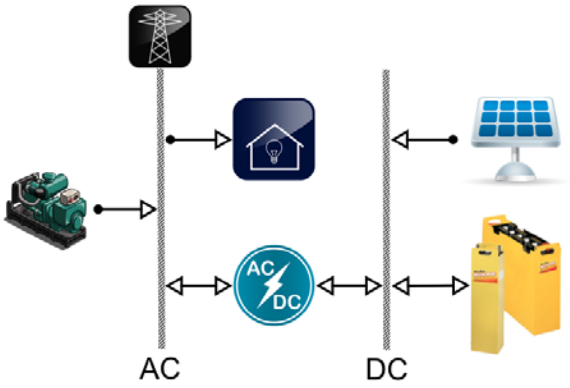

Figure 7. Hybrid PV-diesel micro-grid configuration

2.3.2. Optimized system design

An optimized system design is achieved in several steps. First, the availability of appliances to provide the energy services is assessed through a market survey (Appendix H). Secondly, an inventory of the available PV system components is established from wholesale suppliers. Thereafter, a selection of appropriate technology is made. Finally, the battery bank, PV module and charge controller are sized with an analytical and simulation-based sizing method.

Battery selection

PV power is predominantly provided through lead-acid batteries. The available lead-acid battery types with their common characteristics are presented in Figure 8 (Hankins, 2010). A distinction between flooded and valve-regulated lead-acid batteries is made. Flooded batteries are mostly widely available at relatively low cost, but are vulnerable to deep-discharges. A battery with an 80% minimum state of charge (SoC) means that below a 20% depth of discharge (DoD) the battery gets damaged, which significantly shortens its lifetime. The lined boxes in Figure 8 represent the batteries typically used for PV systems. The system's battery size is depending on the energy requirement, the efficiency of the battery and several other factors. The input parameters for battery sizing are given in Table 6.

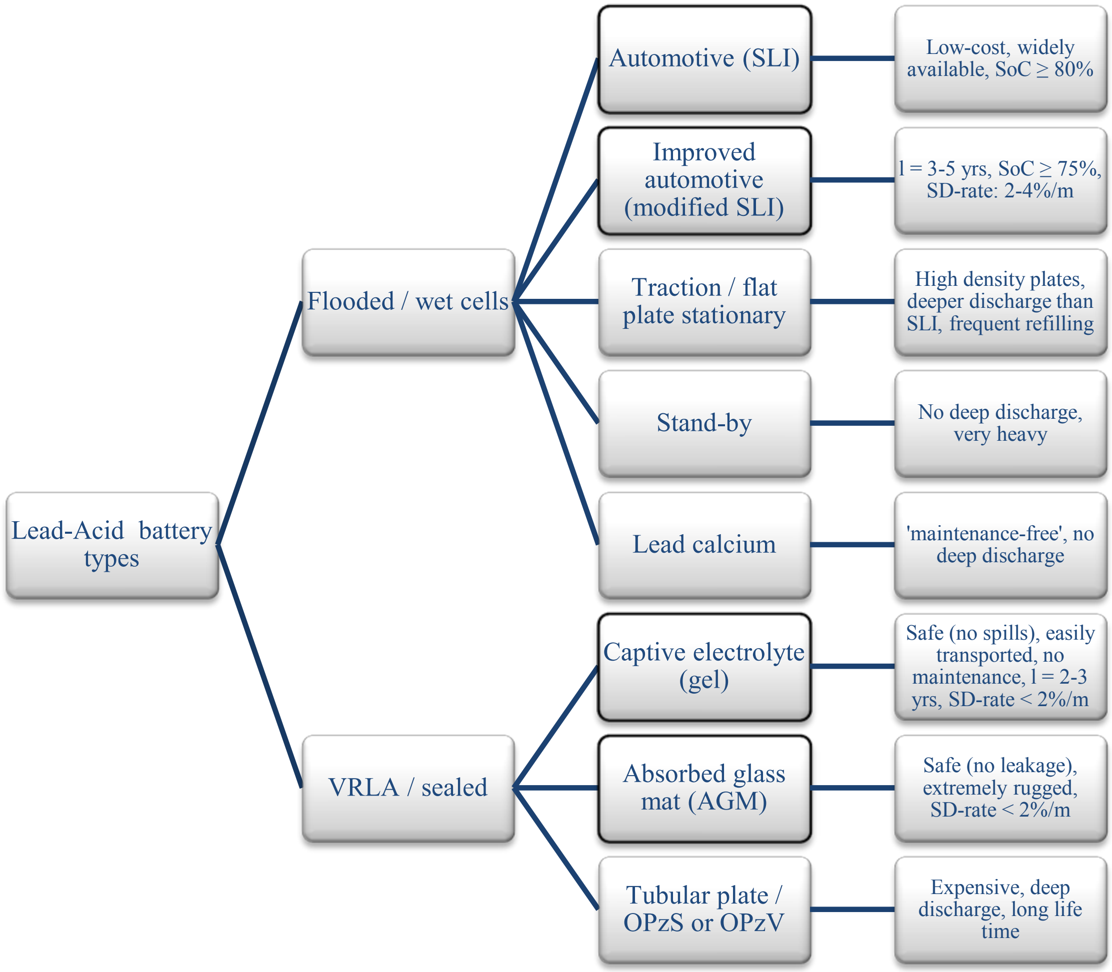

Figure 8. Lead-acid battery types with their common characteristics

The captive electrolyte (gel) and absorbed glass matt (AGM) are selected for system sizing, since they are safe to the user, easily transportable through a rough terrain and requires little maintenance.

Charge controller selection

The controller manages the electrical flows from PV module to battery and from battery to load. The system voltage is equal to the controller voltage. The controller size is calculated by using the maximum current from the PV array ($I_{sc,input}$) and the maximum load demand from the user ($I_{sc,output}$), given in Equation 13 from Appendix C. There are four types of charge controllers (Hankins, 2010):

1. *Series-type:* connected in series between module and battery; measures battery voltage and disconnects when it reaches full SoC set by a high voltage level (HVL). Resets after battery SoC drops below HVL by load use.

2. *Shunt-type:* connected in parallel with module and battery, regulates power to the battery according to the SoC and diverts excess power from the module to a shunt load, e.g. solar water heater, once the battery reaches full SoC.

3. *Pulse-width modulation (PWM):* it adjusts the charging rate from the module according to the battery voltage or SoC, to maximise the battery charging capacity.

4. *Maximum Power Point Tracker (MPPT):* maximizes the available power from the module by using a battery-charging voltage equal to the maximum power point voltage (V_{mpp}).

MPPT controllers are only cost-effective in large systems, where the extra output form the PV array compensate for the extra investment costs. For the small off-grid systems the PWM controller type is selected.

Sizing method

It is appropriate to distinguish between rural and peri-urban in the optimization, due to the disparity in load demand, accessibility and user's ability to pay. An optimization for a peri-urban community is based on the present and future load. The access to basic energy services for rural households appears to be limited, which requires a different approach. An improved energy service level is defined according to the basic energy service requirements in the peri-urban community, resulting from the demand assessment. It is assumed that the present use of basic energy services in such communities is representative for usage patterns in the rural areas once supplied with electricity. PV system sizing methods are classified into two categories: analytical sizing and simulation based sizing (Chaurey, *et al.*, 2010a). Analytical sizing is typically used for small size PV systems. It is not used for sizing PV systems larger than 500 W_p and for sizing a hybrid micro-grid (Hankins, 2010), because it tends to oversize the battery capacity. However, the project designer chooses a sizing method on the available time, data and knowledge (Cabral *et al.*, 2010). Some differences between the two methods are listed in Table 5.

Table 5. Differences in analytical vs. simulation based system sizing

Analytical sizing method	**Simulation-based sizing method**
Straightforward, using simple analytical equations	Complex, due to considered stochastic behavior
Readily available equations for sizing	Optimization software required (e.g. HOMER)
Reliability limited to the consistency of average data	Generates more reliable capacity requirement results
Tends to oversize the required battery capacity	More realistic prediction of required PV system size
Battery capacity determines the reliability by choosing a appropriate days of autonomy	Both battery and PV array capacity determine the reliability

The analytical sizing method results in a relatively high battery capacity compared to simulation-based sizing. Typically, batteries have a short operational lifetime compared to PV modules. As a result, analytical sizing leads to relatively high battery replacement costs during the project lifetime. On the other hand, simulation-based sizing is focused on minimizing costs by varying both battery and PV module capacity for increased reliability requirements. This operation is performed with help of the optimization software HOMER.

Analytical sizing

The analytical sizing equations for the PV module, battery bank and charge controller are given in Equation 2 – Equation 4, respectively. The assumptions made for variables in these equations are presented in Table 6 and Table 7.

The PV module size is depending on the daily load requirement (L_D), the efficiencies of the system components (η_x) and several factors that determine the performance ratio (PR). The PR is defined as the ratio of the final PV system yield to the reference yield. The difference between the insolation ($EHFS$) and the actual output of the PV array has many different causes, e.g. losses due to cell temperature (f_{temp}), dust on the modules (f_{dust}), systems mismatch due to shadow ($f_{mismatch}$).

Equation 2. PV module sizing (Chaurey, et al., 2010b)

Table 6. Input parameters for battery sizing

Description	Symbol	Pico PV	SHS	SCS	MGRID	Source
Operating voltage	V	12	12	12	24	(SunTransfer GmbH, 2010)
Actual days of autonomy [I]	day	1.3	2.9	2.4	-	Calculated value
Inverter efficiency	η_{inv}	-	90% [II]	-	95%	(Chaurey, *et al.*, 2010b)
Charge-discharge efficiency	η_{xy}	70% [III]	85%	70% [III]	90%	(Chaurey, *et al.*, 2010b)
Max depth of discharge [IV]	$MDoD$	60%	60%	60%	60%	(Hankins, 2010)

[I] The days of autonomy is calculated assuming an average DoD of 50% for the Pico PV system.
[II] SHS supplying AC power for peri-urban community; DC for rural community, leaving out the inverter efficiency.
[III] Depending on battery type: Li-ion: 85 – 95%; NiMH and NiCd: 65 – 85%; Lead-acid: 70 – 84% (Rydh, *et al.*, 2005).
[IV] The MDoD depends on the battery type used.

Table 7. The assumptions for the PV module sizing

Description	Symbol	Pico PV	SHS	SCS	MGRID	Source
Charge controller efficiency	η_{cc}	-	85%	85%	95%	(Chaurey, *et al.*, 2010b)
Losses – PV cell temp. (%)	f_{temp}	10%	10%	10%	10%	(Chaurey, *et al.*, 2010b)
Losses – dust or dirt (%)	f_{dirt}	5%	10%	5%	5%	Assumption
Losses – module shade (%) [I]	f_{shadow}	20%	15%	10%	5%	Field survey estimate
Performance ratio	PR	51.8%	55.1%	65.4%	73.3%	Calculated value

[I] Losses due to dust and dirt on the panels is assumed to be higher for SHSs, because panels are not easily reached and household residents have no job obligatory to clean them regularly. [II] Shadow losses are assumed to be higher for SHS with increased system size, because more attention is paid to shadow free mounting sites.

2.3.3. POWER DISTRIBUTION NETWORK

The power distribution network (PDN) is evaluated for the hybrid micro-grid system. The PDN costs are depending on the spread and terrain of the village. The optimization model ViPOR is used to calculate the least-cost PDN configuration for a village. ViPOR is developed by NREL and stands for *Village Power Optimization Model for Renewables*. According to the spread of loads, load sizes and capital costs of isolated and grid technologies, ViPOR computes the least-cost configuration of loads either supplied by an isolated or a grid connection. This section describes the spatial and non-spatial inputs, (including loads, generation sources, terrain and distribution costs) and outputs of the model.

Spatial and non-spatial inputs

In section 2.2.4 the average daily electrical demand for low, middle and high service levels are defined. Each service level is assigned a load type. Each household is identified through a location and a load type, referred to as a load point. All load points are localized and classified during the field survey, using a detailed map of the community. After the field survey the load points are mapped out in Google Earth. All load point coordinates from Google Earth are copied to a text file, imported to ViPOR and assigned a load type. A load point connected to a centralized distribution grid or an isolated is assigned the same daily load in the case study of Chapter 2. Although, it is expected that SHS loads turn out lower than micro-grid loads, due to their limited power delivery, a maximum load controller for each micro-grid connection will limit its electricity supply as well (Inversin, 2000).

A *source type* is defined as an electricity generation option with an accompanying *generation cost curve (GCC)*. The GCC shows the cost development for a changing system scale as a result of varying loads. It is computed using software package HOMER. Capacity sizes and their corresponding capital, replacement and O&M costs for PV system components are defined in HOMER, with a pre-defined discount rate. All system components are scaled according to varying loads (with a pre-defined daily load profile) and inserted solar resource data, to generate the GCCs. These curves are imported in ViPOR to calculate the optimal configuration for minimized costs.

A *source location* is defined as a potential site for power generation from a centralized distribution grid in the defined area. ViPOR calculates the optimal location, or multiple locations with separate distribution networks, through cost minimization if more than one source location is identified, with a maximum of 10 locations. Each source location is identified in the field by estimating shadow effects to minimize potential site shading during a year. Thereafter, the coordinates are imported to ViPOR and assigned the source type *centralized distribution grid.*

Terrain is an important design parameter in the optimal PDN layout. Different types of terrain, result in differences in relative costs of conductor wiring running through it. To account for these geographical differences, a terrain cost multiplier (TCM) is defined. Table 8 shows the assumed terrain types with their corresponding TCMs. Terrain analysis is incorporated in ViPOR by assigning terrain types to grid cells that form a community map. The time spend on terrain analysis is determined by the specified terrain grid cell size.

Table 8. Terrain types and corresponding assumed cost multipliers

Terrain type	Terrain cost multiplier
Water	20
Forest	4
Grassland	1
Roads	0.5

The centralized distribution grid needs a few economic inputs to calculate the distribution costs. All relevant components are presented in Table 9.

Table 9. Default parameters influencing the Power Distribution Network (PDN) of a micro-grid

Parameters	LV line	MV line	Transformers	Connection charge	Project	*Unit*
Capital Cost	$3 / m	$ 5 / m	$ 500 / unit	$ 112 / connection [I]	-	-
O&M Cost	2 %	2 %	2 %	2 %	-	*% C_{cap} / yr*
Lifetime	25	25	25	20	20	*years*

LV = low voltage; MV = medium voltage; Constraint: maximum LV line length = 400 m. Real interest rate (i) = 12%.
Source: (NREL, 2005). [I] (Chaurey, *et al.*, 2010b), based on 5000 Rs. per connection; 1 US$ = 44.68 Rs.

The actual wire costs are calculated by multiplying the capital cost values from Table 9 by the TCMs from Table 8. The *maximum low voltage line length* is defined as the maximum line length between a load point and the transformer to which it is connected (NREL, 2005). This constraint is meant to limit voltage drops and line losses.

Outputs

Once the inputs are defined, the optimization process is started. ViPOR uses an optimization algorithm, referred to as *simulated annealing*, to maximize the net present value of profit (NREL, 2005), due to the definition of on-grid and off-grid payments. The outputs are four-fold:

1. A map of the least-cost configuration;
2. A breakdown of costs and revenues of the optimal configuration;
3. The number of isolated and centralized loads;
4. The LV and MV line length and the number of transformers needed.

