

A socio-technical approach to increasing the battery lifetime of off-grid photovoltaic systems applied to a case study in Rwanda



Andrew F. Crossland ^{a,*}, Oghenetejiri H. Anuta ^b, Neal S. Wade ^b

^a School of Engineering and Computing Sciences, South Road, Durham University, Durham DH1 3LE, UK

^b School of Electrical and Electronic Engineering, Merz Court, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

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ABSTRACT

Off-grid solar photovoltaics (PV) are promoted as an economical renewable energy system for providing electricity in remote locations far from the grid. However, without on-going maintenance, the performance of these systems will diminish due to battery deterioration leaving them unable to provide the service they were initially designed for. This paper presents analysis and results from a four week cross-disciplinary investigative study carried out in September 2012 into the performance of off-grid PV in health centres and schools in rural communities in Rwanda. A socio-technical approach was taken to understand the reasons for failure. A strategy was subsequently developed to influence user behaviour and increase the PV array size to reduce capacity shortage through the year and improve the lifetime of the lead acid batteries found on these systems. According to the results obtained, the total costs to implement off-grid PV systems can be reduced. Furthermore, the proposed strategy reduces the operating costs of PV below that of a diesel generator according to a projection of prices found in Rwanda which is important in a donor led installation model.

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1. Introduction

One fifth of the global population do not have any access to electricity and therefore to important services that rely on or are enhanced by electrical energy such as lighting, communication and labour saving devices [1]. These 1.3 billion people are not spread evenly across the world and lack of access is particularly acute in rural areas of middle and low income countries.

Throughout much of Africa, the cost of connecting to the grid is prohibitively high for small communities distant from existing grid infrastructure [2,3]. For example, it was revealed from interviews with the Rwandan utility, EWSA, that the cost of power connection to the grid is \$US 23,000 per kilometre. In 2008, 40% of Africans had access to electricity, but in sparsely populated rural areas this figure was just 23% [4]. Rural communities supplied with electrical energy are expected to see improvements to quality of life [5]. The availability of electricity increases the human development index of rural households, when compared to households without [6,7].

Diesel generators and off-grid solar photovoltaics (PV) are two technologies for providing power in these locations and their

capital and operational costs have very different characteristics. Both the initial purchase of the off-grid PV system and periodic replacement of the storage battery comprise the majority of the costs of a solar PV system, with zero fuel cost; whereas diesel generators have a relatively low purchase price, but substantial and on-going fuel and maintenance costs. Szabó et al. compare the cost of these alternatives across the African continent in areas where grid connection is unfeasible and find a number of regions where PV is an attractive alternative to diesel as illustrated in Fig. 1 [3]. There are also in-country differences, for example it can be seen that in Rwanda (see white arrow) there are regions where diesel is more feasible and regions where PV is more feasible.

Off-grid PV systems are widely promoted as a means to provide cleaner, safer, more reliable and convenient electricity in rural areas [8]. Off-grid PV systems comprise a solar array, a maximum power point tracker/charge controller, inverter, battery bank and electrical loads. Sometimes hybrid systems are used which include a diesel generator to provide backup power when there is insufficient power generated from the PV array or batteries. The battery bank serves four primary functions:

- preventing power interruptions if clouds or shading reduce PV output during the day;

* Corresponding author. Tel.: +44 7960 443783.

E-mail address: a.f.crossland@gmail.com (A.F. Crossland).

Nomenclature

A	surface area of each PV panel [m^2]	N_{nom}	battery cycle life at a given depth of discharge for a cycle starting at a full state-of-charge [number of cycles]
c_G	irradiance coefficient: the percentage change in efficiency of the panel for each unit change in irradiance [$\%/(W/\text{m}^2)$]	$P_{b,t}$	power out or into the battery bank at time t [kW]
c_T	temperature coefficient, the percentage change in efficiency of the panel for each unit change in temperature [$\%/^{\circ}\text{C}$]	$P_{d,t}$	electrical demand on the PV system at time t [kW]
C	total capacity of the battery bank [kWh]	$P_{PV,t}$	power output from the PV array at time t [kW]
D_d	depth of discharge of battery over a daily cycle [%]	SoC_t	battery bank state-of-charge at time t [%]
$E_{b,t}$	energy stored in the battery bank at time t [kWh]	$SoC_{\text{min},d}$	lowest state-of-charge over a given day [%]
G_t	irradiance at time t [kW/m^2]	Δt	length of time step [s]
L_t	remaining cycle life of battery bank at time t [%]	T_t	ambient temperature at time t [$^{\circ}\text{C}$]
n	number of panels in the array	η_b	battery round trip efficiency [%]
$N_{c,t}$	battery cycle life modified by the final battery state-of-charge, at time t [number of cycles]	η_c	efficiency of the inverter [%]
		η_{PV}	efficiency of the PV array at a given irradiance and temperature [%]
		η_{nom}	efficiency of PV panel at standard test conditions ($1 \text{ kW}/\text{m}^2$, 25°C) [%]

- providing power during the night;
- providing autonomy during a prolonged period of poor weather;
- provision of instantaneous power greater than the PV array rating.

It has been recognised that battery replacement can be a substantial on-going cost, and contributes significantly to the overall system lifetime cost [9,10]. Battery life is reduced when the batteries are deeply discharged, when there is prolonged operation at low states of charge or when they are overcharged [11]. Studies consider the battery lifetime to be between 3 and 5 years [3,12,13], although lifetimes up to 9 years for lead acid batteries have been reported [11]. A number of connected socio-technical factors cause deep battery discharge including growth in demand leading to

overloading, poor system design, low-cycle life of existing battery technology, poor component selection, vandalism and theft, and poor system understanding [6,14–17]. Although widely treated separately, few studies take an interdisciplinary approach to how social and technical factors affect battery life. In view of the significant effect on the battery system attributed to the decisions of both operators and users, Ulsrud et al. highlight the importance of a socio-technical approach to assessing this type of system [18]. Socio-technical approaches are recognised as important in several research areas, particularly for energy systems where both the actions of people and limitations of technology are important factors [19].

Standalone diesel generators are the most common off-grid electrical power source in rural locations [20]. However, high fuel and maintenance costs are problematic for owners. A study by Szabó et al. shows that the cost of diesel in Rwanda relative to other countries in Africa is high due to fuel taxation [3]. It is also challenging to transport fuel in rural areas due to bad roads and long distances to fuel suppliers. Furthermore, poor road conditions are compounded during the rainy season. Schmid et al. show that in Brazil these logistical barriers increase the costs of diesel by 15%–45% [21]. Consequently, renewable energy from micro hydro, wind and solar are being adopted in rural areas, in part due to an assumption that operating costs are lower—despite high battery replacement costs [10].

This paper presents a socio-technical field study of the factors affecting real off-grid systems using measured demand data, system surveys and interviews. The results are used to illustrate how installers can improve the cost competitiveness of off-grid PV systems relative to diesel generators. This work is based upon a survey completed in Rwanda in September 2012.

1.1. Paper structure

Technical and social data from PV systems in Rwanda are used to determine ways of improving battery life and system reliability. The methods for data collection and analysis are outlined in section 2 and a description of the modelling approach is presented in section 3. Section 4 presents the findings at specific sites and the impacts of applying a socio-technical change on system performance. Section 4 also presents a financial comparison of off-grid solar PV to diesel systems. Finally a discussion of findings and conclusions are presented in sections 5 and 6 respectively.

