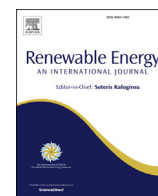


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# Renewable Energy

journal homepage: [www.elsevier.com/locate/renene](http://www.elsevier.com/locate/renene)

## Design of a solar energy centre for providing lighting and income-generating activities for off-grid rural communities in Kenya



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### ARTICLE INFO

#### Article history:

Received 10 July 2017

Received in revised form

4 November 2017

Accepted 17 November 2017

Available online 22 November 2017

#### Keywords:

Solar energy centre

Off-grid rural communities

PVsyst

Solar home systems

Income-generating activities

### ABSTRACT

One of the biggest challenges in the developing world is the provision of affordable and reliable electricity access to rural and marginalized people where grid extension is prohibitively expensive. Many off-grid schemes to date have focused on household lighting with mixed success. Some of the greatest difficulties have been around affordability and sustainability of the service provided, with systems being abandoned or removed due to broken equipment or inability of the user to continue paying for the service. It has been reported that key to the success of the best programs has been the means to improve the economic prospects of the users. In this paper the design of a solar energy centre for a rural village in Kenya, that enables income-generating activities for the community in addition to basic lighting and mobile phone charging provision, will be reported. We have found that it is possible to use the energy centre model to provide power for activities that could offer a source of income for the community, at an affordable cost with equipment available in Kenya today. It is believed that this will allow the community to develop economically and therefore ensure the sustainability of the off-grid power supply.

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### 1. Introduction

According to the UN [1], 1.5 billion people worldwide have no access to electricity and a further billion people have highly unreliable connections. In sub-Saharan Africa 620 million people have no access to grid electricity [2]. In Kenya 35 million people or 75% of the population are in this situation [2]. Indeed, in 2010 only 8.1% of rural communities in Kenya had access to grid electricity [3].

In 2014, the per capita energy consumption in Kenya was just 167 kWh per year [4]. The IEA recommends that the minimum level of access to electricity should be 250 kWh per year for a rural household and 500 kWh per year for an urban household [2]. To put it in context, 250 kWh per year would allow the use of two compact fluorescent lights, mobile phone charging and the use of a fan for 5 h per day for a household of 5 people. Without electricity, communities rely on kerosene lamps for lighting and biomass for cooking, which are expensive, unhealthy and damaging to the environment. The price of kerosene was on average \$0.60/l<sup>1</sup> in Kenya in 2015 [5], placing a heavy financial burden on poor, rural

households.

Kenya established a state corporation, the Rural Electrification Authority, in 2006 with the aim of accelerating rural electrification. Recently the Government of Kenya announced that it was reducing the once-off connection fee from \$320 to \$147 [6] but households must pay for electrical wiring before a connection can be made. According to the World Bank [7], the gross national income of Kenya for 2011 was just \$1160. Therefore, even the reduced connection fee is likely to be beyond the means of poor rural communities. A working paper from the National Bureau of Economic Research in the US [8] backs this up, finding that large numbers of houses in rural Western Kenya within 600 m of transformers are not connected to the grid, essentially living under the grid.

A World Bank report in 2004 [9] found evidence that rural electrification schemes are generally unsuccessful unless the communities being connected have sufficient economic success to be able to afford appliances such as TVs, refrigerators and improved lighting. However, economic progress often depends on the availability of electricity. Off-grid systems can offer communities limited, affordable electricity supplies that bridge the gap and pave the way for grid electrification by creating a market for it.

In Kenya, the high level of solar insolation (>5 kWh/m<sup>2</sup>/day) makes photovoltaic (PV) systems an attractive off-grid power

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<sup>1</sup> Conversion rate for Kenyan Shillings to US Dollars on 16 August 2015 was 1 Ksh = \$0.0098.

solution (see Fig. 1). Three different models for off-grid PV systems for rural communities have been tried around the world: solar home systems (SHS) [10], mini- or micro-grids [11–13], and community energy centres [14,15].

Solar home systems (SHS) have been widely deployed in the developing world, particularly in Bangladesh and India as part of their rural electrification programs [16–19], but also in Sub-Saharan Africa [20,21]. A typical SHS consists of a solar module, battery, charge controller, compact fluorescent lights or LEDs, mobile phone charging point and possibly a power point for small DC appliances such as TVs, fans or radios. Although they are the most popular solution for off-grid rural electrification to date, there have been a number of issues with them including difficulty for users to find the upfront capital costs to purchase a system, over-use resulting in shorter battery life, poor-quality products and/or installation and insufficient system maintenance [17].