2.3.4. Cost assessment

The cost assessment incorporates the initial investment cost (IIC), annualized life cycle cost (ALCC). The cost assessment is performed early in the design process to ensure the lowest life cycle cost for the entire PV project lifetime.

Initial Investment Cost

The IIC is of great importance to estimate the funds needed to implement a PV project. It is calculated by summing up the capital costs of all its PV system components (Equation 14 from Appendix D). For a Pico PV system, all components such as battery and controller are integrated in one single product. Therefore, its capital costs are simply the initial purchase price of the product. The capital costs for a SHS include module, battery, charge controller, inverter, appliance, and balance-of-system (BoS) costs. For the case study, all costs are taken from a PV wholesale supplier. The BoS costs are assumed to be 15% of the module capital costs (Chaurey*, et al.*, 2010b). The SHS in the peri-urban optimization assessment are considered AC, due to the use of multiple appliances that require AC power. The rural communities require basic energy services that can be supplied by DC power, which saves costs on the inverter.

Annualized Life Cycle Cost

The ALCC are all cost incurred over the lifetime of the PV project, spread out annually. It is calculated by multiplying all system component costs by their respective CRF and sum them up. Any annual cost such as operation and maintenance (O&M) and annualized installation costs are added as well (Equation 16 from Appendix D). The battery lifetime is of great importance for the annualized cost analysis, since battery replacement costs typically contribute significantly to the overall cost (Hankins, 2010). The battery lifetime is expressed by the rated cycle life (RCL_{batt}), which coincides with the number of utilization days. A cycle is defined as a charge period, plus a consecutive discharge period. The RCL_{batt} is the number of cycles a battery is expected to last before its capacity drops to 80% of its original capacity (Hankins, 2010). The capacity fraction that is removed from the battery strongly depends on the depth of discharge (DoD). The state of charge (SoC) is the converse of DoD. The average DoD per cycle and average battery temperature during the battery life is important to determine its cycle life. Besides, mistreatments like deep discharges or high discharge rates also result in substantial shorter lifetime. The average DoD is estimated by dividing the required battery capacity by the capacity of the selected battery. The correlation of DoD to the battery life cycle is a power function, which is highly specific for each battery type. Manufacturers typically provide technical product sheets with RCL_{batt} data for different DoD fractions (Appendix M and Appendix O).

The replacement of PV components is part of the ALCC and therefore incorporated in this study. They are calculated using Equation 5.

Equation 5. Annualized Life Cycle Cost due to replacement (NREL, 2004)

3. Case Study Results

The results for the case study are presented in this section. The resource and demand assessment results in section 3.1 and 3.2, respectively, serve as an input for the optimization in section 3.3.

3.1. Resource Assessment

The community coordinates from Appendix E are the only input to obtain the monthly averaged insolation data from PVGIS, which is shown in Figure 9. The yearly average irradiance on a horizontal plane is 5.65 and 5.18 kWh/m^2/day for Sussex and the rural communities, respectively. An accompanying fixed optimal inclination of 14° for the entire year is obtained. The largest irradiation difference is shown between March and August: 42 – 48%. The shading analysis in Sussex resulted in two potential year-round shade-free sites to serve as source locations for a PV micro-grid.

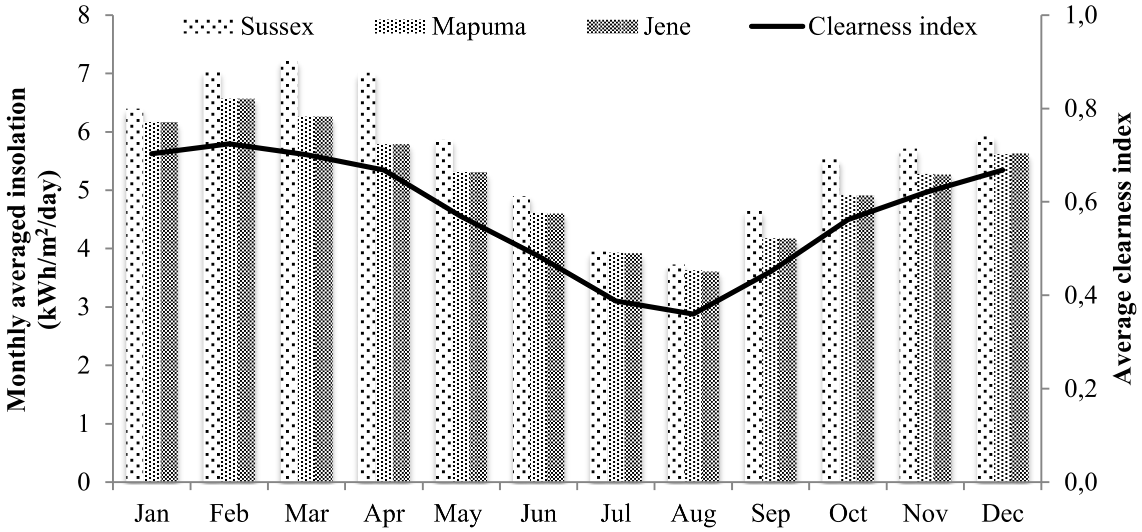

Figure 9. Monthly average insolation and clearness index for three communities in Sierra Leone (Appendix F)

Interpretation Results – Resource Assessment

The irradiation results from Figure 9 include both direct and diffuse radiation. They change along with the average clearness index during the entire year. The clearness index illustrates that the cloud cover varies by a factor two during the year: 0.36 in August, up to 0.72 in February. This disparity in cloud cover is explained by the two seasons that exist in Sierra Leone: the wet and dry season.

The two shade-free sites are shown as triangles in Figure 24. Source location 1 is a schoolyard for children from a primary and secondary school, and source location 2 is a grass field that is privately owned. Both locations are inputs for the ViPOR analysis. However, the advantage of location 1 is the attention a PV facility could create for young people going to school. Synergies for educational programmes about solar energy make it an interesting location.

3.2. Demand assessment

The results of the demand assessment for the target communities are presented according to the sub-sections in chapter 2: energy use, energy expenditure, load assessment and energy service priorities. The demand is assessed through questionnaire based household surveys. The surveys are carried out for 26%, 32% and 63% of the existing households in Sussex, Mapuma and Jene, respectively.

3.2.1. ENERGY USE

Figure 10 shows the share of households in the target communities that use the energy carriers available to them for domestic purposes. The results are obtained from the field surveys by using the *fuel and electricity source* questionnaire from Appendix J.

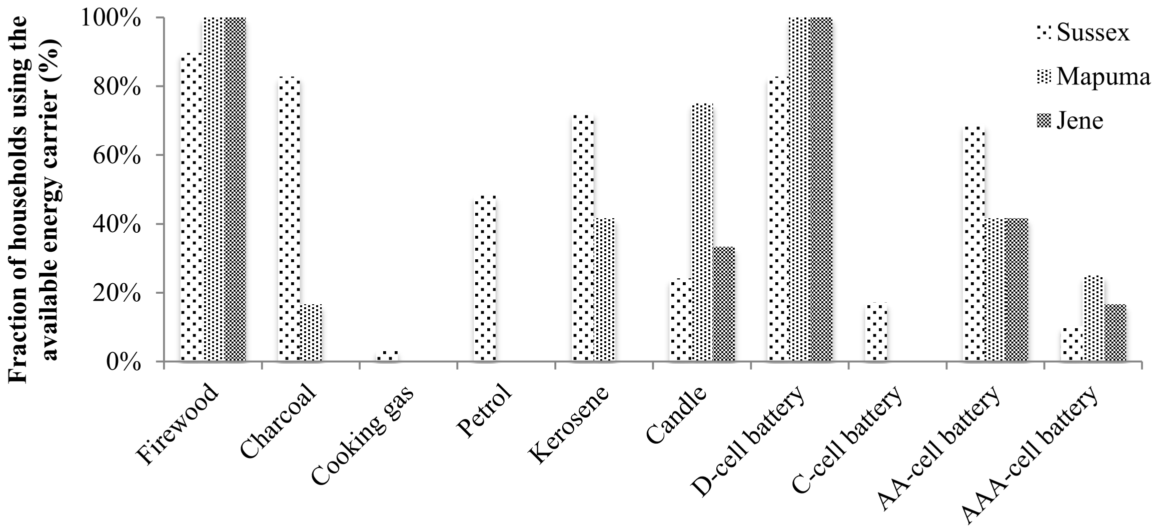

Figure 10. The share of households in the communities that use the available energy carriers

People in Sussex especially rely on firewood, charcoal, kerosene and D/AA-cell batteries. Cooking gas, candles, and C/AAA-size batteries are not abundantly used. A 48% share of its households consumes petrol. In contrast, none of the rural households use petrol. Also, cooking gas and C-cell batteries are not used by them. Most rural households rely on firewood, candles and D-cell batteries and to a lesser extent on kerosene, charcoal and small sized batteries.

The total primary energy use for the communities of interest is presented in Figure 11. The average capita per household is 7.0 for Sussex, 8.4 for Mapuma and 11.9 for Jene.

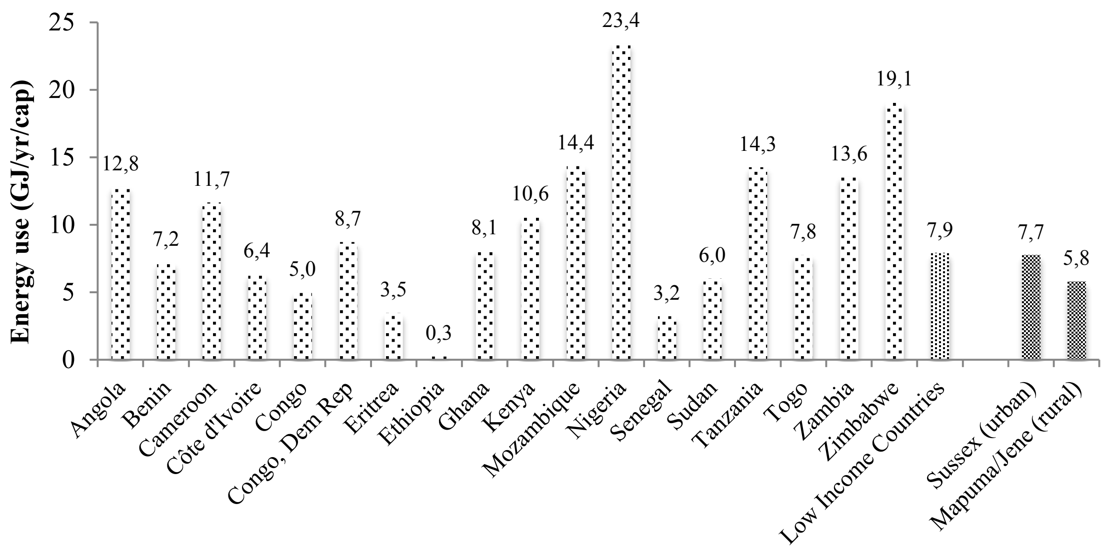

Figure 11. Total primary energy use per year. Light shaded bars: low income African countries in 2005 (IEA, 2007); dark shaded bars: results from questionnaire based household surveys in 2010

If the surveyed communities are assumed representative for the country Sierra Leone as a whole, a comparison with other SSA countries can be made, based on the 35.8% urban and 64.2% rural population distribution in 2008 (SSL & ICF Macro, 2009). In this case, "Sierra Leone" is below the low-income country average with 6.5 GJ/yr/cap. Sussex figures are assumed representative for urban use and the average figures from Mapuma and Jene for rural use. Firewood and charcoal dominate the results for Sussex. A lower share of households use firewood in Sussex compared to the rural communities, while Sussex's primary energy use is higher. This is explained by the relatively high share of charcoal and petrol use in Sussex, which represents respectively 30% and 10% of its total primary energy use. Besides, the rural communities have on average 10 capita per household compared to 7 for Sussex. The results are obtained by questionnaire based household surveys performed in 2010. Battery use is excluded from the analysis, to make Sierra Leonean figures comparable to the statistics from IEA.

Interpretation Results – Energy Use

Sierra Leone is characterized by a remarkable climate difference between the wet and dry season, which influences the fuel choice for cooking. For example, charcoal is preferred in the wet season since wet firewood hardly burns. Therefore, the rate of consumption is determined for the dry and wet season. People in the surveyed communities rely heavily on firewood. Since the average temperature is 27°C and rather constant over the year, people almost use no firewood for heating purposes. That means firewood is mainly used for cooking and preparing hot water. In Sussex charcoal is often used for cooking and to iron school uniforms. For rural households the graph from Figure 10 says different. There is a remarkable contrast in charcoal use for Sussex and the rural communities. There are mainly two reasons: rural households hardly use charcoal for cooking and hot water heating purposes. Besides, they use the remains of burned firewood for ironing. These remains are allocated to firewood use and thus not reflected in Figure 10. The petrol consumption in Sussex suggests that about half of the households own a home generator to generate electricity. However, even though petrol is solely used for generators, it does not mean that half of the households really own one. In some cases, people borrow a generator from a relative or neighbour and leave in some remaining fuel as payment. A 76% share of the households in Sussex use kerosene, predominantly for lighting. Some households own kerosene stoves or use kerosene to let firewood catch fire for cooking. Kerosene used for lighting purposes is substitutable, while using it for a cooking is not. When a kerosene stove is used, the kerosene consumption is allocated to the services lighting and cooking on an equal share.

The rural households use relatively more candles for lighting. Batteries are commonly used for flashlights, radios and cassette players. Vinnic (zinc chloride) and Tiger are two widely available non-rechargeable battery brands[3]. Vinnic last longer then the Tiger, but are more expensive. The Vinnic type is mainly used in Sussex, while the rural households prefer to purchase the Tiger batteries. During the field surveys it became clear that batteries are disposed off in a haphazard manner in the direct environment, even dumping it into the forest or rivers. This observation is endorsed by the Population and Housing Census report, which describes the problem of poor management of rubbish disposal (SLL, 2004). Therefore, a PV system in combination with re-chargeable batteries could potentially reduce pollution caused by battery disposal.

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[3] Chinese manufacturers produce both battery types. The manufacturer specifies the capacity of Vinnic batteries (Table 16, Appendix G) from while there is no such information on Tiger batteries. Assuming that the price is reflecting the relative capacity, the capacities of Tiger batteries are estimated.

3.2.2. Energy Expenditure

The monthly energy expenditure is needed to establish finance payment schemes for the PV system users. The total average energy expenditure and SEE for the locations of interest is shown in Table 10. The money spent monthly on fuels that is potentially displaced by a PV system is $22 for Sussex and $5 for the rural communities.

*Table 10. Energy expenditure of an average household in Sussex, Mapuma and Jene**

	Sussex		Mapuma		Jene	
Fuel sources	$ / Month	Share (%)	$ / Month	Share (%)	$ / Month	Share (%)
Firewood	9.45	23%	-	-	-	-
Charcoal	7.48	19%	1.87	27%	-	-
Cooking gas	0.87	2%	-	-	-	-
Petrol	13.72	34%	-	-	-	-
Kerosene	2.67	7%	0.34	5%	-	-
Candles	0.59	1%	1.50	22%	0.64	13%
Batteries	5.49	14%	3.16	46%	4.36	87%
Sub-total *Non-SEE*	17.80	44%	1.87	27%	-	-
Sub-total *SEE*	**22.47**	**56%**	**5.01**	**73%**	**5.00**	**100%**
Total / household	40.27	100%	6.88	100%	5.00	100%

* Based on 1 $ = 3543 SLL.