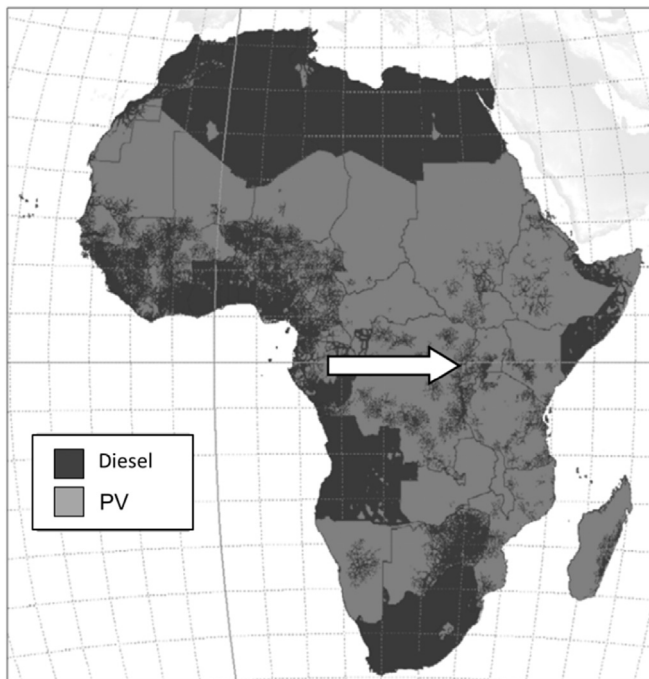


Fig. 1. Regional differences in the feasibility of PV and diesel across Africa. The arrow marks the location of Rwanda [3].

2. Data collection

2.1. Study area

Rwanda is located in equatorial east Africa and has a temperate climate. The annual average daily solar radiation in Rwanda (4.8–5.5 kWh/m²/day) is favourable for PV [22,23]. Partly as a consequence of this, the Government of Rwanda (GoR) is considering PV to supplement the power grid [24]. Under the GoR “Vision 2020” plan, there are targets for 35% of the population to be electrified by 2020 [25] and policies by the GoR have led to rapid electrification rates of over 400% between 2000 and 2012. However, 98.7% of the 8.2 million rural population remain unconnected to the grid [26,27]. In many cases, grid connection to these people will be difficult and expensive to accomplish as the current grid infrastructure is relatively small, aged, inefficient, and experiences regular disruptions in supply [23]. With a current available generation capacity of 83.2 MW, Rwanda derives 48% of capacity from diesel and heavy fuel oil thermal generators, which are expensive.¹ Consequently, the electricity tariff in Rwanda is one of the highest in the region at \$US 0.24/kW, this is in comparison to \$US 0.06/kW in Burundi, \$US 0.05/kW in Tanzania, \$US 0.17/kW in Uganda and \$US 0.16/kW in Kenya [28,29].

The Vision 2020 plan has a target for 5 MW of generation capacity from renewable energy (PV, micro-hydro, wind) and 100% electricity access for schools, health facilities and government offices through the grid or off-grid systems [24]. More than \$28 million was invested by the GoR and partners into solar PV programmes between 2009 and 2012 [30] including the installation of solar PV for 300 schools over 5 km away from the grid [31]. PV systems are also donated by foreign organisations, often in partnership with the GoR, to provide electricity for health centres and schools located in remote areas. The performance of these systems in health centres and schools presents a representative sample upon which this study is based.

The results presented here are based on a social and technical survey of ten PV systems installed at eight health centres and one school in Rwanda (one large health centre had two independent PV systems). The location of these systems is shown in Fig. 2 with three north western systems near to the town of Ruhengeri, two south eastern systems near to the town of Rusumo, three central systems near to Lake Mugasera and a school south of Lake Muhazi. The research was conducted in September 2012.

2.2. Data collection method

Semi-structured interviews were conducted with managers and/or technicians at each site. Areas of inquiry included the benefits and problems of off-grid PV systems, availability of energy, impact on health and education, the level of understanding and general perceptions. Load surveys were used to determine the connected equipment and usage patterns. This included, where possible, the installation of a smart meter to measure energy consumption. A system survey [32] was used to assess the quality and configuration of the PV array, battery bank, converter/inverter, wiring, system enclosure and surrounding environment.

Weather data was provided by the Rwanda Meteorological Service for locations in the vicinity of the sites. This data provides an annual time series of the irradiance G_t and ambient temperature, T_t at one-minute resolution. Significant variation in the irradiance is found in this data with times during the day where there

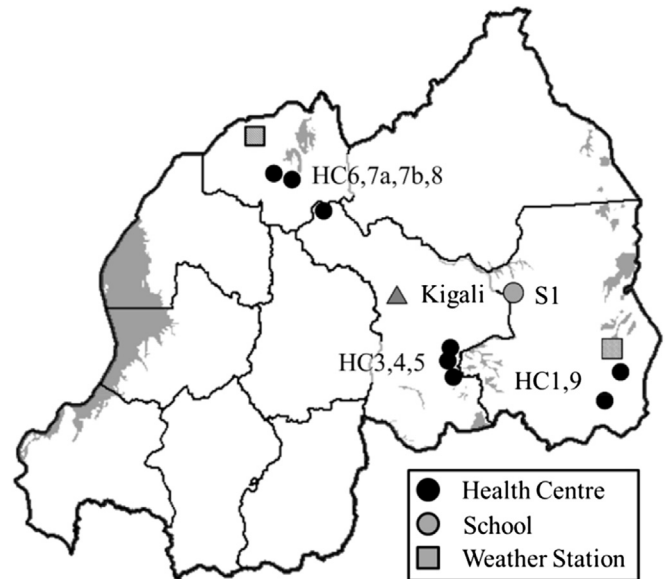


Fig. 2. Location of survey sites and weather stations in Rwanda. The capital, Kigali, is shown alongside main administrative regions (provinces) and major water masses.

is very low irradiance (<100 W/m²) particularly during the rainy season and times of high irradiance (>800 W/m²) during the dry season. Over a year, temperatures range from 16 °C in the early morning to 32 °C in the mid-afternoon.

2.3. Data collection results

2.3.1. System type and use

The size of the systems seen in Rwanda are summarised in Table 1. System capacity ranges from 1.4 kWp to 3.4 kWp and a much larger variation in battery bank capacity. There is little correlation between the two, indicating differences in energy requirements at the sites and/or design practices between installers. The majority of systems were stand-alone PV, although the grid and diesel generators were available at some sites. Systems were between 3 and 72 months old and in various states of usability.

The most important benefits of electricity provision at rural health centres and schools were found to include security/safety lighting and computers for communication and administration. Medical benefits include keeping vaccines cool on site, sterilizing equipment and avoiding the use of kerosene lamps in maternity wards. At health centres, a variety of laboratory equipment was found, with the most common being centrifuges, haematology analysers and humalysers, microscopes, and rotators. Sterilizers were less common. Vaccine fridge freezers were at all of the health centres although they were disconnected when problems occurred with the PV system. In schools, lighting allows students to study at night. Lighting was provided by a mixture of fluorescent tubes and CFL energy saving bulbs at all of the sites. Typical load profiles for health centres and schools are shown in Fig. 3. It can be seen that health centres have consumption almost 24-h a day which highlights the need for the battery to provide power at night. Schools were found to have a high demand in the day to power lights and administration equipment and in the evening to provide lighting for homework clubs and entertainment equipment.