An alternative model to the solar home system is the minigrid (also called a microgrid or picogrid depending on the system size). Minigrids consist of centralized power generation e.g. an array of PV modules, a bank of batteries, an inverter to convert from

generated DC to AC power and a distribution system including poles, wires and consumer units [13,23]. In addition to providing power to homes, minigrids can be used to power services such as water pumping and street lighting. Another advantage of minigrids is that by supplying AC, appliances are more readily available and cheaper for the consumers. Loka et al. [12] reviewed a PV-based microgrid in India and found the levelized cost of electricity (LCOE) for an equivalent diesel generator was estimated to be more than twice the cost of the PV microgrid. They reported that the key factors to the success of the project were: active involvement of the community from the outset, having a comprehensive maintenance plan and providing spare parts for the system. Ulsrud et al. [11] looked in detail at a well-established solar minigrid in India. Over time the electricity needs of the community outstripped what the scheme could supply leading to battery degradation and illegal connections to the distribution system. The authors noted the importance of planning in advance for system growth to meet this increasing demand. In some cases, households installed a SHS in addition to using energy from the minigrid. There were also issues with maintenance and acquiring spare parts and setting an

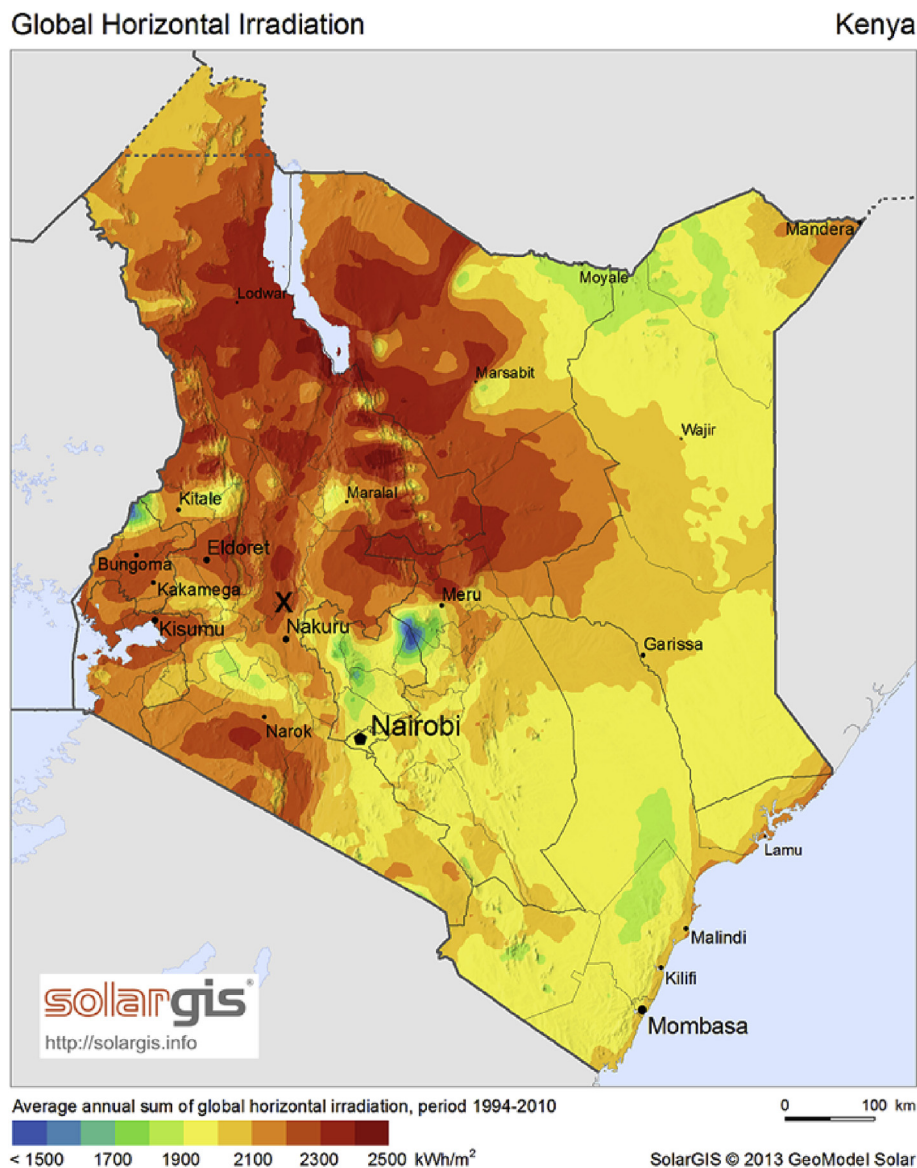


Fig. 1. Map of Kenya showing annual average global horizontal irradiation [22]. The location of the village considered in this paper is marked with "X".

affordable tariff. Millinger et al. found that 75% of the 69 minigrid power plants evaluated in India had too little output to meet the needs of the community due to the unaffordable cost of implementing a microgrid system large enough to supply their requirements [18].