Interpretation Results – Energy Expenditure

As becomes clear from Figure 10 and Table 10, households from Sussex buy their firewood, while the rural households collect it themselves. In Sussex, the firewood consumption is more than three times that of charcoal, on a mass basis. However, the charcoal is roughly three times more expensive compared to firewood, which gives it a slightly lower share in the overall energetic expenses. Petrol and batteries dominate the SEE in Sussex. Kerosene is used in smaller quantities than petrol and has a lower price. The high charcoal price results in hardly any charcoal consumption in the rural communities. Furthermore, rural people tend to produce it themselves from collected firewood. The SEE for the rural households comes from batteries and candles that provide lighting and radio use.

The national average expenditure per capita in Sierra Leone is $0.71 per day in 2010[4]. However, this figure is not the same for the three communities, since large differences in living standards were observed in the field. Assuming that the surveyed communities are representative for the national average of Sierra Leone, a share of SEE on daily expenditure is estimated, based on the 36% urban and 64% rural population distribution in 2008 (SSL & ICF Macro, 2009). Sussex figures are assumed representative for urban use and the average figures from Mapuma and Jene for rural use. It results in an average share of 7% in the total household expenditure.

[4] In order to put the energy expenditures from Table 10 into perspective, it is compared to the gross domestic product (GDP) of Sierra Leone. Its GDP in 2008 was $262 per capita, with an average annual growth rate of 6.5% (World Bank, 2010). Assuming that the growth has continued, it results in a GDP of $297 per capita in 2010, which is the year the energy expenditures were determined in the field. The annual average household final consumption expenditure is 87.3% of the GDP for the period 2000-2008 (World Bank, 2010). It is assumed that 2010 has a similar expenditure share.

3.2.3. Load Assessment

The daily load or demand for electrical energy consists of several components: the present load to run the owned appliances and the load from kerosene, candle and battery use substitution. The average appliance power ratings are taken from a market study performed in the capital Freetown (Appendix H) and serve as a reference for the appliances owned by households in the field. The appliance ownership, its number and daily use, is inquired in questionnaire based household surveys. The ownership and total daily load results are shown in Figure 12 and Figure 13, respectively.

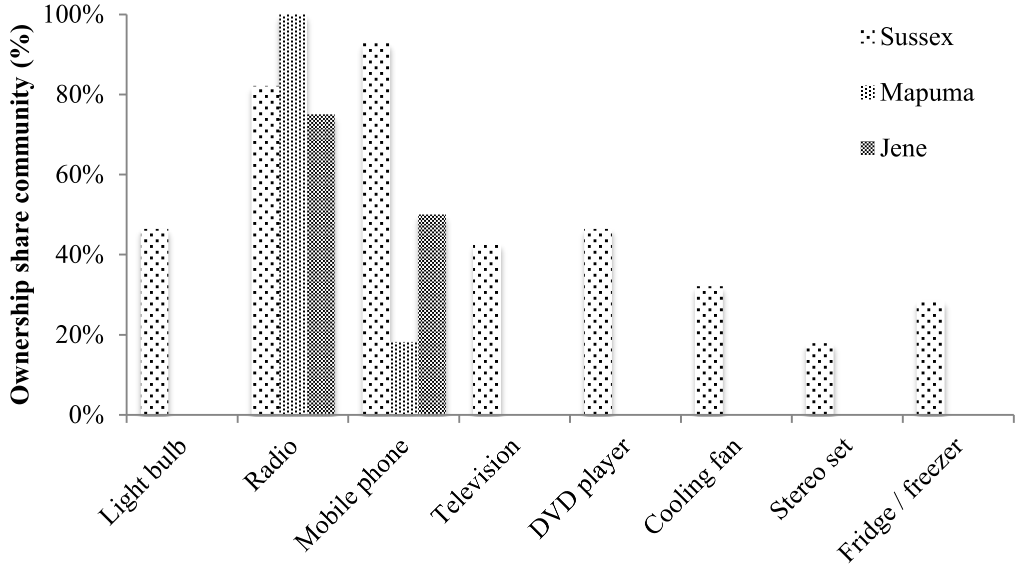


Figure 12. Domestic appliance ownership share for community Sussex, Mapuma and Jene

Figure 12 shows that all appliances are found in Sussex, while the rural communities are limited to radios and mobile phones. Furthermore, less than half of the households in Sussex use appliances other than the radio and mobile phone.

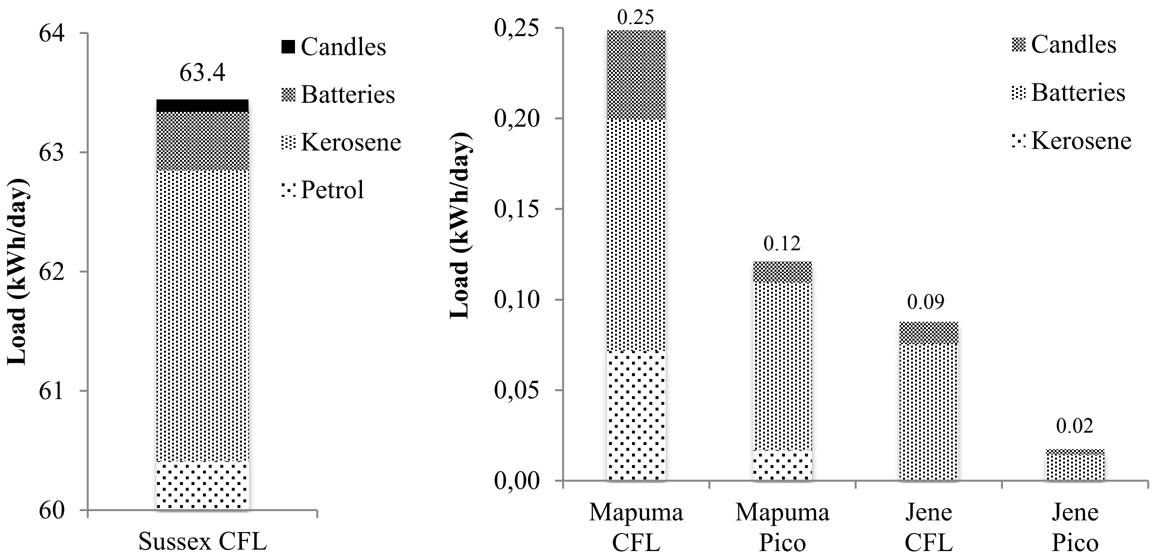


Figure 13. Potential daily load for Sussex (left), Mapuma and Jene (right)

Figure 13 depicts a daily load of 63 kWh for Sussex if CFL bulbs displace the kerosene and candles, while Mapuma and Jene show a potential daily load of 0.2 and 0.1 kWh for CFL bulbs, respectively.

Figure 13 indicates that providing the existing energy services by PV requires a relatively small amount of electricity for rural communities compared to Sussex. The daily load of 63 kWh for the entire community is used for the optimization assessment. Figure 13 shows a relatively small contribution of kerosene, candle and battery use compared to petrol. If the contribution of petrol is neglected, the peri-urban community has a daily load of 2 kWh. The potential load from Figure 13 (right) is based on substitution of fuel-based lighting for an equal luminous flux from an efficient light bulb, either CFL or LED. However, considering the lack of basic lighting in the rural communities, a substantial improvement in lighting services is desired. Figure 12 shows that the rural households only use radios and mobile phones. Radios run on dry cell batteries and mobile phones are charged in other villages. Flashlights, candles and to a lesser extent kerosene lamps, are the typical light sources. An improved energy service level concerning lighting, radio use, and mobile phone use, as shown in Table 11, forms the starting point for the analysis of various PV systems on their cost-effectiveness.

Table 11. Improved energy service level used for the cost analysis of PV systems for the rural communities

Energy service	No. of items	Daily use	Source
Lighting	3 lamps	4.3 hours / day [I]	Sussex field survey
Listening to radio	1 radio	5.3 hours / day [II]	Mapuma field survey
Communication	3 mobile phones [III]	3 Wh batt; lasts 6 days	Mapuma field survey

[I] Represents number of hours people use their light bulbs once they own a home generator in Sussex; [II] The people in Mapuma use their radio on average for 5.3 hours per day. [III] Three mobile phones are assumed based on the results from Sussex.

Most rural houses in Mapuma and Jene consist of two rooms and a small patio. Therefore an improved lighting level provided by three lamps per household is desirable. On average households own one radio. Running them on power provided by PV will avoid the recurring costs on dry cell batteries.

Daily load profile

The daily load profile is drawn by the consultation of local residents, shown in Figure 14. People tend to use their light bulbs from 7 pm onwards, since it gets dark around that time. The television and DVD-player are predominantly used simultaneously, starting from 8 pm onwards. The use of the cooling fan starts at the same time to have comfort during entertainment and cooling of the running appliances. On average, people stop watching TV and DVD within two hours and tend to listen to the stereo set after that, approximately from 10 pm onwards. The freezer is assumed to run in the morning hours, since people tend to freeze the freshly catch of fish after returning from night fishing. The average daily appliance use determines until what time appliances stay on. The resulting daily load profile is shows two peaks: one during the evening hours and one during the early morning.

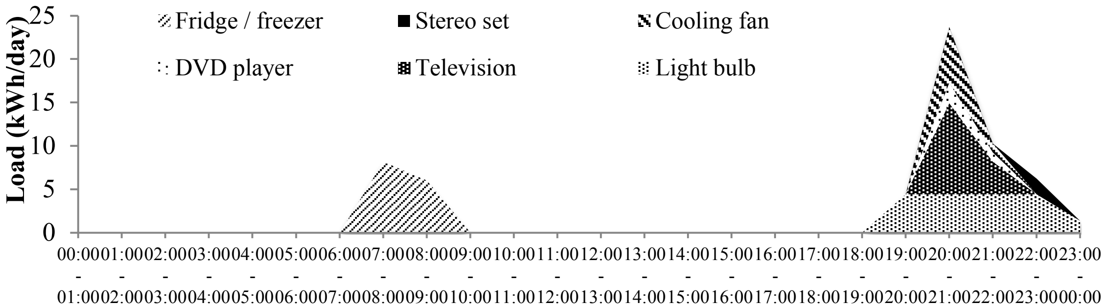


Figure 14. Daily load profile for peri-urban community Sussex

Load growth

A load growth of 32% for 2010 – 2030 is estimated for an urban household in Sierra Leone (Daioglou, 2010).[5] The growth for rural areas is not considered, since an improved energy service level scenario is used. Sussex is assumed to be an urban community. The average annual growth for the household expenditure and population driver is respectively 3.4% and 2.1% for the period 2010 – 2030. These two drivers are inputs to the model and determine the load growth.

Interpretation Results – Load Assessment

The ownership figures show a significant difference between Sussex and the rural communities, where households do not own appliances other than mobile phones and radios. The radios are either plain or combined with cassette player. In Sussex 93% of the households own at least one mobile phone, while less than 48% of the households own a home generator. Thus, people most probably charge mobile phones for business purposes, which was confirmed by local people during the survey. However, the price paid for mobile phone charging is not included in the substitutable expenses from Table 10, since it was assumed negligible and noticed during the field survey. Furthermore, 82% of the households in Sussex own a radio. Since radios are used during the day, while the home generators are not switched on, all radio use is assumed to be battery powered. The daily electricity delivered by batteries to run these radios is 186 Wh. Except for mobile phones and radios; a home generator powers all appliances. The assumption of 100% substitution of petrol by electricity from a PV system is only valid if the electricity demand is fully covered. For example, as soon as people are not able to watch television due to an overload of the PV system they will switch on their generator. Therefore, the SHS is sized according to the required load for all appliances. If only low energy use appliances such as light bulbs, radios and mobile phones are covered by the PV system, most people will still use their generator for running other appliances. The load drop for the generator will not result in substantially lower petrol consumption. That means the PV system is not reducing substantial amounts of petrol and the SEE will be low.

[5] Note: growth figures are generated by running the energy model by Daioglou and are not taken from (Daioglou, 2010).

3.2.4. Energy Service Priorities

Knowing people's aspirations to acquire certain appliances is interesting for promoting a PV project and getting the support of community members. The energy service priorities are determined using the priority matrix from Appendix K in the questionnaire based household surveys. The results of the mean priority index are shown in Figure 15. The light bulb and freezer have the highest priority in Sussex and Jene. In Mapuma, the light bulb and the radio are assigned the highest priority. Also, the mobile phone and stereo set have a relative high priority in the communities. The fan and DVD-player score relatively low.

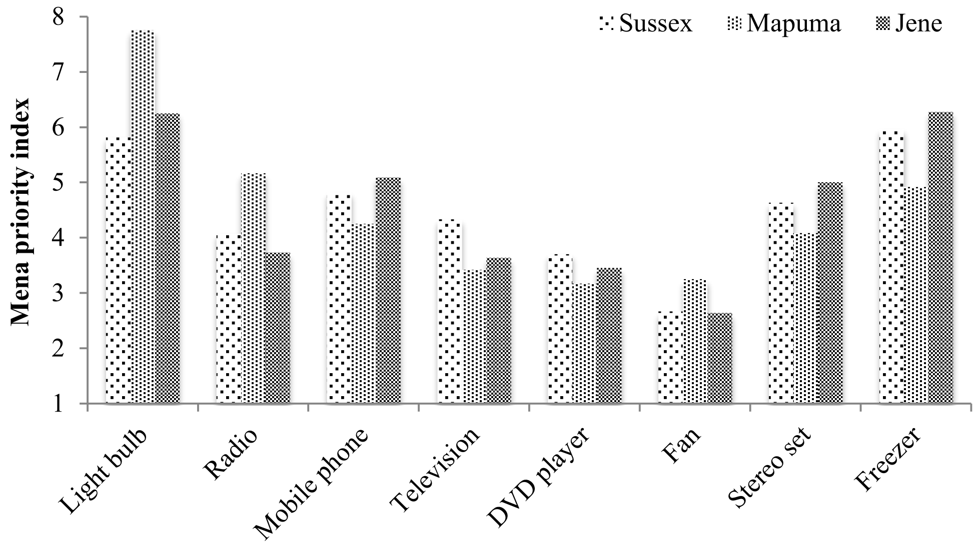


Figure 15. Results of the appliance priority questionnaire

The results for Sussex from Figure 15 are used to classify the households in a low, middle or upper energy service level, due to the large differences in living standards observed in the field. For the rural communities such disaggregation is not made, since no substantial living standard differences exist. Besides, the classification method is inapplicable to rural households, because they do not own most appliances. For Sussex, the light bulb and freezer are classified as *essential*, the cooling fan as *non-essential* and the remaining appliances as *useful*. The ownership shares of the item categories are calculated for each household. Thereafter, households are classified according to Table 12, resulting in a 64% low, 29% middle and 7% upper energy service level (ESL). The average daily loads from Table 12 are used for the optimization. The monthly SEE accompanying these daily loads is \$11, \$40 and \$56 per household, for respectively low, middle and upper ESL.