2.3.2. Problems identified on sites

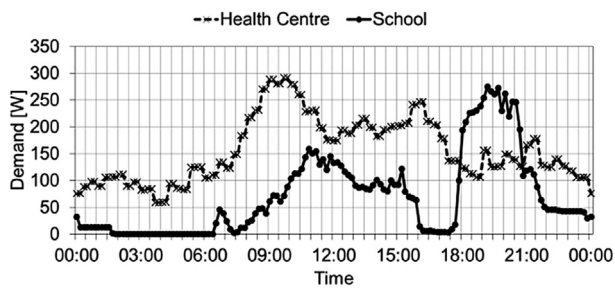
Interviews with installers and users confirmed that battery life was the key limiting factor of system performance in Rwanda. The survey revealed a number of factors which reduce the life and

¹ Information provided to researchers in personal communication with the Electricity, Water and Sanitation Authority, Rwanda.

Table 1

Summary of the PV/storage/diesel system configuration and condition at nine of the sites visited.

	System	HC1	HC2	HC3	HC4	HC6	HC7a	HC7b	HC8	HC9	S1
Configuration	PV	X	X	X	X	X	X	X	X	X	X
	Grid									X	
	Diesel generator	X	X							X	
	Number PV panels	28	8	8	24	16	12	12	16	28	4
	Array size [kWp]	3.4	1.4	1.0	2.9	1.9	1.4	1.4	3.4	3.4	0.5
	Number of batteries	8	12	4	24	15	8	12	8	4	1
	Battery bank capacity [kWh]	17.6	26.4	8.8	63.4	27.7	19.2	28.1	22.1	8.8	1.2
	Daily demand [kWh]	6.0	n/a	3.2	n/a	6.0	4.0	4.0	n/a	n/a	1.7
	Approx. age [months]	24	42	3	12	36	24	24	12	72	10
Condition	Severely deteriorated	X	X							X	
	Usable				X	X	X	X			X
	Healthy			X					X		

**Fig. 3.** Typical demand profile for school with peak in evening and low night-time demand and health centre with morning peak and significant continual demand.

reliability of the PV systems (Table 2), with the most frequently identified issues as follows:

- **High night-time use:** demand outside of daylight hours was more than half of that during daylight hours. High night-time use was found at all of the sites where demand monitoring was installed, this was due to a number of factors such as; medical tests being conducted in the evenings, security and safety lights and late night computer use.
- **Poor maintenance access:** poor access to spare parts or maintenance personnel.
- **Overloading/load growth:** additional equipment installed leading to power shortages and excessive battery discharge. Specific evidence of load growth was found at half of the systems surveyed, and was highlighted by the project partner in Rwanda as the major contributor to premature battery failure.
- **Perception that solar is free:** most sites explicitly indicated that they perceived solar energy as free in comparison to diesel generators which influenced the way that they use electricity.

Table 2

Social and technical factors affecting PV system performance recorded at the study sites.

	System	HC1	HC2	HC3	HC4	HC6	HC7a	HC7b	HC8	HC9	S1
Social factors	High night-time use	X	n/a	X	n/a	X	X	X	n/a	n/a	X
	Poor maintenance access	X			X	X					
	Overloading/load growth	X	X				X	X		X	
	Perceive solar as free		X	X							
Technical factors	Poor understanding				X	X	X	X		X	
	Undersized PV array		X		X	X	X	X	X		
	No lightning protection					X					
	Rainy season shortages	X	X		X	X	X	X	X		X
	Poorly oriented panels						X				
	No condition monitoring				X	X			X		

- **Poor understanding/education:** most sites had poor understanding of their system leading to unfavourable loading patterns or poor maintenance.
- **Undersized PV array:** the PV arrays usually took several days to fully recharge the battery bank.
- **No lightning protection:** no arrestor was installed to prevent lightning strikes damaging system components.
- **Shortages during rainy season:** insufficient generation during the rainy season causing low availability.
- **Poorly oriented panels:** panels were shaded or not oriented North-South.
- **No condition monitoring:** charge controller does not monitor battery temperature.

2.4. Scenario modelling

As a result of this survey and data collection, models were made of the PV systems at a number of the sites. The analysis in this paper uses a bespoke Matlab [33] model for social and technical analysis of PV system performance. HOMER is subsequently used for economic comparisons between PV and diesel systems.

The model is used to model both social change, technical change to the design and a combination of these approaches.

2.4.1. Social scenario

Controlling the factors of load growth and high time use are investigated as a social scenario. Under the base case scenario, a load growth of 8% each month is applied in accordance with the worst case load growth seen in Rwanda. Under an improved social scenario, a lower load growth of 5% is envisaged and these new loads are only used in the day to protect the batteries. This represents users who fully understand the impact of load growth on system lifetime. Furthermore, demand restrictors are used to keep power below 100 W during the evening. Additional load during this time is shifted to the daytime.

2.4.2. Technical improvement scenario

A significant technical factor identified by the survey was an undersized solar array relative to the battery capacity. This is a consequence of design practice as installers design the systems to provide two to three days of autonomy. At many of the sites however, it would take several days for the PV array to fully recharge the battery bank from 20% SoC. This leaves the battery bank at a low SoC for prolonged periods and accelerates its deterioration. A technical scenario of an increased PV array is therefore investigated. This is implemented as an additional string of panels (between 33% and 100% of current array size depending on the array configuration) for sites HC1, HC2 and S1 and two additional panel strings at HC3 and HC6. The larger array increase is needed for HC7a and HC7b due to the longer and more severe rainy season at the sites.

3. System modelling

3.1. Matlab model for PV/battery systems

The Matlab model allows an assessment of the performance, battery cycle life and reliability of the systems in this study under base-case, social, technical, and socio-technical scenarios. Generation, demand and state-of-charge (SoC) calculations are validated using the U.S. National Renewable Energy Laboratory (NREL) software, HOMER version 2.81 [34].

For each ten minute time step, the Matlab model calculates the power flow into or out of the battery, $P_{b,t}$ with

$$P_{b,t} = P_{PV,t} - \frac{P_{d,t}}{\eta_c}, \quad (1)$$

where $P_{PV,t}$ is the output from the PV array, $P_{d,t}$ is the demand and η_c is inverter efficiency. A non-intrusive AC load monitor was installed to collect electrical demand data at each site over a period of at least two weeks. The Matlab model allows load growth and demand shifting to be applied to these demand profiles as required under the social scenarios (see 3.1.4). The demand pattern is repeated to give long term electrical demand on each system.

The energy in the battery, $E_{b,t}$, is calculated using

$$E_{b,t} = \min \left(C, \max \left(0, E_{b,t-1} + \begin{cases} \frac{P_{b,t} \eta_b \Delta t}{\eta_b} & P_{b,t} > 0 \\ -\frac{P_{b,t} \Delta t}{\eta_b} & P_{b,t} < 0 \\ 0 & P_{b,t} = 0 \end{cases} \right) \right), \quad (2)$$

which considers the battery round-trip efficiency, η_b , the length of the time step, Δt , and previous energy in the battery $E_{b,t-1}$. The energy in the battery cannot be greater than the energy capacity, C , of the unit or lower than zero. The SoC, which represents the available energy in the battery as a percentage, is calculated using

$$SOC_t = \frac{E_{b,t}}{C}. \quad (3)$$

The initial SoC of the battery bank is assumed to be 50% and, according to design sheets from installers, an appropriate inverter efficiency is 91%. The battery round trip efficiency is taken as 80% and the charge and discharge losses, η_b , are assumed to be the same in the each direction. The SoC is not allowed to fall below 20% as is commonly implemented in the settings of a battery charge controller.

3.1.1. PV array output

The PV output, $P_{PV,t}$ is calculated using the conversion efficiency of the panels η_{PV} , at a given temperature and irradiance, the

incoming irradiance, G_t the panel area, A and the number of panels, n as

$$P_{PV,t} = \eta_{PV} \cdot G_t \cdot n \cdot A. \quad (4)$$

The efficiency of the array, which is related to the temperature and irradiance, is calculated using

$$\eta_{PV} = \eta_{nom} + c_G(1000 - G_t) + c_T(T_t - 25). \quad (5)$$

Properties of a Suntech STP120S-12 panel (Table 3) were used as these were common in the surveyed sites.

3.1.2. Battery cycle life

Cycle life is defined as the number of complete charge–discharge cycles that a battery can perform before its remaining capacity is less than 80% of the initial capacity. In this analysis, a modified rainflow cycle counter is used to model the battery cycle life [36]. This considers the deterioration in life of the battery after a cycle of a given depth of discharge and ending at a given SoC. A double exponential equation for calculating the nominal cycle life for a given cycle depth of discharge, N_{nom} , was obtained using the Matlab curve fitting tool. This uses data from a representative battery datasheet [37] to give the coefficients α , β , γ and δ in

$$f(x) = \alpha \cdot e^{-\beta x} + \gamma \cdot e^{-\delta x}. \quad (6)$$

For each daily cycle, the depth of discharge, D , is used to calculate N_{nom} using

$$N_{nom} = \min \left(5700, \left(1.25 \times 10^4 \right) \cdot e^{-0.1158D} + 2070 \cdot e^{-0.01537D} \right), \quad (7)$$

where $0 \leq D \leq 100$

This is valid for cycles beginning and ending at full charge which was not the case for cycles seen in Rwanda (see Fig. 6). The approach of using just (7) is similar to that used in HOMER.

The modified rainflow cycle model used in this analysis extends (7) by adding a linear relationship between the nominal cycle life and the final depth of battery discharge of the cycle, $SOC_{min,d}$. This method determines the number of times that the battery can cycle, accounting for non-ideal start and end charge levels, using

$$N_{c,t} = 450 + SOC_{min,d}(N_{nom} - 450). \quad (8)$$

In order to estimate the effect of the SoC on the cycle life, the cycle life deterioration, L_t , is calculated using

$$L_t = \sum_{t=1}^T \frac{1}{N_{c,t}} \quad (9)$$

When L_t reaches 1, then the battery cycle life is reached and the time taken to reach this point is recorded. This is defined in the datasheet for the battery as the point where capacity decreases to 80% of the nominal capacity.

Table 3
Properties of Suntech STP120S-12 PV panel [35].

Parameter	Value
Efficiency at standard test conditions, η_{nom} [%]	11.97%
Irradiance coefficient, c_G [%/(W/m ²)]	-5.625×10^{-5}
Temperature coefficient, c_T [%/°C]	-0.48
Panel surface area, A [m ²]	1.002

3.1.3. Availability

During the social surveys, users frequently said they experienced power shortages as their systems deteriorated. Each PV system is considered unavailable if the battery SoC falls below 20%. At this SoC, charge controllers usually prevent further battery discharge and the system will be unable to power loads throughout

Fig. 4. Here, load growth is applied as a uniform increase in daily demand each month. It can be seen that under current circumstances, a battery life of less than 2 years is expected. This was the typical experience of the installers and users surveyed in Rwanda. Further, a modest, uncontrolled load growth causes significant reduction in availability.

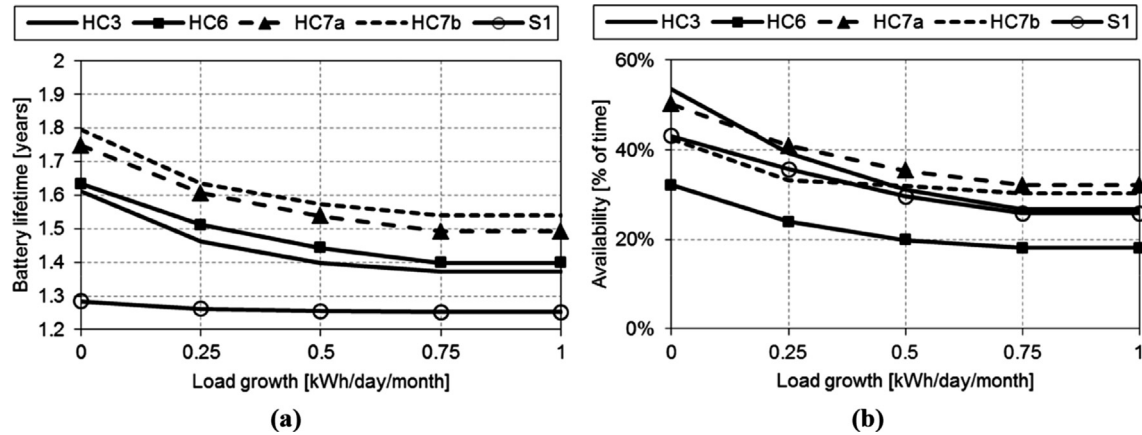


Fig. 4. Battery cycle life (a) and availability (b) of the systems showing decline under increasing load growth scenarios.

the night or during periods of low irradiance such as when under cloud cover.

3.1.4. Demand profile adjustment

Demand profiles are adjusted in the Matlab model through load shifting and load growth. Shifting moves load above a threshold from one time of day to another. Load growth is a percentage increase in daily demand applied uniformly over a selected time period.

3.2. HOMER model

HOMER is an optimisation tool which can be used to design and analyse on or off-grid renewable energy systems. It is used in this paper to complete an economic comparison of off-grid PV and diesel systems for the survey sites. Economic and performance assumptions used for the analysis are shown in Table 4. HOMER provides a net present cost (NPC) of the different system configurations which includes capital, replacement, maintenance and fuel costs.

Both the Matlab and HOMER models showed that the battery SoC is consistently very low as shown in the base-case in Fig. 6. The simple rainflow counting battery life model in HOMER does not distinguish between cycles that occur at high and low depths of discharge and is over optimistic when predicting cycle life for the sites (greater than 8 years). In economic analysis, battery lifetime is fixed using data from the Matlab model to account for this.

4. Results

The Matlab model described in section 3.1 is now applied to systems HC3, HC6, HC7a, HC7b and S1. These sites are selected because it was possible to gather smart meter data from these operational systems.

4.1. Cycle life and availability

From applying the Matlab model to the sites, it was found that the base case battery life (less than 2 years) and availability (less than 60%) are highly dependent on the load growth as shown in

Using results from the survey, the Matlab model is used to investigate different social and technical methods for improving system performance. These are summarised in Table 5.