Table 12. Definition of energy service levels and service level factors for Sussex

Category	Low level	Middle level	High level
Essential	< 100%	< 100%	100%
Useful	≤ 60%	> 60%	100%
Non-essential	< 100%	< 100%	100%
Service level factor	64%	29%	7%
No. of households	71	31	8
Min. daily load (Wh/day)	1	598	927
Max. daily load (Wh/day)	714	1,425	2,825
Average daily load (Wh/day)	153	1,117	1,862
Monthly SEE	\$11	\$40	\$56

Interpretation Results – Energy Service Priorities

The light bulb and freezer are considered essential items. That is endorsed by the fact that 96% of the people that consume petrol own a light bulb (Figure 12). However, only 59% of the households with a generator own a freezer. The difference in priority and actual ownership is explained by the relatively high costs of purchase and operation for freezers. Therefore, if people can afford a freezer, it is likely they will buy one. The priority index should be interpreted with care, since people tend to assign more importance to the appliances not yet in possession. Besides, it is assumed that the priorities of the interviewees represent their household's priorities, while there might be individual differences within the household. Household members that pay for domestic appliances are usually the best-informed respondents. However, in the field it is not always possible to interview the best-informed respondent. The relatively low freezer ownership of 29% could explain partly the high freezer priority. Another influencing aspect is the main economic activity in the community, namely fishing. Interviewees indicated that they would like to keep their catches fresh for consumption and sales. The combination of low ownership share and high priority for freezers could potentially be an interesting focus for promoting a PV project in Sussex with maximum support from its members.

3.3. Optimization assessment

The technologies under study are discussed in section 2.3.1. The optimization assessment covers only techno-economic aspects of the systems. The results are presented separately for the rural communities (section 3.3.1) and the peri-urban community (section 0). The economical evaluation concerns both the initial investment and annualized life cycle costs.

3.3.1. Rural Communities

The cost result of PV systems for a rural household is depicted in Figure 16. The Pico PV system has a fixed size: 10 W_p module with a 9 Ah battery. The reliability rates are generated using HOMER. The SHS has a 30 W_p module and 31.6 Ah battery, which is the lowest available size. The SCS is sized with three 100 W_p modules and with the same batteries as the Pico PV systems. The SHS and SCS are sized as close as possible to the reliability of the Pico PV system, with a minimum reliability of 88%, calculated by modelling the Pico PV system into HOMER.

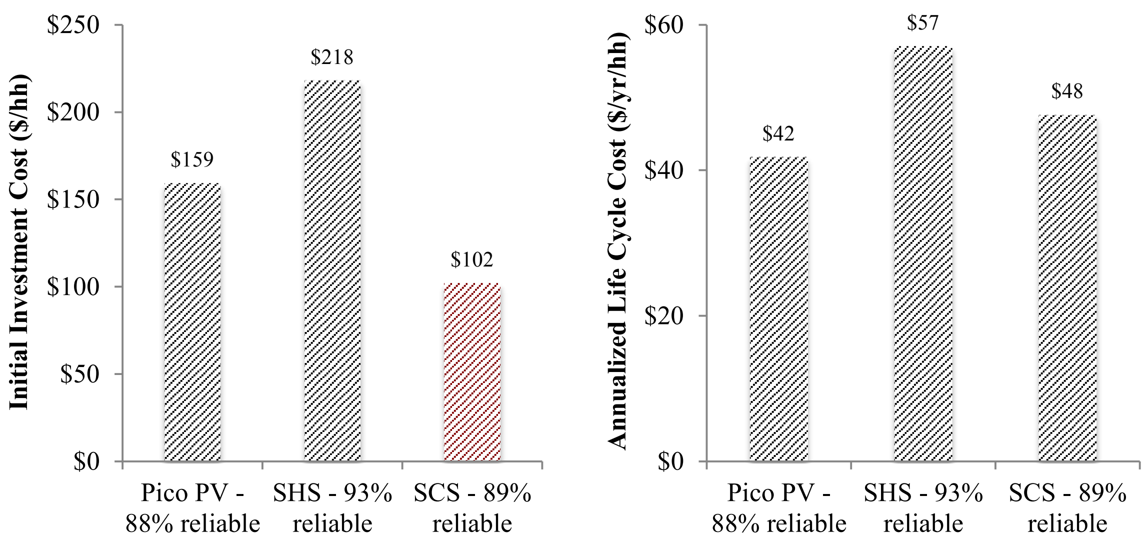


Figure 16. IIC and ALCC for PV systems (L_D = 18 Wh/d for Pico PV; 67 Wh/d for SHS, i = 12%; l_p = 20 yrs)

The SCS requires the lowest initial investment according to Figure 16 (left): $102 per household. The bar is red shaded, because from a user perspective there is no initial investment at all, unless an up-front rental deposit is assumed. Figure 16 (right) shows that the Pico PV system performs best from an ALCC perspective: $42 per year. However, its reliability is 88%, which means that the system has an unmet load equivalent to 44 days per year. The SHS and SCS have an unmet annual load equal to respectively 26 and 40 days, but can be increased as shown in Figure 17.

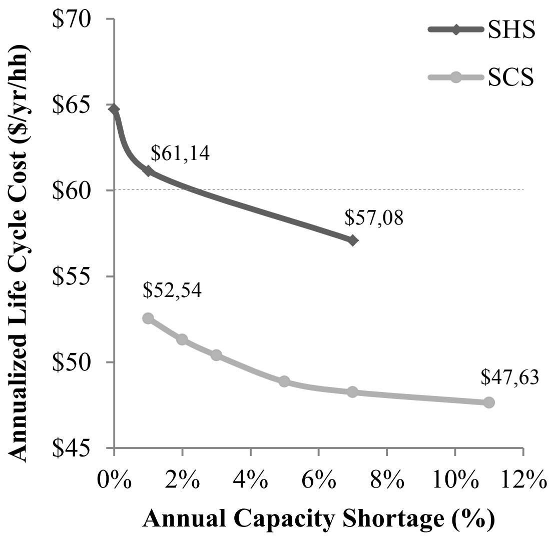
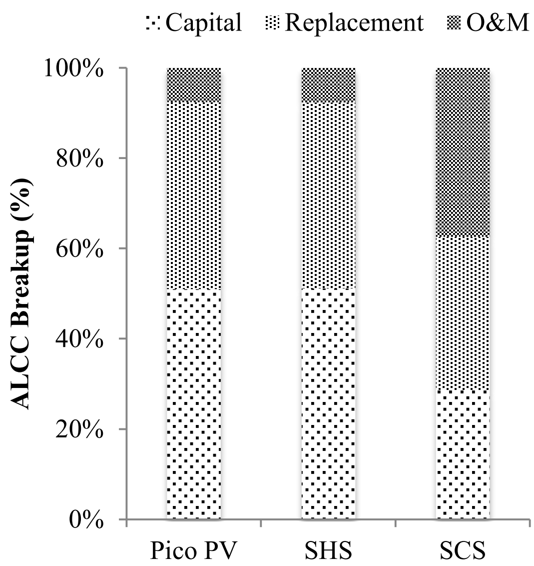


Figure 17 shows the influence of an increased reliability by increasing the PV array, since the battery size of the Pico PV systems is fixed for the SCS. The ALCC increases with 5% for the SHS and 10% for the SCS, when going from the size capacities from Figure 16 to a reliability of 99%. The ability to pay is $60 per year for rural households, given in Table 10. The SHS is not fully affordable by the user, while the SCS option is affordable for all reliabilities. However, the SCS is not able to reach 100% load coverage, unless the battery capacity is expanded.

Figure 17. Increased ALCC for increased reliability

The breakup of ALCC in capital, replacement and O&M costs is shown in Figure 18 (left). About half of the ALCC for Pico PV and SHS constitutes initial capital costs, while O&M has a small share of 8%. For SCS, the O&M share in the cost breakup is significantly larger. Figure 18 (right) shows a cost comparison based on useful light output. The predominantly fuel-based light sources are shown for comparison. They depict a substantially higher cost of useful light output, compared to the PV systems. The SHS performs best from the useful light output perspective: $0.05 per k-lumen-h of light generated. The costs are roughly twice as high for Pico PV and three times as high for the SCS.



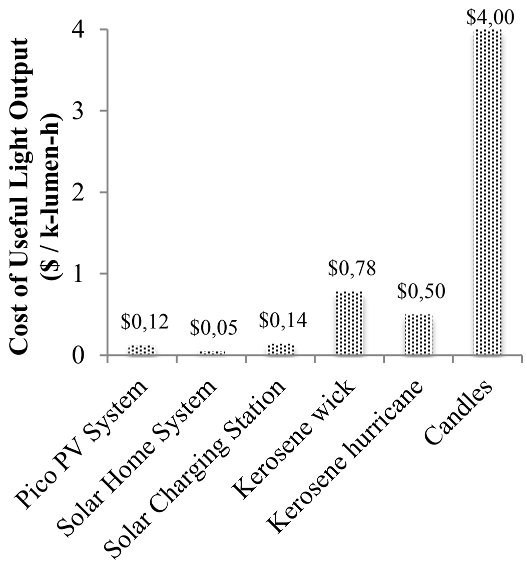


Figure 18. Left: ALCC breakup, right: Cost of Useful Light Output for Pico PV, SHS and SCS

Interpretation Results – Rural Communities

Figure 16 shows the lowest IIC for the SCS. The reason is threefold: (1) A SCS has scale benefits of a centralized PV facility in a community. Small modules are relatively expensive compared to larger ones: \$2.25/W_p for a 10 W_p module and \$2.05/W_p for a 100 W_p module. (2) A SCS has lower losses due to shadow, which reduces PV array costs. The losses due to module shading and dirt are assumed less, since a shade-free site is chosen for the SCS and the operator cleans the PV modules. (3) The capacity oversize per household is reduced.

The investor makes the initial investment of \$102 per household from Figure 16, not the user. The Pico PV systems are distributed on a fee-to-service basis, thus there are no initial investments for the user. The fee to break-even for the SCS annualized costs is \$4.38 per month, or 87% of the SEE. Thus, the SCS is an economically viable concept in providing improved basic energy services to the rural households. This break-even fee is in the range of the \$5 charging fee used in Nicaragua for the Solar Battery Charging Stations project in 2006 from the World Bank (World Bank, 2008). Since the users of a SCS only use the service when they can afford to, a regular payment commitment is avoided. From a user-perspective this is convenient, while the risk of no regular profits for the investor could be substantial as is shown in the just mentioned Nicaragua case. Such risk is reduced when an extensive demand assessment is performed to map people's ability to pay and their energy priorities.

The ALCC from Figure 16 (right) includes capital, replacement and O&M costs, spread out annually over the project lifetime. In contrast to the initial investment cost, the annualized cost is higher than Pico PV for the SCS. Such difference is due to the operational costs for personnel that run the charging station and make repairs. Pico PV and SHS users are responsible for repairs themselves, while SCS repair costs (excluding capital costs of displaced components) are incorporated in the salary of the SCS operator. Besides, the user cost burden for Pico PV and SHS might be higher in reality due to the limited accessibility of rural areas for repair shops.

The component lifetime determines to a great extend the replacement costs. The module's lifetime is longer than the 20-year project period for all systems. Thus, module replacement is not incorporated in the ALCC, which results in dominating battery replacement costs. Figure 18 (left) shows high capital cost shares for Pico PV, which is attributed to the low battery replacement cost (18% of total capital costs). The battery replacement costs for the SHS are 33% of the capital costs. Its similar share of replacement cost as the Pico PV system is explained by the higher battery lifetime of the SHS. The high share of O&M cost for the SCS is caused by the employment of personnel for operating the station. The Pico PV system does not incorporate such operational costs since the user owns it.

Figure 18 (right) shows the distinction in cost of useful light output between the SHS and the other PV systems. The SHS is equipped with CFLs of 5W that produce 250 lumen each. The Pico PV and SCS systems are equipped with LED lamps of 1.2W that produce about 74 lumen each. This difference in power rating leads to a larger sized SHS, and thus higher costs. However, the relatively high costs are surpassed by the higher luminous flux supplied by the SHS. The higher lighting quality represents the distinctive advantage of the SHS.

3.3.2. Peri-urban Community

The results from section 3.1 and 3.2 serve as an input for the optimization in HOMER. Other inputs and assumptions are given in Table 23 from Appendix N. Additionally, for the hybrid micro-grid the power distribution network is optimized with ViPOR, discussed in section 2.3.3. The annualized cost results for the low, middle, and upper energy service level (ESL) are shown in Figure 19. The x-axis shows the reliability as a fraction of the annual unmet load to the total load requirement. The SEE is shown as a dotted line for all three levels in the graph. The curves show a diminishing decrease of costs for a decreasing reliability of the system. In 2010, the user is able to pay for a SHS with 100% reliability for low, 99% reliability for middle and 92% for upper energy service level. Oversizing the PV system at the beginning of the project, to account for load growth up to 2030 does not affect the ability to pay much for the low ESL households. A system up to 99% reliability for the 2030 load requirement is achievable. However, the middle and upper ESL households are affected substantially.

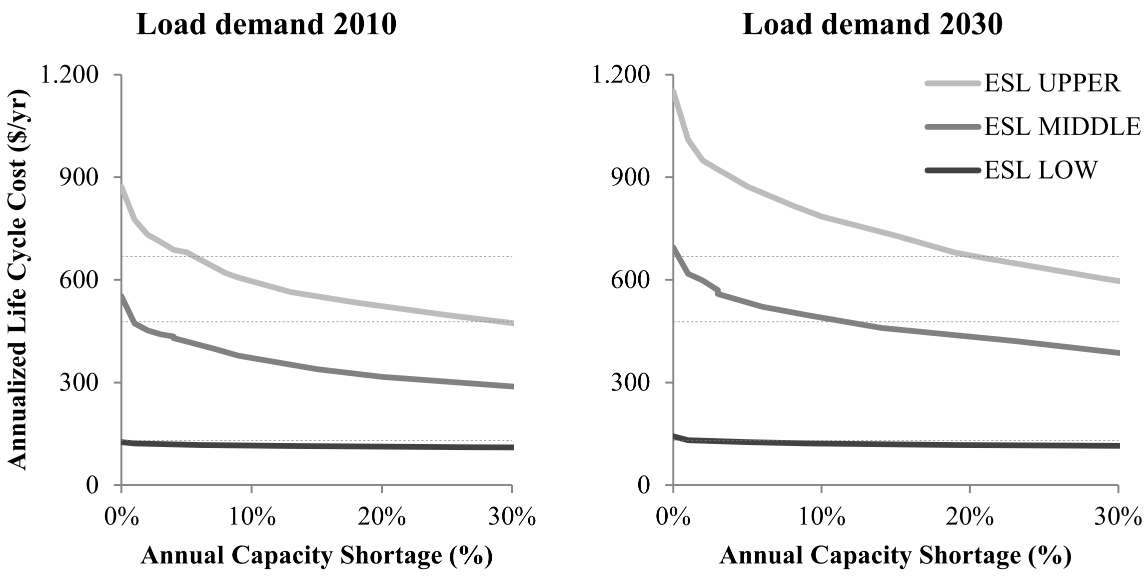


Figure 19. ALCC results for different energy service levels in 2010 and 2030

The cost breakdown for the hybrid micro-grid and its least-cost configuration of the power distribution network (PDN) is shown in Appendix Q for 2010 and 2030. Loads are differentiated in energy service levels and considered on-grid. The hybrid micro-grid is designed to meet 80% of the total load requirement by PV (Hankins, 2010). The rated load of the diesel generator is 30 kW. A real interest rate of 12% is assumed (World Bank, 2010) and a project lifetime of 20 years. Other assumptions are provided in Table 8 and Table 9 from section 2.3.3.