Fig. 5(a) shows the predicted cycle life under the different scenarios and Fig. 5(b) shows the expected availability of the systems in the first two years. According to Fig. 5(a), battery replacement is needed after less than two years at all of the sites under the base-case. This is worst at S1 which has just one battery. As shown in Fig. 5(b), the availability of the system is only improved by an increase in the PV array size as this allows faster recharge of the battery bank from very low states of charge. From the surveys it is known that improved availability would improve customer satisfaction.

Fig. 6 depicts the SoC of the battery in the first two years for each site under each scenario. Black areas show when the battery has a high SoC and white areas indicate a low SoC. Under the base-case, all of the sites operate with batteries at very low SoC as a result of the undersized PV array. The effect of load growth is significant, and can be clearly seen in Fig. 6 as the SoC deteriorates to extremely low values before battery failure. At all of the sites, social change by itself produces modest improvement in cycle life and availability. Expansion of the PV array produces a larger increase in both cycle life and availability at all sites. This is because, as shown in Fig. 6, this generally maintains the battery bank at a higher SoC. Although the technical change does improve cycle life and availability, there still remains periods of low SoC. These can be seen as horizontal bands in the SoC maps (Fig. 6) where there is particularly low irradiance. These periods present undesirable performance for users due to potentially lower availability.

When added to technical change, social interventions in adjusting the demand profiles are more effective. As a result, cycle life above three years is achieved at all of the health centres and increases to two and a half years at the school. This shows that although the sites are currently constrained by low generation, there are significant benefits to be gained through improved user behaviour once technical change is made. The use of modern alternative battery technologies such as lithium ion, longer life lead acid batteries and flow batteries together with socio-technical changes should provide an even longer battery life, but the effect of technical and social change remains consistent.

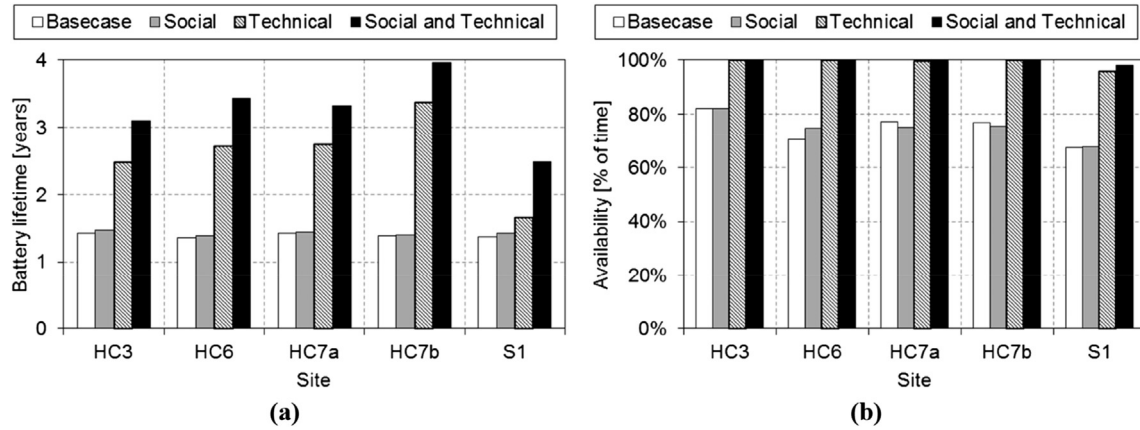


Fig. 5. (a) Battery cycle life and (b) availability of each system in first two years of operation. Note that the availability will practically decrease over the life of the battery as it ages.

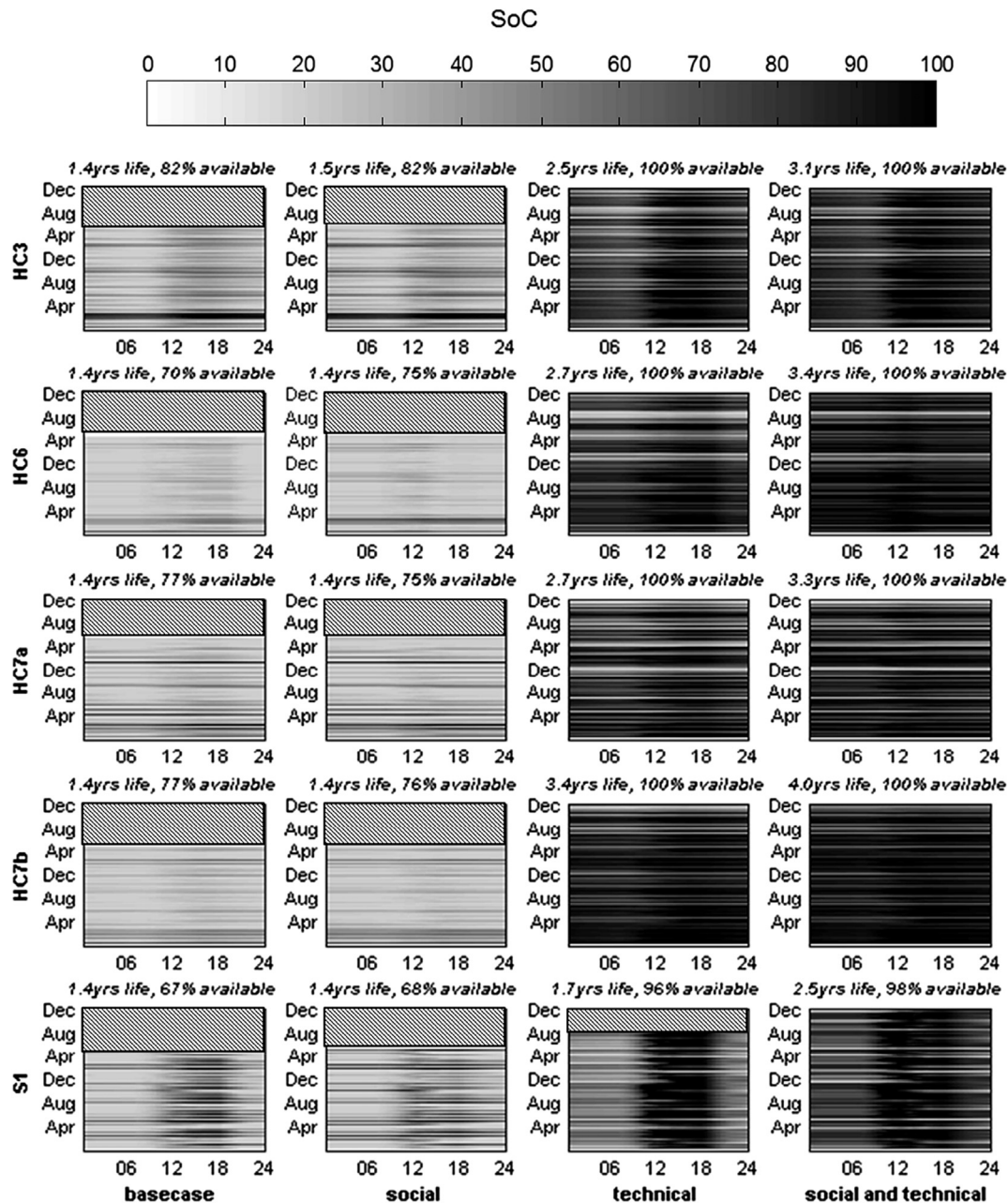


Fig. 6. State-of-charge of systems over first two years of operation where changes in shading indicate the battery health. Where batteries have reached end-of-life (<80% capacity) the figure shading is hatched.