Figure 20 and Figure 21 show the results of the cost comparison between the hybrid micro-grid and the SHS. The total net present costs for the whole system is 216k$ for the load in 2010 and 280k$ for 2030. The expected load growth between 2010 – 2030 results in a cost increase of 29%. This includes all capital, replacement and O&M costs for the system. The PDN accounts for 17% in the total costs for 2010, and 13% for 2030. The annualized PDN cost is roughly $40 per year for each connected load. It is a result of allocating the PDN costs equally for all loads. The centralized PV system costs are allocated on the basis of electricity consumed. In this way, all households equally contribute to the distribution network, but have variable costs according to their electricity consumption patterns.

The annualized PDN cost includes cost of the distribution line network and service connections. It constitutes 87% capital costs and 13% O&M costs. An annualized cost breakdown of the centralized PV system shows 74% PV system costs (PV array, battery bank and PCU), 22% diesel, and 4% O&M.

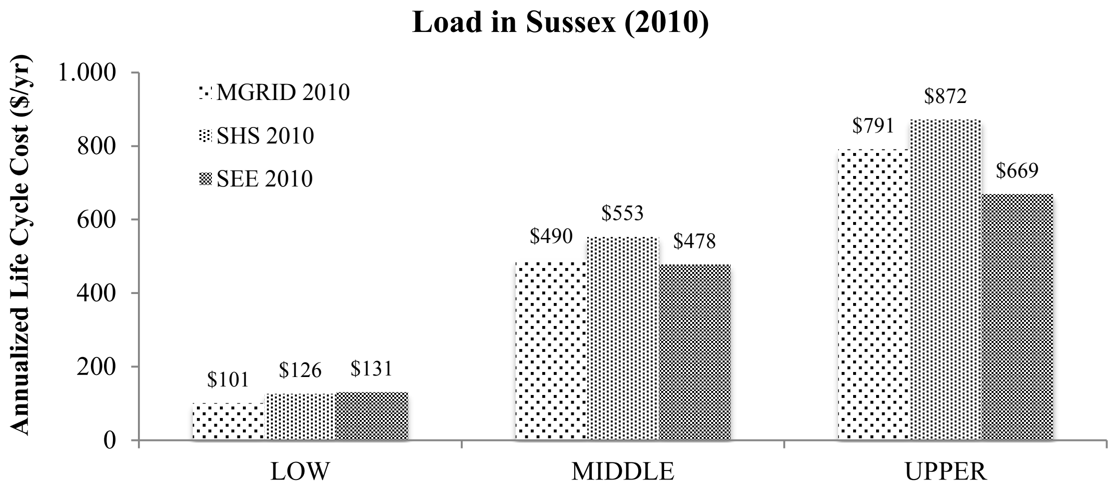


Figure 20. ALCC for low, middle and upper energy service level households in Sussex with daily load 2010

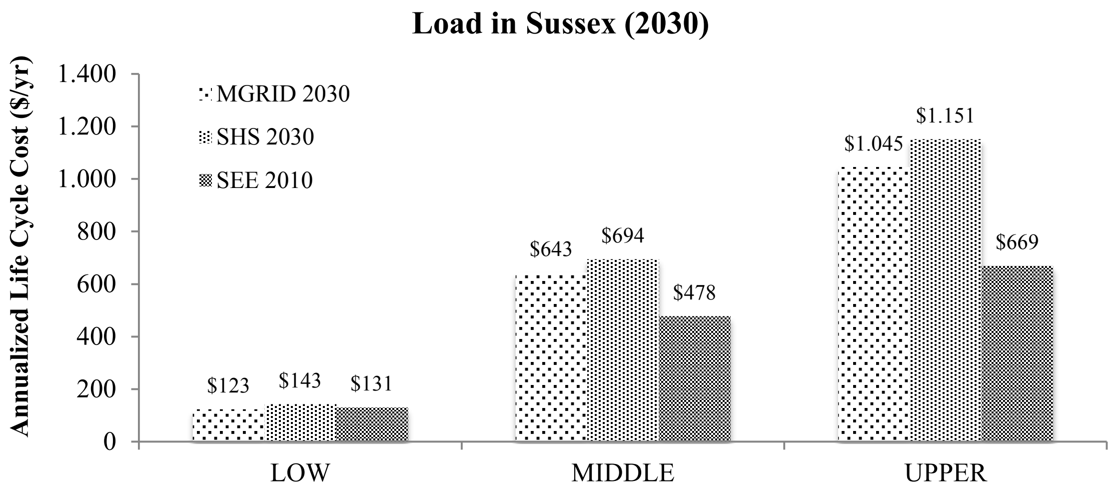


Figure 21. ALCC for low, middle and upper energy service level households in Sussex with daily load 2030

Both Figure 20 and Figure 21 show lower annualized costs for the micro-grid compared to the SHS, with an increasing difference from the low, middle to upper energy service level. That means the micro-grid becomes more cost-competitive with increasing loads. The households classified as *low* are able to contribute fully to the annualized cost of both systems, for the present daily load. However, this is not the case if one considers the expected load requirement in 2030 for the SHS. The *middle* and *upper* households would need to spend more than their SEE in order to cover the annualized costs for both systems. Their willingness to pay more for a PV system will determine the interest in changing their energy supply system. If their willingness to pay is less than the difference in ALCC and SEE, the *middle* and *upper* households need donor-finance schemes to make them economically viable.

Interpretation Results – Peri-urban Community

The capacity shortage for a PV system occurs during the wet season, when cloudy weather reduces the solar power production. The seasonal variability of irradiation requires a well-founded decision on PV array and battery size in its optimization. A consumer ideally wants to have access to affordable and reliable electricity during the entire year. However, a trade-off between these two requires a compromise between costs and capacity shortage. For example, a SHS sized to supply 99% of the total annual load for a household classified as *middle* results in annualized cost of $473 during a 20-year period (Figure 19: left). The reliability of 99% corresponds to roughly four days of unmet load during a year. A *middle* household spends on average $478 per year on substitute fuels and batteries to supply its energy services. That means such a household is able to contribute fully to the system's annualized costs. However, its initial investment amounts $2,554, which is more than 5 years of SEE savings. This shows that a financial scheme that annually amortizes the loan fees for people is essential to make the contribution of the household possible.

Several aspects of the system explain the fact that the hybrid micro-grid is more cost-effective. The cloudy weather during the wet season, indicated by the clearness index in Figure 9, requires much storage capacity for the SHS. The diesel generator of the hybrid micro-grid generates power to meet the demand during cloudy periods. In this way, the system saves on additional module and battery capacity otherwise needed for cloudy days. Also, the daily load profile from Figure 14 suggests that the demand for electricity is high for only a short period during a day. The unequal distribution of electricity demand over the day generates high peak loads. The diesel generator is able to cover the peak loads, and therefore avoids the need for additional battery capacity to cover the peaks. However, the SHS does need the additional capacity to cover the peak load.

The decline of PDN share in the total cost from 2010 to 2030 is explained by the constant PDN costs. The PDN costs only depend on the length of distribution line and the number of service connections. An increase in the daily load hardly affects the PDN costs. The difference between 2010 and 2030 constitutes an increase in daily load without considering any new service connections. The result is a decline in PDN share. In reality the number of households in the community will most probably grow in the period 2010 – 2030. In that case, the decline of 4% in PDN share will be less.

The micro-grid becomes more cost-competitive with increasing loads for the same reason described for the decline in PDN share. The costs for PV array, battery bank and inverter all raise with increasing load requirement. However, the PDN cost stay constant with no change in number of service connections. If the scale benefits and a reduced system capacity for the micro-grid surpass the additional cost for the PDN, an incremental change in load leads to a relatively small change in micro-grid cost compared to a SHS.

The *middle* and *upper* households would need to spend more than their SEE in order to cover the annualized costs for both systems. An alternative is to reduce the reliability of the PV system. The hybrid micro-grid is designed to have no capacity shortage during the year. However, Figure 19 shows that an increase in annual capacity shortage for a SHS substantially reduces its system costs. A SHS with a reduced reliability of 1% for *middle* and 6% for *upper* in 2010 becomes viable for a user, according to its ability to pay. For the daily in 2030 the picture is worse: a reduced reliability of 1% for low, 14% for middle, and 21% for upper. A desirable reliability level is ideally chosen based on people's willingness to pay for reduced capacity shortage.

DISCUSSION

The results presented in Chapter 3 are established using several assumptions. The most important ones are discussed in this section, in the order of the presented results. Further, a short sensitivity analysis is performed and some recommendations for a follow-up study are made.

A reliability assessment of the HelioClim-1 database reveals that monthly averages of daily global horizontal irradiation from the database have a root mean square (RMS) error of 600 Wh/m^2 (Huld*, et al.*, 2005). Such RMS results in a maximum deviation in the monthly irradiation results from Figure 9 of 8 – 16% for actual irradiation conditions, which is more accurate than the 20 – 30% range that interpolation techniques would provide. The monthly irradiation results serve as an input for the optimization in HOMER. The generation of synthetic hourly data in HOMER from the monthly mean typically leads to a less than 5% difference in sizing variables and a less than 2% difference in economical output variables (Lambert, 2004).

The mass of typical units for fuel is determined by measuring its weight on a hanging scale prior to the household surveys, by sample measurements. It is assumed that the mass of the units from the surveys is equal to the measured samples. Deviations in the typical units used in the field compared to the sample measurements will lead to divergent energy use results. Most units are standardized according to a specially assigned cup, pint or bag for purchase, with a known volume, which diminishes possible deviations. However, in the case of firewood the variations in bunch size in the field are substantial. Therefore, the usual price paid for the bunch is used as a measure for its size and weight (Table 18 from Appendix G). The energy expenditure variations are influenced as a consequence of fluctuating fuel prices, Sierra Leonean currency exchange rate (SLL – US dollars), and the inflation rate. However, a report on *International Fuel Prices in 2009* published by GTZ shows that the diesel price in Sierra Leone from 2004 onwards was rather stable (GTZ, 2009). Therefore, the influence of the fluctuating fuel prices during 2010 is assumed non-significant. The effects of the currency exchange and inflation rate fluctuations on the affordability results are assumed negligible, because the substitutable energetic expense results from December 2010 are compared with technology market prices from January 2011.

The end-use applications play an important role in sizing a PV system. The more efficient they are, the lower the energy requirement and the smaller the PV and battery size need to be. From an economic point of view, it could be worth spending more on efficient lamps and appliances while saving costs on your PV system. The household residents need to be aware about this, in order to create the incentive to do so. Besides, the efficient lamps and appliances need to be available at the local market. A decrease in load demand due to efficiency measures leads to a smaller sized system, which in its turn results in lower costs. The cost-effectiveness of an efficiency measure should be investigated in order to lower PV system costs. If the reduction in load demand and its accompanying reduced system costs outweighs the investment in an efficiency measure, it should be incorporated in the detailed project report. Switching from incandescent to fluorescent lamps is an important option to consider. The most widely sold incandescent bulb is 40W, according to the market survey executed in Freetown. The cost-effectiveness of replacing all incandescent bulbs in a community could be evaluated for more extensive research, defining an efficiency multiplier, the capital cost of the efficiency package and the lifetime of the investment.

The selection of a different reference Pico PV system for the cost comparison of various PV systems in rural communities, could lead to divergent results. The chosen reference system complies with norms and standards being developed by Lighting Africa and is therefore considered a high quality system. However, available Pico PV systems vary greatly in product quality. An initial investment cost reduction for a differently chosen system is probable, but will likely adjoin a reduced reliability and lighting quality. Besides, the annualized life cycle cost is expected to be higher in such case, due to a lower battery quality. The chosen reference system is preferred in this study for three reasons: (1) It is able to supply the relevant energy services (lighting, radio use and mobile phone charging), (2) its distribution in Africa is favoured as being a Lighting Africa associate, (3) the technical specifications and recent market prices for its product components are available. Changing the energy service level from Table 11 will also influence the outcome of the cost analysis. For example, if only one lamp per household is required, the Pico PV system will perform better in terms of reliability, because more battery capacity is available to provide lighting.

The relative weight people assign to the cost, reliability and lighting quality of the photovoltaic system prove very relevant to be investigated in a follow-up PV project that uses a demand-pull approach. First, it is useful to know the maximum up-front cost people can bear in purchasing a PV system. Secondly, people's willingness to pay more for a higher reliability is interesting to estimate in order to determine the optimal reliability of a system. Finally, it is relevant how to know how people appraise lighting quality. The difference between CFL and LED lamps lead to high differences in luminous flux and system capacity size. Inquiring the specific activities people carry out after daylight hours could be useful in setting minimum requirements.

The spread of the village, its terrain, the number of service connections and their daily load determine the cost-competitiveness of the hybrid micro-grid compared to the SHS. Also, the diesel price and generator cost are of influence, but depend to a large extent on the chosen renewable fraction. The higher this fraction gets, the smaller their influence becomes. It is assumed that all households equally contribute to the distribution network. However, large loads close to the source location contribute relatively little to the PDN cost in terms of wire length and bear large costs for the centralized system, due to cost allocation based on consumed electricity. On the other hand, relatively far located small loads can significantly increase the PDN costs, but do not contribute substantially in the centralized costs. In order to secure the viability of a micro-grid, such unviable load connections should be avoided. The point that revenues break-even with incremental costs is ideally calculated for each new service connection. Revenues are earned by setting a fee. The ability to pay is relevant to check the feasibility of such fees. The drawback of finding the break-even fees is that it becomes more complex, certainly when terrain types are also taken into account. A solution is to use spatial distribution optimization software like ViPOR to deal with such complexities.

Mounting hardware, transport, installation, operator salary and project overhead costs are not included and prices are taken from a wholesale supplier, excluding VAT. Including the remaining costs most likely favor the SHS, since installation costs for a hybrid-micro-grid are substantial. Reliable data on such costs were not available, but are important for further improvement of the analysis. However, a sensitivity analysis is performed for the SHS to examine the influence of a change in PV system cost, interest rate or daily load on the net present cost. The value ranges used for the analysis are given in Table 13. Figure 22 shows the result of the sensitivity analysis. The PV system cost is the most influencing parameter in the optimized SHS design. Further, the daily load shows also a significant influence. The real interest rate is inversely related to the total net present cost, because a higher rate will diminish the present value of cost incurred in the future of the project.

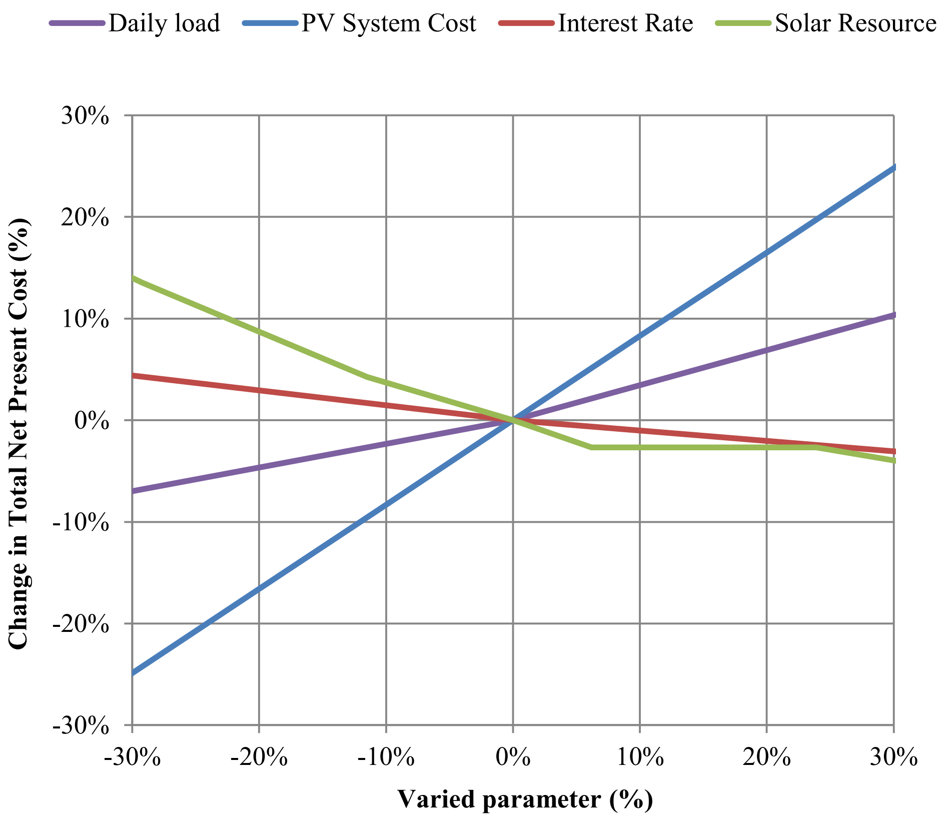


Figure 22. Sensitivity analysis of influential parameters on the total NPC of a SHS (Reference: L_D = 153 Wh/d, total NPC = \$940, i = 12%, l_p = 20 years)

Table 13. The value ranges for parameters influencing the total NPC of a SHS in Sierra Leone

Parameter	*Symbol*	Value range	Unit	Source
Solar resource [1]	I	3 – 8	kWh/m^2/yr	Huld *et al.* 2005
Real interest rate	i	1 – 27	%	TradingEconomics.com: 2000-2010
Daily load	L_D	0.1 – 4.0	kWh/hh/day	Household survey results
PV cost multiplier	C_{PV}	50 – 150	%	Assumption

[1] The solar resource shows considerable geographical variation in Africa (Huld*, et al.*, 2005): roughly 3 – 8 kWh/m^2/day.

In this study is reflected on some critical preconditions for a successful system design, viz. proper sizing and techno-economic efficiency. Some non-technical parameters that influence the success or failure of a PV project are not discussed, such as institutional suitability, system modularity, simplicity and safety. Institutional suitability covers aspects like the willingness of the community to participate in operation and maintenance practices, synergies between locally active NGOs and governmental programmes in respect to the PV electrification project. Modularity is explained by the terms scalable and replicable: scalable to different system sizes and replicable in other locations or countries through easy design adaptation. Simplicity and safety speak for themselves. These non-technical parameters are left out of the analysis, since objective measurable indicators do not represent them. A multi-criteria analysis that includes all these aspects is interesting for a follow-up study. Furthermore, a detailed project report serves as a necessary input for the establishment of a financial framework. So, a follow-up study is preferably focused on other system design preconditions and financial arrangements of the PV project. The results from this study show that the initial investment barrier is significant and should be amortized over the lifetime of the project. In order to achieve such a critical barrier removal, a proper financial framework needs to be constructed.

CONCLUSION

This work portrayed the study of improving domestic energy services in off-grid communities of developing countries by photovoltaic systems. Relevant assessments that precede the implementation of a photovoltaic electrification project were addressed. These assessments were applied to a case study in order to analyse various photovoltaic systems on their cost-effectiveness in achieving improved energy services. Two rural communities and one peri-urban community were studied in Sierra Leone through questionnaire based household surveys.

From a techno-economic perspective a resource, demand and optimization assessment is relevant for improving domestic energy services by photovoltaic systems. The satellite-based irradiation data proved helpful in having readily available and reasonable accurate estimates of the solar resource. The demand assessment of questionnaire based household surveys proved useful to increase understanding about the potential improvements a photovoltaic project could make in a community. Assessing the energy expenditure demonstrated to be very important in determining the affordability of the people and therefore the viability of a user financed project. The optimization proved to be desirable for lowering the risks of poor technical performance in the field and for designing cost-effective systems.

For the rural communities, it was verified that the relative weight of up-front cost, reliability and lighting quality of the photovoltaic system determine the most desirable system in the project design. The solar charging station demonstrated to have the lowest initial investment costs per household, both from a user and investor perspective. Its fee-for-service delivery model proved viable, considering the user's ability to pay for annualized costs. The initial investment barrier for the other systems requires a financial framework that amortizes the costs over the project lifetime in order to realise a user financed photovoltaic project. The Pico PV system showed the lowest annualized life cycle costs. However, its reliability in supplying the defined energy service level is rather limited: a maximum of 88% annual load coverage. Although, the other systems proved to have higher annualized cost, their reliability can be increased against limited incremental costs. The annualized costs of the solar charging station are still affordable by the user if the maximum reliability of 99% is chosen. The user is most probably not able to pay for the solar home system's annualized costs above 93% reliability. For full annual load coverage its viability depends on donor financing. The clear benefit of the solar home system is the low cost of useful light output for the user. The system is costlier, but supplies lighting of a significant higher quality. To conclude, the solar charging station showed the most potential to supply reliable and affordable improved energy services to the rural communities.

For the peri-urban community, it was found that the hybrid micro-grid demonstrated lower costs per connected load for households with a low and middle energy service level, due to scale and capacity reduction benefits. These benefits outweigh the additional costs for the power distribution network. The capacity reduction is made possible by covering daily peak loads and cloudy day shortages with the diesel generator. In contrast, the solar home system needs additional capacity to cover the daily peak loads and cloudy day shortages. On the other hand, the solar home system is more competitive for households with an upper energy service level. The reduced costs due to scaling of the solar home system surpass the mentioned cost benefits of the hybrid micro-grid. Also, a reliability reduction of only 1% makes the solar home system more cost-effective. To conclude, the reliability of the solar home system strongly determines the cost-competitiveness compared to the hybrid micro-grid.

For the peri-urban community, the hybrid PV-diesel micro-grid showed lower annualized life cycle costs compared to the solar home system. However, reliable data on installation costs for both systems are important for further improvement of the analysis. The spread of the village, its terrain, the number of service connections and the daily load determine the cost-competitiveness of the hybrid micro-grid compared to the solar home system. For a hybrid micro-grid, the break-even point of user fee and incremental cost for each service connection is important. The user's ability to pay is relevant to estimate the feasibility of such connection fees. Besides, the use of optimization software for the distribution network increases the viability of the micro-grid. The micro-grid becomes more cost-competitive with increasing loads, because the power distribution network cost stays constant for an equal number of service connections. Once the scale benefits and a reduced system capacity for the micro-grid surpass the additional cost for the distribution system, an increase in load leads to a more cost-effective micro-grid compared to the solar home system. The households classified as *low* are able to contribute fully to the annualized cost of both systems, for the present daily load. The *middle* and *upper* households would need to spend more than their SEE in order to cover the annualized costs for both systems. Their willingness to pay more for a PV system will determine the interest in changing their energy supply system. An increase in capacity shortage for a solar home system substantially reduces its system costs and makes them more affordable by the user. A desirable reliability level is ideally chosen based on people's willingness to pay for reduced capacity shortage.

APPENDIX A. OPTIMUM INCLINATION FOR AFRICAN CONTINENT

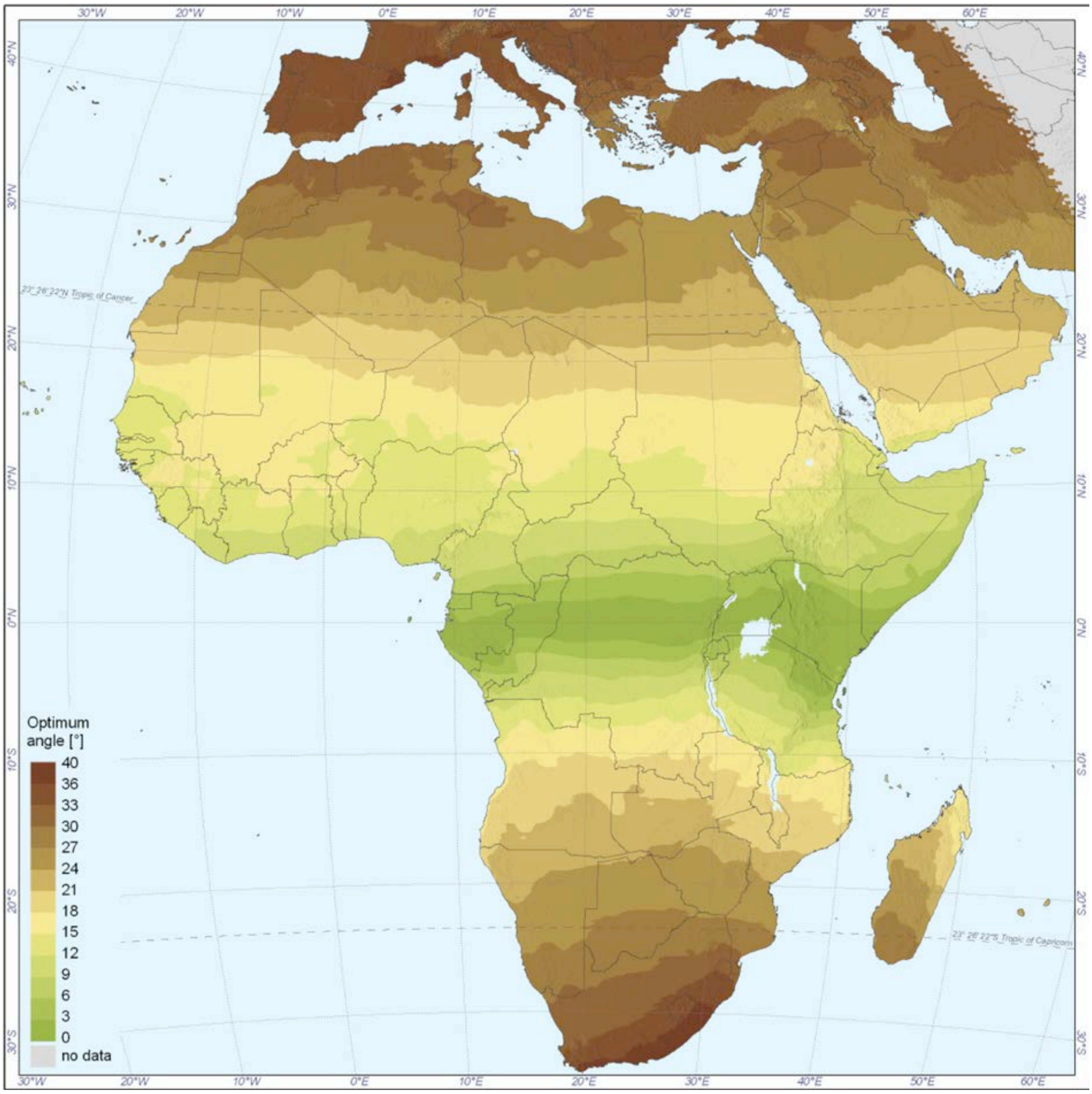


Figure 23. Optimum inclination of equator-oriented modules to maximize yearly energy yield (JRC EC, 2011)

APPENDIX B. DEMAND ASSESSMENT EQUATIONS

Equation 7. Yearly and primary energy use

APPENDIX C. OPTIMIZED SYSTEM DESIGN EQUATIONS

Equation 11. Battery sizing formulas for PV system options (Chaurey, et al., 2010b)

APPENDIX D. COST ASSESSMENT EQUATIONS

Equation 14. Initial Investment Cost formulas

Equation 16. Annualized Capital Life Cycle Cost (Chaurey, et al., 2010b)

APPENDIX E. SATELLITE-BASED MAPS OF TARGET COMMUNITIES

Figure 24. Satellite-based map of peri-urban community Sussex (Lat. 8.347° N, Lon. 13.231° W)

Figure 25. Left: satellite-based map of Mapuma (Lat. 7.590° N, Lon. 11.308° W);
Right: satellite-based map of Jene (Lat. 7.579° N, Lon. 11.345° W)

APPENDIX F. RESOURCE ASSESSMENT RESULTS

Table 14. Monthly average irradiation and clearness index for Sussex, Mapuma and Jene

Month	Sussex ($Wh/m^2/day$)	Clearness Index	Mapuma / Jene ($Wh/m^2/day$)	Clearness Index
January	6,400	0.703	6,170	0.669
February	7,040	0.724	6,570	0.670
March	7,220	0.701	6,260	0.606
April	7,010	0.668	5,790	0.553
May	5,870	0.569	5,310	0.518
June	4,900	0.484	4,610	0.458
July	3,950	0.388	3,930	0.388
August	3,730	0.360	3,630	0.350
September	4,650	0.451	4,180	0.404
October	5,530	0.562	4,920	0.495
November	5,710	0.620	5,280	0.565
December	5,920	0.668	5,620	0.626
Year (average)	**5,650**	**0.575**	**5,180**	**0.525**

APPENDIX G. ENERGY USE DATA

Table 15. Common household use of fuels with their measured mass and volume

Energy carrier	Common Use	Typical unit	Mass / Volume	*Unit*
Firewood	Cooking / Hot water	Extra small bunch	4	*kg*
		Small bunch	6	*kg*
		Medium bunch	8	*kg*
		Large bunch	12	*kg*
		Extra large bunch	20	*kg*
Charcoal	Cooking / Hot water / Ironing	Charcoal bag	15.09	*kg*
		Plastic bag	1.04	*kg*
Cooking gas	Cooking	Gas tank	12.90	*L*
Kerosene	Lighting / Kerosene stove	Pint	0.568	*L*
		Tomato-cup	0.114	*L*
Petrol	Electricity generation	½ gallon rubber	2.273	*L*
		1 gallon rubber	4.546	*L*
		2 gallon rubber	9.092	*L*
		5 gallon rubber	22.73	*L*
Candle	Lighting	Small single piece	0.041	*kg*
		Large single piece	0.081	*kg*
		Small packet (6 p)	0.244	*kg*
		Large packet (8 p)	0.651	*kg*

Table 16. Vinnic dry cell battery technical specifications

Typical local name	Size / IEC	Capacity (mAh)	Voltage (V)	Watt-hours (Wh)
Large size battery	D / R20P	6,500	1.5	9.75
Medium size battery	C / R14P	2,740	1.5	4.11
Finger battery	AA / R6P	940	1.5	1.41
Finger less battery	AAA / R03	380	1.5	0.57

Assumption: in Sussex people predominantly use Vinnic batteries and in the rural communities Tiger battery use is best represented. As a consequence, 100% Vinnic use for Sussex and 100% Tiger use for rural is assumed in the load computation.