Table 4
Economic and performance assumptions in HOMER model.

Parameter	Cost	Notes
PV Panel*	US\$ 4000/kW	Concurrent with a survey of a number of system vendors in Rwanda
VRLA battery unit cost*	US\$ 928 per unit, \$344/kWh	
Converter*	US\$ 1000/kW	
Diesel generator	US\$ 865/kW	See Ref. [38]
PV O&M	1% of capital cost	
Diesel cost (including transportation costs of 10%)	\$1.6/litre	
Additional fuel transport cost	10%	Chosen for evaluation
Generator O&M	\$0.025/hour/kW	See Ref. [39]
Nominal interest rate	7%	See Ref. [40]
Project lifetime	10 years	As is typical in Rwanda

4.2. Financial impact of social and technical changes

The cost of any energy system is an important consideration for site owners, operators and donors. This includes a consideration of capital and operating costs as well as the total cost over the project lifetime. The white bars in Fig. 7 illustrate the capital cost of the different scenarios at the different sites according to the HOMER analysis. Under both scenarios, the diesel has a much lower capital expenditure (CAPEX) than standalone PV systems. It can be seen that the socio-technical scenario increases the capital cost of standalone PV systems as expected due to expansion of the array.

Operating costs are compared in the black bars in Fig. 7. For all of the health centres under the base-case scenario, the operational expenditure (OPEX) for the PV system are higher compared with the diesel generator system over the 10 year project lifetime. This is due to the large number of battery replacements and is contrary to the perception that diesel generators have higher running costs than PV. As previously stated, a two year battery life was typical in Rwanda and confirmed by the analysis in this paper.

The socio-technical changes dramatically reduce the operating cost for PV systems at all of the sites. The running cost is significantly reduced because the additional string added to the panels and the change in user consumption leads to a reduction in the number of battery replacements. This results in cheaper operating costs for PV systems relative to diesel generators. However, at all of the health centres, a diesel generator still has a lower overall cost over the 10 year project lifetime. Only at site S1 is PV the cheaper option and the difference is marginal. Diesel only has 100% availability with reliable access to fuel and no breakdowns.

The analysis in Fig. 7 is completed using prices for PV and diesel which were correct at the time of study in Rwanda. However, the on-going technology development and falling global prices for PV and batteries combined with increasing prices for diesel mean that an analysis with projected component prices is necessary to inform medium to long term decision making. Fig. 8 shows net, CAPEX and OPEX for the five sites with prices of \$1.5/W for PV, \$800 per unit for batteries and \$3.2 per litre diesel. These prices represent indicative reduced component prices for PV systems and also fuel

price increase based on the escalation rates in Rwanda over the past ten years. As expected, the projected prices improve the business case for PV at all of the sites. For the school, the projected prices also cause PV to be more profitable than a diesel generator in the base-case. However, for all of the other sites, the socio-technical changes to PV design and operation are needed for PV to be a cheaper alternative over a 10 year investment than a diesel generator.

5. Discussion

This study has presented a method for determining the battery life of off-grid PV systems under different technical and social scenarios which has then been used to show that both social and technical changes are important for improving the life of the systems.

5.1. The current performance of PV systems studied

The provision of electricity at rural health centres and schools is important in improving the effectiveness of the services that they deliver. However, systems which are expensive to operate or have power shortages constrain the provision of lighting, administration, medical and educational facilities. Interviews conducted with system owners in Rwanda found that batteries were perceived to have failed after 2 years. Only one site was considered to be in good condition after more than two years (HC6) and there was dispute amongst the interviewees about system functionality. The cycle life (a reduction in capacity of 20%) was subsequently shown to be less than 18 months using the model in this paper. Knowing that the batteries were in a low SoC and were failing after two years showed the importance of a battery model which considers the extra impact of cycles that begin and end at a low SoC. The sites were also found to have an average availability of just over twelve hours (mostly daytime), an issue which site owners frequently cited in interviews as reasons for dissatisfaction with their PV systems.

Two of the survey sites had the perception that solar energy is free. This is a result of the PV systems being donated to the schools and health centres with no visible on-going fuel or maintenance cost. Because of the significant costs associated with the battery replacement (around a third of the CAPEX), this is an important misconception. The high replacement costs of the batteries means that PV systems are less cost effective than diesel at all of the health centres surveyed. Relative to PV systems, diesel generators have a high ratio between the operational and capital costs. However, for all of the health centres studied, the operational cost of the generator was still lower than the battery replacement cost. The school studied had a lower operational cost of their PV system relative to a diesel alternative, mostly due to its modest battery bank size.

The technical survey of the systems found that the major contributing factor which reduces system performance was the undersized PV array, which leads to undercharging of the batteries. This subsequently caused prolonged capacity shortages during the rainy season and reduced battery capacity as the cells degrade. Deep-cycle VRLA batteries were installed at all but one of the survey sites in Rwanda, which are rugged and maintenance free but

Table 5
Social and technical scenarios tested for system performance improvements in the Matlab model.

Scenario	Load growth	New equipment used	Array size increased	Night time demand restricted
Base case	8%	All day	No	No
Social	5%	Only during daylight	No	Yes
Technical	8%	All day	Yes	No
Social and technical	5%	Only during daylight	Yes	Yes

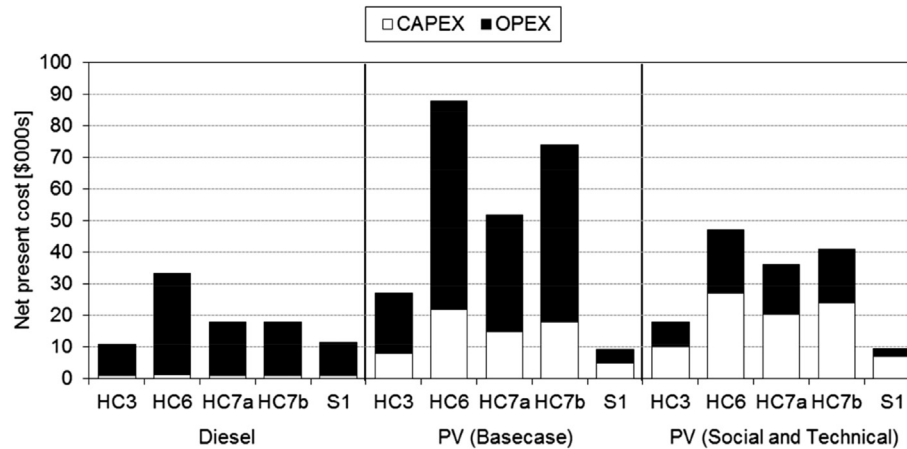


Fig. 7. Capital and operational costs for diesel and PV systems under base-case and social/technical scenarios.

have a shorter cycle life than other battery chemistries such as lithium cells. One site used flooded lead acid cells which needed to be topped up with electrolyte.