Table 17. Tiger dry cell battery technical specifications (calculated values)

Typical local name	Size / IEC	Capacity (mAh) [1]	Voltage (V)	Watt-hours (Wh)
Large size battery	D / R20P	5,014	1.5	7.52
Medium size battery	C / R14P	2,114	1.5	3.17
Finger battery	AA / R6P	725	1.5	1.09
Finger less battery	AAA / R03	293	1.5	0.44

[1] The capacity of Tiger batteries is estimated according to its relative market price, using the formula:

APPENDIX H. MARKET SURVEY IN FREETOWN

Table 19. Selection of the most abundantly available appliances and their specifications

Light bulb	Brand	Type	Lumen	Power rating
Incandescent	Lucky Partners	E27		40
	Philips	B22	410	40
Average				**40 W**
Fluorescent	Energy Saver	Scorpio	-	40
	Philips	Genie	-	5
	Philips	Genie	-	8
	Philips	Genie	570	11
	Philips	Genie	-	14
	Philips	Energy Saver	-	11
	Silvania	B22	-	36
Average				**18 W**

Appliance	Size	Brand	Type	Power rating
Radio		Sonitec	ST-3040	0.2
		Tesco	RAD-108	-
		Lowry	GSRAD0902	-
		Rising	RS 3060	-
		Rising	RS 913A	-
		NAKIVA	GP 8901	-
Average				**0.2 W**
Television	14"	Sharp	14 AG2-S	66
	21"	Sharp	21 AG2-S	88
	14"	Sanyo	CM14SE1M	38
	29"	Sanyo	CM29EF1A	75
	21"	Eurolite	CTV-EL21J1	75
Average				**68 W**
DVD player		Sony	DV-801A	10
		Sharp	12-D709	12
		Philips	DVP5220	10
		Solstar	DVD251 SS	20
		INEC	DVD-977D	25
Average				**15 W**
Stand / Desk Fan	16"	Elekta	EFNS-1661 MKII	55
	16"	Veto	VSF-40B	50
	16"	Atlantic	FT40-1 / FT40-5	40
	16"	Binatone	DF-1650DLX	55
	16"	Shape Trust	ST-1612	40
	16"	Solstar	FS 1601 SS	55
Average				**49 W**
Stereo set		Sanyo	DC-DA1460M	15
		Solstar	MTS 726 SS	50
Average				**33 W**
Refrigerator / Freezer	91	SNK	EL-150RF	83
	350	Eurolite	EL-350K	174
	200	Eurolite	EL-200K	108
	32	Haier	HFH-50	75
	330	Solstar	CF 330B SS	200
	146	Atlantic	BD/C-146	108
	-	Sharp	SJ-20U-G2S	106
	250	Hitachi	R-Z25AG7D	163
Average				**127 W**

Note: It is assumed that the available light bulbs and appliances in Freetown are representative for the actual owned items in the surveyed households.

APPENDIX I. ENERGY USE RESULTS

Table 20. The primary energy use in Sussex, Mapuma and Jene

Energy carrier	Energy content	*Unit*	*Sussex*	*Mapuma*	*Jene*	*Unit*
Firewood	16.0*	*MJ / kg*	25.709	45.987	29.935	*GJ / yr / hh*
Charcoal	30.0*	*MJ / kg*	13.406	2.786	-	*GJ / yr / hh*
Cooking gas	25.7**	*MJ / L*	0.199	-	-	*GJ / yr / hh*
Petrol	34.2**	*MJ / L*	4.515	-	-	*GJ / yr / hh*
Kerosene	36.6**	*MJ / L*	0.942	0.277	-	*GJ / yr / hh*
Candle	45.8**	*MJ / kg*	0.070	0.209	0.104	*GJ / yr / hh*
Capita / hh			7.0	8.4	11.9	*Cap / hh*
E_{prim} / capita			**7.7**	**7.5**	**4.1**	***GJ / yr / hh***

Source: * World Bank (2007) Energy Policies and Multi-topic Household Surveys, p. 47: Tab. A1
** Website: http://astro.berkeley.edu/~wright/fuel_energy.html

Table 21. Number of days in the dry and wet season

Dry season months	Days / month	Wet season months	Days / month
November	30	May	31
December	31	June	30
January	31	July	31
February [I]	28	August	31
March	31	September	30
April	30	October	31
Total days (N_{dry})	**181**	**Total days (N_{wet})**	**184**

[I] Based on a regular year, in a leap year February counts 29 days.

APPENDIX J. QUESTIONNAIRE – FUEL AND ELECTRICITY SOURCE MODULE

Code	**F1**	**F2**				**F3**	***Unit***	**F4**				**F5**				**F6**	**F7**				***Unit***			
Question	Do you use [fuel source] or own [power source]?	Where is the [...] used for?				What do you use to buy the [...]?	What is the mass or volume of [unit of fuel]?	After how many days do you buy or collect a new [unit of fuel] during the dry season?				After how many days do you buy or collect a new [unit of fuel] during the wet season?				What is the price you pay per [unit of fuel]?	How many [batteries] do you use for [energy service]?				Number (#) of appliances used for [energy service]?			
Symbol description	Go to F02-F07 for each question for which the response to F01 was "yes"	C = Cooking	WH = water heating	BH = body heating	I = Ironing			L = lighting	R = Radio use	T = Tape use	R/T = Radio/tape	L = lighting	R = Radio use	T = Tape use	R/T = Radio/tape		L = lighting	R = Radio use	T = Tape use	R/T = Radio/tape	L = lighting	R = Radio use	T = Tape use	R/T = Radio/tape
Fuel Sources	Yes [1]; No [0]	Energy service				Local units	Value *Unit*	# of days				# of days				SLL / unit	# of batteries for				# of units for			
Firewood							*kg*																	
Charcoal							*kg*																	
Cooking gas							*L*																	
Petrol							*L*																	
Kerosene							*L*																	
Small candles							*kg*																	
Large candles							*kg*																	
Batteries	Yes [1]; No [0]	Energy service				Energy service	Brand	L	R	T	R/T	L	R	T	R/T	SLL / unit	L	R	T	R/T	L	R	T	R/T
Large size (D-cell)																								
Medium size (C-cell)																								
Finger (AA-cell)																								
Finger less (AAA-cell)																								
Electricity sources	Yes [1]; No [0]	Energy service				Energy service	Brand	Model								Investment	Year of purchase				Value		Unit	
Generator																							W	
Car battery																							Ah	
Solar panel																							Wp	

APPENDIX K. QUESTIONNAIRE – APPLIANCE MODULE

Code	A1	A2	A3								A4	A5
Question	Do people in your house own [items]?	How many [items] do people in your house own?	Which item do you consider more important [... or...]? Row more important = 1; column more important = 0								How many hours during a day do people in your house use the [items]?	How many days does the mobile phone last before it needs to be charged again?
Appliances			Light bulbs (L)	Radio (R)	Mobile phone (M)	TV (T)	DVD (D)	Fan (F)	Pallo set (P)	Freezer (Fr)		
Appliances	Yes [1]; No [0]	# of items	Abbreviation letter of appliance								Hours / day	# of days
Light bulbs (L)			NA									
Radio (R)				NA								
Mobile phone (M)					NA							
TV (T)						NA						
DVD player (D)							NA					
Fan (F)								NA				
Pallo set (P)									NA			
Freezer (Fr)										NA		

APPENDIX L. DEMAND ASSESSMENT RESULTS

Table 22. Potential daily load for Sussex, Mapuma and Jene

Community	Sussex	Mapuma		Jene	
Light device	CFL	CFL	Pico	CFL	Pico
Unit	kWh / day	kWh / day	kWh / day	kWh / day	kWh / day
Petrol [I]	60.413	-	-	-	-
Kerosene [II]	2.438	0.072	0.017	-	-
Batteries [III]	0.488	0.128	0.189	0.075	0.053
Candles [IV]	0.105	0.049	0.012	0.012	0.003
Total	**63.443**	**0.249**	**0.218**	**0.088**	**0.056**

[I] Based on electricity consumption figures, calculated by Equation 9, since petrol is solely used for running appliances. Assumption: # of bulbs * 40W * # of hours daily use (*X*); for bulb 1: 100% * *X*; for bulb 2: 50% * *X*; for bulb 3-6: 25% * *X*; for bulb >6 10% * *X*, since the more bulbs are owned, the lower their utilization factor becomes. A person is only able to estimate for how long they use their bulbs for lighting daily, rather than for how long each bulb is switched on in the house.

[II] Calculated by Equation 1. Assumption: 2 simple wick lamps + 1 hurricane lamp per household, no pressurized lamps. The justification for this assumption is that 54% of households live in a 1 or 2 room dwelling (SLL, 2004), and people tend to use one lamp per room and at least one outside the house for social activities. Luminous flux figures are taken from Table 2.

[III] CFL: calculated by taking the energy content of consumed batteries; Pico: calculated by Equation 10.

[IV] Calculated by Equation 1. In households mostly two candle sizes are used, stated in Table 15 as *small* and *large*. Their respective weights are 41 and 81 grams, determined by sample measurement.

APPENDIX M. ASSUMPTIONS PICO PV AND SCS

Pico PV Systems

The average DoD per cycle is used to estimate the battery lifetime. Battery temperature and deep discharges or high discharge rates are not considered, since a charge controller will prevent deep discharges and the loads will not cause high discharge rates. The lifetime of the HRL645 lead-acid (PbA) gel battery of the reference Pico PV system is approximately 650 cycles at the 80% original capacity level, assuming 50% DoD (Figure 26). The days of autonomy for the evaluated Pico PV systems is found with the solver function, fixing the average DoD to 50%, since the rated cycle life for this value is known from Figure 26: 650 cycles at 80% capacity. In the case of Pico PV the user becomes the owner of the system. A local dealer will provide the system for a retail price to the user.

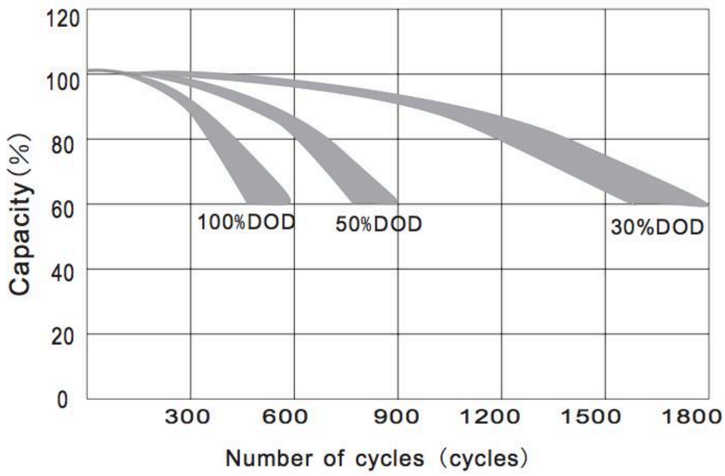


Figure 26. Rated cycle life for Pico PV (SunTransfer GmbH, 2010)

Solar Charging Station

The SCS option is a decentralized village PV facility, which generates solar power to charge multiple Pico PV systems. In this case study, the SCS provides lighting (ST2), radio use and mobile phone charging, differentiated in ESLs. The Pico PV systems are distributed among the households in the community on a fee-to-service basis. The user fees for fill-ups cover maintenance and replacement of batteries. The project developer purchases all Pico PV systems for a wholesale price, excluding the small PV module. That means, $C_{0,batt,Pico}$ for SCS > $C_{0,batt}$ for Pico PV.

APPENDIX N. ASSUMPTIONS HOMER OPTIMIZATION ASSESSMENT

Table 23. Technical inputs to HOMER for an individually owned solar home system in Sussex

	Type	Size	Capital	Replacement	O&M	Sizes to consider	Lifetime
PV Input [1]	sc-Si / mc-Si	10 – 175 W	$ 2.05 – $2.25 / W	$ 2.05 – $2.25 / W	-	10 – 4,200 W_p	25 years
Battery Input [2]	6V VRLA gel	180 Ah	$ 240	$ 240	$ 4.80/yr	2 batt/string: 12V	Variable
Inverter [3]	Pure Sine	180 – 1,600 W max.	$80 – $610	$80 – $610	-	180, 350, 750, 1,600 W	15 years
Charge controller	PWM type	6 amps	$39	$39	-	6 amps	25 years

[1] Source: Wholesale supplier EFA. Inclination: 14°, azimuth: 0°, albedo: 20%.

[2] Source: (Deka, 2011): charge-discharge efficiency: 85%, minimum state of charge: 40%, life throughput: 578 kWh.

[3] Source: peak efficiency: 90% (Hankins (2010), p. 71). Economics: i = 12%, l_p = 20 years, dispatch strategy: load following. Loads are 100% covered during the year. Operating reserve: 10% of hourly load.

Table 24. Assumptions made for the hybrid PV-diesel micro-grid in Sussex

	Type	Size	Capital	Replacement	O&M	Sizes to consider	Lifetime
Generator[1]	Diesel generator	30 kW	$ 500/kW	$ 400/kW	$ 0.015/h	30 kW	25,000 hours
PV Input[2]	sc-Si	175 W	$ 359	$ 359	-	14.0 – 52.5 kW	25 years
Battery Input[3]	2V VRLA gel	1,380 Ah	$ 980	$ 980	$ 19.60/yr	12 batt/string: 24V	Variable
Inverter-charger[4]	Pure sine	3,000 W max.	$ 1,710	$ 1,710	-	3.0 – 18.0 kW	15 years

[1] Source: (ARE & USAID, 2011): minimum load ratio: 30%.

[2] Source: (PVGIS, 2011): inclination: 14°, azimuth: 0°, albedo: 20%.

[3] Source: (Deka Solar, 2007): charge-discharge efficiency: 85%, minimum state of charge: 40%, life throughput: 2,314 kWh.

[4] Source: EFA (2011); peak efficiency: 90% (Hankins (2010), p. 71). Economics: i = 12%, l_p = 20 years, dispatch strategy: load following. Loads are 100% covered during the year. Operating reserve: 10% of hourly load.

APPENDIX O. ASSUMPTIONS SOLAR HOME SYSTEM

The influence of the DoD on the SHS battery life cycle is shown in Figure 27 (right) for Valve-Regulated Lead-Acid (VRLA) gelled electrolyte (gel) and Absorbed Glass Mat (AGM) batteries. The curves are based on BCl 2-hour capacity tests.