5.2. The value of social and technical changes

The impact of increasing the size of the PV array was investigated using the model in this paper. This was found to have a larger impact on the battery life and availability than social changes because, without an upgrade to the PV array, there are periods during the rainy season where the battery SoC falls and the undersized PV array is unable to recover the charge. As shown in Fig. 6, this technical change means that the state of charge is kept above 50% for the majority of the time at all of the sites, and the availability increases to nearly 100%. Although this increases the system capital cost, an upgrade to the PV array ultimately reduces the overall system costs as the frequency of battery replacements and the underlying costs are lowered. The PV array should be sized to allow the battery bank to be fully recharged in one day considering that system owners will generally increase their underlying electricity demand over time.

The interviews and smart meter data revealed that load growth and excessive use at night time were the main social factors which contribute to the low battery lifetime and impaired autonomy. High night time use was observed at all the sites where demand

data was collected. In health centres night time use included for office equipment, lighting, laboratory testing or to provide entertainment whilst in schools night time use was predominantly to provide lighting for evening classes and homework clubs or for showing films. Load growth was found to occur at all but one of the health centres because access to electricity encourages sites to purchase or be donated additional medical, educational and administrative equipment. As shown in Fig. 4, a modest amount of uncontrolled load growth has a high effect on battery cycle life and autonomy.

The impact of changing user behaviour was considered using the model in this paper. Specifically, the model was used to investigate the impact of sites shifting some of their night-time demand to the daytime and consciously restricting additional loading on the systems. This change was ineffective on the current systems due to the prolonged undercharge of the batteries. However, at least 6 month improvement in battery life was seen at all of the sites when social and technical changes were combined.

Improving staff understanding of the limitations of PV systems could alter the usage patterns and load growth, and therefore make their systems more financially viable and increase availability. Practically, this may be challenging since donated equipment has important medical and educational benefits and provision of lighting at night has important safety and medical uses (for example, night time maternity services). It was also

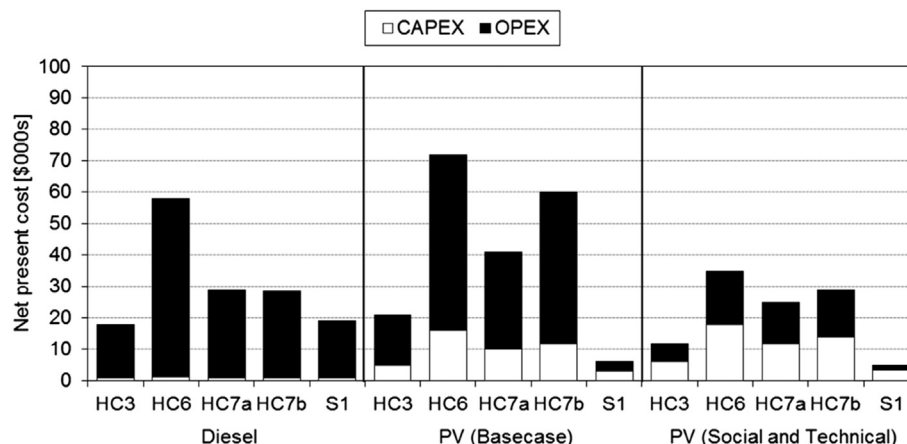


Fig. 8. Capital and operational costs for diesel and PV systems under projected prices.

observed that health centres generally carried out laboratory tests at night and the practicalities of deferring this load needs to be understood.

In the base-case, the replacement costs for batteries are higher than the fuel costs for diesel generators. However, as shown by the HOMER analysis, the running costs of a system with socio-technical changes are much lower than the fuel costs associated with a diesel generator. Where donor agencies expect their clients to meet the OPEX of a system, the suggested social and technical changes are particularly beneficial to the clients as they significantly reduce the OPEX of PV systems. It should be noted that these results are sensitive to the current pricing conditions in Rwanda. The current trend of falling PV costs with technology improvements and rising diesel costs will make off-grid PV more favourable as illustrated in Fig. 8. Furthermore, there is the added benefit of not relying on fuel resupply to run PV systems. During periods of fuel shortage or lack of capital for purchasing fuel, PV systems, even with weakened batteries can still provide some form of power supply during the day.

5.3. Donor context

Most health centres and schools have energy systems provided by donor organisations. In this context, sites are sometimes expected to meet the OPEX of their systems. In this case, PV with the socio-technical changes recommended in this paper, provides much lower operating costs and is therefore more suitable for such a donor model. In addition, a PV system with deteriorated batteries can still provide energy, albeit with restricted performance. This is not the case for diesel generators where a site that cannot meet fuel costs is left without any electricity. Overall, it should be noted that there was general satisfaction with PV systems in the centres visited, as health practitioners and educational staff valued having a renewable and clean technology over a diesel generator.

5.4. Study limitations

The cost and feasibility of alternative battery technologies such as lithium-ion, small-scale flow batteries and longer life lead acid also require further investigation. With a different battery model, the proposed social technical approach is important in understanding how to maximise the life and minimise the cost of systems even with different batteries. This paper focussed on the VRLA batteries found in Rwanda since other battery types were not available in country. The approach presented in this work is shown to make a contribution to the better use of available technology.

6. Conclusions

Off-grid solar PV is an important renewable technology for providing electrification to rural communities. This is especially true for schools and health centres where Government and donor funding are available to fund such energy systems. However, the high capital cost and low battery life can make PV uncompetitive compared to diesel generators if an interdisciplinary approach is not taken to their design and operation. The issues with battery deterioration can be resolved by enacting a socio-technical approach to designing and managing such systems.

For system owner and operators:

- The acquisition of new or donated electrical equipment is common and causes premature deterioration of batteries. Owners should be aware of the cost of adding any new equipment to the system. If this is purchased, they should be encouraged to use it during the day.

- High night-time electrical demand can impose deep cycles on the batteries. System owners and operators should look at ways of shifting demand from the night-time to the daytime where it can be powered using the solar PV array.

System designers should also reflect these factors:

- PV arrays were generally found to be undersized: A design rule that results in a battery capacity with three days of autonomy needs to be matched by an increase in the PV array size to allow the battery bank to sufficiently recharge in less than a under anticipated seasonal conditions.
- Designers should account for the load growth that is known to result from the provision of electricity to communities which previously had none.

A detailed technical report on this study including the interview questions is available at [32].