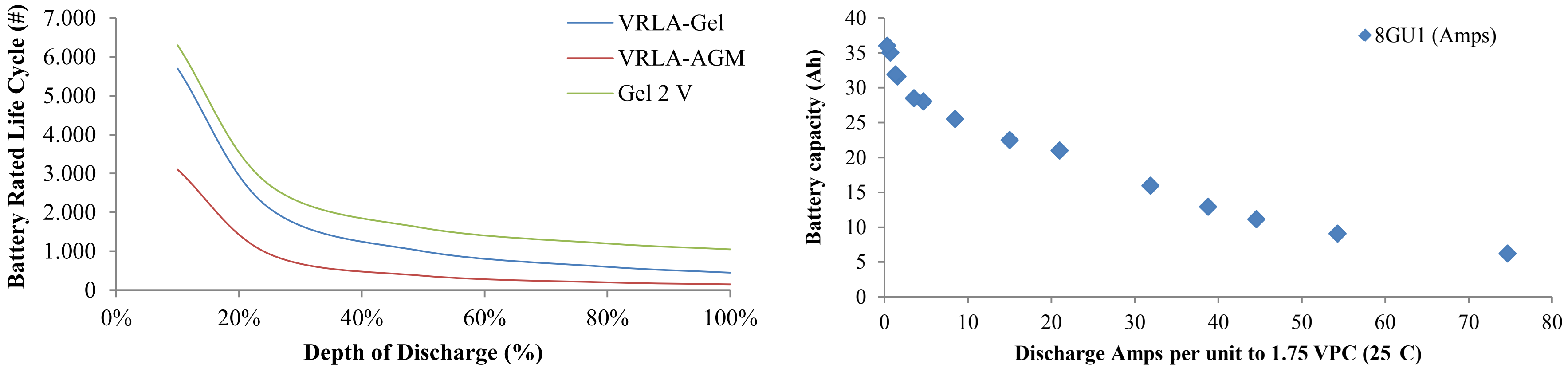


Figure 27. Left: Gel/AGM batteries (Deka Solar, 2007); right: capacity curve for 12V VRLA gel battery

Table 25. Technical characteristics of available DC lamps

Brand Unit	Type DC-bulbs	Lum. flux (Φ_v) Lumen (lm)	Power rating (P) Watt (W)	Efficacy (E_c) lm/W	Capital cost (C) US dollars ($)	Lifetime (l) Years (yr)	CRF (α) Dimensionless	ALCC $ / yr	E_c / ALCC ratio lm/W / $/yr
Steca Solsum	**ESL 5**	**250**	**5**	**50**	**9.00**	**5.7**	**0.251**	**2.26**	**22**
	ESL 7	370	7	53	9.00	5.7	0.251	2.26	23
	ESL 11	650	11	59	9.00	5.7	0.251	2.26	26
Phocos	CL 1205	250	5	50	9.00	5.1	0.274	2.46	20
	CL 1207	350	7	50	9.00	5.1	0.274	2.46	20
	CL 1211C	630	11	57	9.00	5.1	0.274	2.46	23
	CL 1211W	670	11	61	9.00	5.1	0.274	2.46	25

CRF = capital recovery factor, ALCC = annualized life cycle costs. The light bulb type with the lowest power rating and highest lifetime is chosen for the cost assessment: Steca Solsum ESL5.

APPENDIX P. INPUTS PV SYSTEM OPTIMIZATION FOR RURAL HOUSEHOLDS

Table 26. Load requirement for one light point for different PV system options

Description	Symbol	Pico PV	SHS	SCS
Light bulb power rating (*W*)	P_i	1.19	5	1.19
Daily use (*h/day*)	U_i	4.3	4.3	4.3
Power rating (*W*)	P_i	1.19	5	1.19
Daily use (*h/day*)	U_i	4.3	4.3	4.3
Load requirement (*Wh/day/hh*)	$L_{D,hh}$	17.94	67.18	17.94
Load requirement (*Wh/day/com*) [I]	$L_{D,com}$	681.8	2552.8	681.8

[I] The load requirement for Pico PV and Solar kiosk option are identical, since both options use Pico PV systems for light provision.

Table 27. Output parameters concerning technical efficiency

Description	Symbol	Pico PV	SHS	SCS
Battery size requirement (*Ah*)	C_{batt}	4.5	13.9	4.5
Nearest available battery size (*Ah*) [I]	$C_{batt,A}$	9.0	31.6	9.0
Oversize battery capacity (*Ah/hh*)	$C_{PV,O}$	4.5	17.7	4.5
Average depth of discharge (%)	*DoD*	50%	44%	50%
Battery lifetime (years)	l_{batt}	1.8	3.1	1.8
PV module size requirement (*Ah*)	C_{PV}	9.4	27.2	282.0
Nearest available PV module size (W_p) [I]	$C_{PV,A}$	10.0	30.0	300.0
Oversize PV module capacity (W_p/*hh*)	$C_{PV,O}$	0.6	2.8	0.5

[I] The nearest available battery and PV module size is used to minimize the initial investment costs.

[II] The available battery capacity with the lowest ALCC is used to minimize annualized life cycle costs.

Table 28. Cost results of the PV system options for rural communities

Technology	*Parameter*	*Initial Investment Cost*	*Cost Breakup*	*Annualized Capital Life Cycle Cost*	*Lifetime (years)*	*Annualized Replacement Life Cycle Cost*	*Annualized O&M Cost*	*Total Annualized Life Cycle Cost*	*Cost of Useful Light Output*
Pico PV System	PV module (10 W_p)	$56.07	35%	$7.51	20	-	-	$7.51	
	PowerBox (9 Ah)	$28.33	18%	$3.79	1.8	$14.82	-	$18.61	
	LED lamp	$17.71	11%	$2.37	19	$0.04	-	$2.41	
	Controller, BOS	$57.25	36%	$7.67	10	$2.47	-	$10.13	
	O&M						$3.19	$3.19	
	Total per household	**$159.37**	**100%**	**$21.34**		**$17.32**	**$3.19**	**$41.85**	**$0.12**
	Total (community)	**$6,055.96**	**-**	**$810.76**				**$1,590.19**	
Solar Home System	PV module (30 W_p)	$66.00	30%	$8.84	25	$(0.18)	-	$8.65	
	Battery 12V (31.6Ah)	$72.00	33%	$9.64	3.1	$19.47	-	$29.11	
	Controller (6 amps)	$39.00	18%	$5.22	15	$0.59	-	$5.81	
	Light bulb	$27.00	12%	$3.61	5.7	$3.20	-	$6.82	
	Balance-of-System	$9.90	5%	$1.33	10	$0.43	-	$1.75	
	O&M						$4.36	$4.36	
	Installation	$4.28	2%	$0.57			-	$0.57	
	Total per household	**$218.18**	**100%**	**$29.21**		**$23.51**	**$4.36**	**$57.08**	**$0.05**
	Total (community)	**$8,290.76**	**-**	**$1,109.96**				**$2,876.30**	
Solar Charging Station	PV array (3 x 100W_p)	$615.00	16%	$82.34	25	$(1.71)	-	$80.63	
	PowerBox (38 x 9Ah)	$1,076.61	28%	$144.14	1.8	$563.04	-	$707.18	
	LED lamp (3x)	$672.88	17%	$90.08	19	$1.48	-	$91.56	
	PowerBox hardware	$957.74	25%	$128.22	10	$41.28	-	$169.50	
	Controller (20 amps)	$63.00	2%	$8.43	15	$0.96	-	$9.39	
	Balance-of-System	$184.50	5%	$24.70	10	$7.95	-	$32.65	
	O&M						$77.60	$77.60	
	Personnel costs						$600.00	$600.00	
	Installation	$310.41	8%	$41.56			-	$41.56	
	Total per household	**$102.11**	**-**	**$13.67**		**$16.13**	**$17.83**	**$47.63**	**$0.14**
	Total (community)	**$3,880.15**	**100%**	**$519.47**		**$613.01**	**$677.60**	**$1,810.08**	

APPENDIX Q. VIPOR OPTIMIZATION RESULTS

Table 29. Cost breakdown of ViPOR optimization results for a hybrid PV-diesel micro-grid in Sussex

	Total Net Present Cost ($)	Initial Capital Cost ($)	Total Annualized Cost ($/yr)	Annualized Capital Cost ($/yr)	Annual O&M Cost ($/yr)	Annual Fuel Costs ($/yr)
Micro-grid 2010	183,496	134,630	24,382	18,024	1,018	5,340
PDN 2010	32,797	28,871	4,337	3,760	577	-
Total	216,293	163,501	28,719	21,784	1,595	5,340
Total per load	**1,966**	**1,486**	**261**	**198**	**15**	**49**
Micro-grid 2030	246,191	187,092	32,578	25,048	1,801	5,729
PDN 2030	33,366	29,363	4,409	3,822	587	-
Total	279,557	216,455	36,987	28,870	2,388	5,729
Total per load	**2,541**	**1,968**	**336**	**262**	**22**	**52**

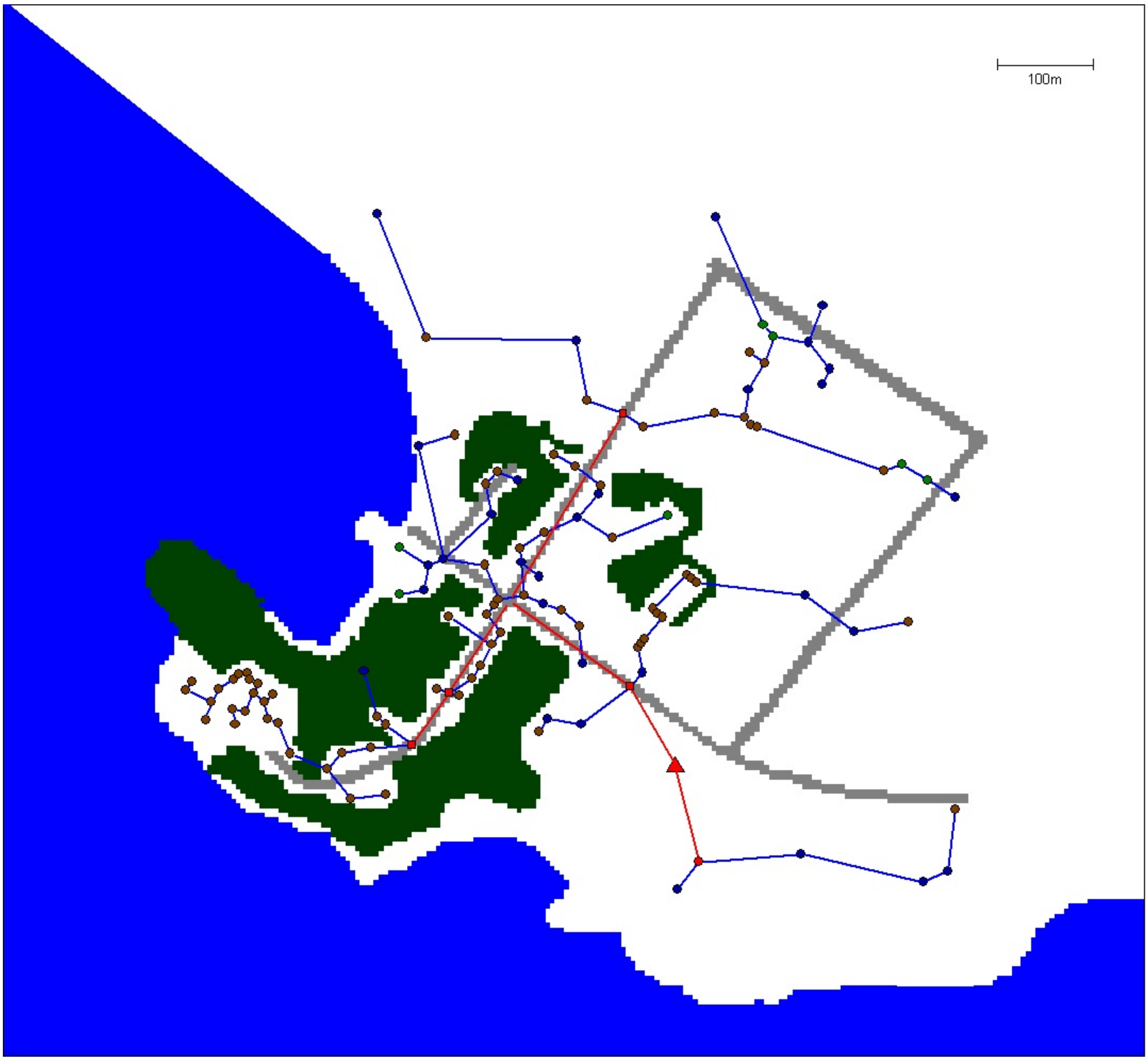


*Figure 28. Least-cost hybrid PV-diesel micro-grid power distribution network for 2010 in Sussex**

* The red lines are medium voltage, while the blue lines are low voltage. The triangle is the source location and the dots are the loads (braun = low ESL; blue = middle ESL; green = upper ESL).

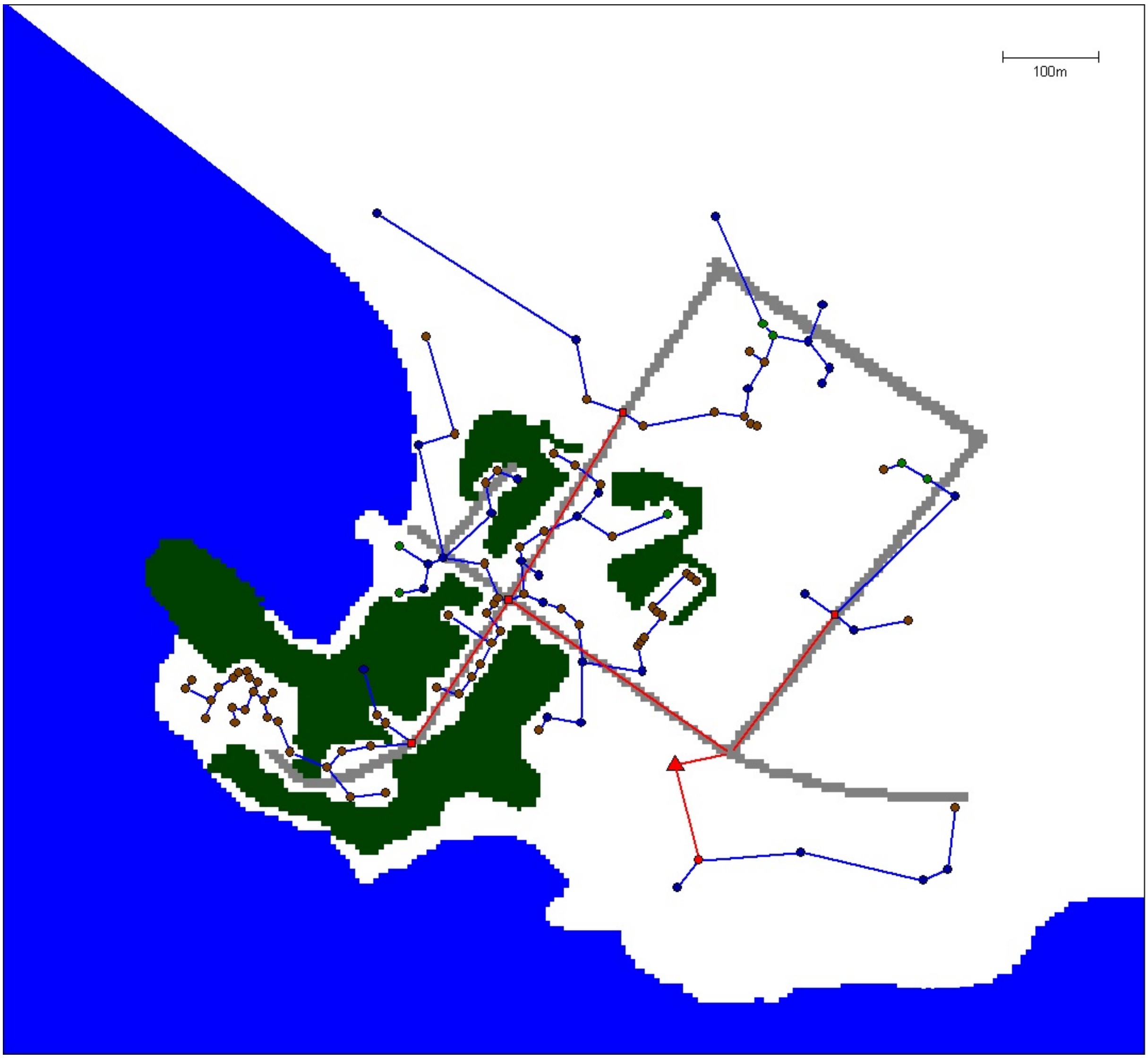


Figure 29. Least-cost hybrid PV-diesel micro-grid power distribution network for 2030 in Sussex

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