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References

- [1] United Nations. Sustainable energy for all. 2012 [Online]. Available, <http://www.se4all.org> [accessed 13.01.2015].
- [2] Dekker J, Nthuntho M, Chowdhury S, Chowdhury SP. Electrical power and energy systems economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa. *Int J Electr Power Energy Syst* 2012;40(1):104–12.
- [3] Szabó S, Bódis K, Huld T, Moner-Girona M. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environ Res Lett* Jul. 2011;6(3).
- [4] Belward A, Bisselink B, Bódis K, Brink A, Dallemand J, de Roo A, et al. Renewable energies in Africa. Energy. 2011 [Online]. Available, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC67752/reqno_jrc67752_final_report.pdf [accessed 04.08.2013].
- [5] Iemsomboon P, Tangtham N, Kanjanasuntorn S, Bualert S. Modeling community quality of life indicators for developing solar home system in remote areas. *Energy Procedia* Jan. 2011;9:44–55.
- [6] Chaurey A, Kandpal TC. Assessment and evaluation of PV based decentralized rural electrification: an overview. *Renew Sustain Energy Rev* Oct. 2010;14(8):2266–78.
- [7] Deloitte “IEC. Securing tomorrow's energy today: policy & regulations energy access for the poor. 2013 [Online]. Available, http://www2.deloitte.com/content/dam/Deloitte/in/Documents/energy-31_resources/in-enr-energy_access_for_the_poor-noexp.pdf [accessed 13.01.2015].
- [8] Balint PJ. Bringing solar home systems to rural El Salvador: lessons for small NGOs. *Energy Policy* 2006;34:721–9.
- [9] Yamegueu D, Azoumah Y, Py X, Zongo N. Experimental study of electricity generation by solar PV/diesel hybrid systems without battery storage for off-grid areas. *Renew Energy* Jun. 2011;36(6):1780–7.
- [10] IEA. Testing of batteries used in stand alone PV power supply systems. 2002 [Online]. Available, http://www.iea-pvps.org/index.php?id=9&elD=dam_frontend_push&docID=376 [accessed 13.01.2015].
- [11] Diaz P, Lorenzo E. Solar home system battery and charge regulator testing. *Prog Photovolt Res Appl* Sep. 2001;9(5):363–77.

- [12] Muselli M, Notton G, Poggi P, Louche A. PV-hybrid power systems sizing incorporating battery storage: an analysis via simulation calculations. *Renew Energy* May 2000;20(1):1–7.
- [13] Koutroulis E, Kolokotsa D, Potirakis A, Kalaitzakis K. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. *Sol Energy* Sep. 2006;80(9):1072–88.
- [14] Sovacool BK, Agostino ALD, Bambawale MJ. The socio-technical barriers to solar home systems (SHS) in Papua New Guinea: 'choosing pigs, prostitutes, and poker chips over panels'. *Energy Policy* 2011;39(3):1532–42.
- [15] Obeng GY, Evers H-D. Impacts of public solar PV electrification on rural micro-enterprises: the case of Ghana. *Energy sustain Dev Sep.* 2010;14(3):223–31.
- [16] Jacobson A. Connective power: solar electrification and social change in Kenya. *World Dev* 2007;35(1):144–62. <http://dx.doi.org/10.1016/j.worlddev.2006.10.001>.
- [17] Gustavsson M. With time comes increased loads—an analysis of solar home system use in Lundazi, Zambia. *Renew Energy* Apr. 2006;32(5):796–813.
- [18] Ulsrud K, Winther T, Palit D, Rohrer H, Sandgren J. The solar transitions research on solar mini-grids in India: learning from local cases of innovative socio-technical systems. *Energy Sustain Dev Sep.* 2011;15(3):293–303.
- [19] Muggenburg H, Tillmans A, Schweizer-Ries P, Raabe T, Adelman P. Social acceptance of PicoPV systems as a means of rural electrification — a socio-technical case study in Ethiopia. *Energy Sustain Dev Mar.* 2012;16(1):90–7.
- [20] Díaz P, Arias CA, Peña R, Sandoval D. FAR from the grid: a rural electrification field study. *Renew Energy* Dec. 2010;35(12):2829–34.
- [21] Schmid AL, Hoffmann CAA. Replacing diesel by solar in the Amazon: short-term economic feasibility of PV-diesel hybrid systems. *Energy Policy* May 2004;32(7):881–98.
- [22] Safari B, Gasore J. Estimation of global solar radiation in Rwanda using empirical models. *Asian J Sci Res* 2009;2(2):68–75.
- [23] Safari B. A review of energy in Rwanda. *Renew Sustain Energy Rev Jan.* 2010;14(1):524–9.
- [24] Rwandan Ministry of Infrastructure. Republic of Rwanda, national energy policy and strategy 2008–2012. 2009.
- [25] Republic of Rwanda Ministry of Finance and Economic Planning, "Rwanda vision 2020," 2000 [Online]. Available, <http://www.minecofin.gov.rw/home/ministry/key-documents/rwanda-vision-2020.html> [accessed 13.01.2015].
- [26] Bensch G, Kluge J, Peters J. Impacts of rural electrification in Rwanda impacts of rural electrification in Rwanda. *Inst Study Labor Ger* 2011;(6195).
- [27] World Bank. World bank database, Rwanda. 2013 [Online]. Available, <http://data.worldbank.org/country/rwanda> [Accessed: 24-Jun-2013].
- [28] Republic of Rwanda Ministry of Finance and Economic Planning. Economic development and poverty reduction strategy 2013–2018. [Online]. Available: <http://www.rcsprwanda.org/spip.php?article256> [accessed 13.01.2015].
- [29] The Minister for Energy and Mining. Investment opportunities in renewable energy Burundi investment opportunities in renewable energy Burundi. 2012 [Online]. Available, [http://www.bi.undp.org/content/dam/burundi/docs/publications/Investment opportunities in renewable energy Burundi.pdf](http://www.bi.undp.org/content/dam/burundi/docs/publications/Investment%20opportunities%20in%20renewable%20energy%20Burundi.pdf) [accessed 13.01.2015].
- [30] Uwamahoro Y. Rwanda electricity access scale up program and swap development. 2008 [Online]. Available, http://siteresources.worldbank.org/EXTAFRREGTOPENERGY/Resources/717305-1264695610003/6743444-1268073536147/7.3.Rwanda_sector-wide_approach.pdf [accessed 30.07.2013].
- [31] The New Times. First solar powered school set for launch. 2011 [Online]. Available, <http://www.newtimes.co.rw/news/index.php?a=45876&i=14769> [accessed 24.06.2013].
- [32] Crossland A, Anuta O, Wade NS, Durham Energy Institute. Can enhanced electrical storage unlock off-grid photovoltaic systems in rural Rwanda?. 2013 [Online]. Available, <http://www.dur.ac.uk/dei/research/projects/offgridrwanda/> [accessed 08.03.2013].
- [33] MathWorks. Matlab. 2013 [Online]. Available, <http://www.mathworks.co.uk/products/matlab/> [accessed 21.06.2013].
- [34] HOMER energy. 2013 [Online]. Available, <https://www.homerenergy.com/> [accessed 23.07.2013].
- [35] Suntech. 195W monocrystalline solar module.
- [36] Bindner H, Cronin T, Lundsager P, Manwell JF, Abdulwahid U, Baring-Gould I. Lifetime modelling of lead acid batteries. 2005 [Online]. Available, http://orbit.dtu.dk/fedora/objects/orbit:88309/datastreams/file_7710966/content [accessed 06.06.2013].
- [37] Deka Solar. Photovoltaic batteries. 2012 [Online]. Available, <http://www.dekabatteries.com/assets/base/0919.pdf> [accessed 09.03.2013].
- [38] Reuters. Rwanda raises fuel prices, cites higher global oil costs. 2013 [Online]. Available, <http://206.132.6.105/article/newsOne/idAFJ0E92B01K20130312> [accessed 13.01.2015].
- [39] Lau KY, Yousof MFM, Arshad SNM, Anwari M, Yatim AHM. Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. *Energy* Aug. 2010;35(8):3245–55.
- [40] Trading Economics. Rwanda interest rate. 2013 [Online]. Available, <http://www.tradingeconomics.com/rwanda/interest-rate> [accessed 26.08.2013].