Some recent studies have suggested that whether a minigrid or SHS is best depends on the size of the village that is being considered [18,23]. As a result of some modelling of villages in India, Chaurey et al. [23] found that microgrid systems are more financially viable than solar home systems for villages with 500 houses in flat terrain with 3 or 4 items per household being powered for an average of 4 h every day. However, microgrids were not found to be economically viable, therefore requiring subsidies, for small communities (50–100 households) or where the households were widely spread incurring a larger cost for the power distribution network. In comparison, it found that subsidies would always be required when using SHS to electrify the villages [23].

Another model for providing off-grid rural communities with access to power is the ‘energy centre’, a hybrid of the two previous systems. There is centralized power generation but no distribution; instead people pay for example to rent solar lanterns for use in their homes or to charge their mobile phones at an energy centre which hosts the PV modules, the battery bank and charge controller. This idea was first proposed by TERI in India with their “Lighting a Billion Lives” (LaBL) project [24,25]. In this project, solar lanterns are charged at central solar charging stations and rented to local families in the evenings. It is based on a business model where the service is operated and managed by a local entrepreneur. In a recent paper by Ulsrud et al. [14] the authors describe an expansion of this model in the first implementation of an energy hub in a village in Kenya, which is used to charge rented solar lanterns and mobile phones, and offers central services such as photocopying, typing, hair-dressing and television.

All of the existing PV-based off-grid rural electrification schemes have faced similar challenges that need to be considered when designing any off-grid system. A good summary of the difficulties in deploying PV systems in developing countries can be found in Chaurey et al. [26], including lack of sustainable business models, lack of regulatory mechanisms, poor integration with rural electrification policies, donor-projects distorting market prices, use of unreliable components, poor installation and maintenance, inability to collect payments, lack of stakeholder participation and user training, among others. Key success factors include: availability of capital subsidies or cheap credit to spread the cost for the poorest communities; not subsidizing the cost of electricity used; involving the community from the beginning in the electrification project; training local individuals to provide maintenance and repair services; and financial provision for long-term maintenance and, if necessary, system up-grades [20]. Finally, Borah et al. [15] compared the main types of solar systems for rural village electrification in India (solar home systems, solar charging centre and AC or DC microgrids). They found that the key to the success of the projects depended less on the technology and more on the institutional and financial aspects. They found that subsidy-based models did not perform as well as viable business-based models; and end user ownership plays a vital role in the success of the models.

In light of the findings of earlier works, it was decided that the feasibility of a solar energy centre for supplying basic electricity services and supporting income-generating activities for an off-grid community in rural Kenya should be investigated. The aim of the study was to provide affordable, high-quality services to meet the energy needs of the village without the need for subsidies or grants. By providing services so as to enable income-generating activity, which allows the economic development of the community, it is hoped that a market can be created for further services. This is the

first time that this has been proposed using an energy centre model (as far as can be told from a detailed literature search). The objectives were to evaluate the current socio-economic situation at the case study site; to identify the energy service requirements of the community; to design a system to meet these aspirations within the economic constraints of the community; to design a financial model and perform risk and sensitivity analysis on the proposed solution. This methodology allows different services to be assessed for economic feasibility in advance so loss-making activities are not installed, resources are not wasted and subsidies are not required. This paper will focus on how services could be delivered through a solar energy centre and the pricing structure needed to make them attractive to investors.

The paper is arranged as follows: Section 2 describes the methodologies used in this paper covering socio-economic data collection (2.1), technology selection (2.2), system sizing (2.3), financial model (2.4) and technoeconomic, sensitivity and risk analyses (2.5); Section 3 presents the results and discussion covering the socio-economic survey (3.1), system design (3.2), technoeconomic analysis and pricing model (3.3), sensitivity and risk analysis (3.4); Section 4 gives the conclusions of the research.

## 2. Methodology

Multidisciplinary methods were used in the study. A summary of the general process of the system development and design can be found below. More details of each part of the methodology can be found in the following subsections.

Protocol:

1. Assess the needs of the community, their ability to pay and the services required using methods such as community surveys, interviews and service value tests.
2. Assess the equipment available in the local or national market: solar modules, charge controllers, batteries, solar home systems, solar lamps and equipment for income generating activity. Assess the cost of purchasing, installing and maintaining these systems in the local market through local market research.
3. Use software, such as PVSyst,<sup>2</sup> to find the optimum system design: minimising cost while maximising availability.
4. Calculate a simple payback model via Net Present Value (NPV), Internal Rate of Return (IRR) and Levelised Cost of Electricity (LCOE) inputting capital costs, operating costs & discount rate (determined by local market conditions) and from this eliminate non-profitable set-ups.
5. Conduct sensitivity analysis: vary discount rate, operating costs, capital costs, rental income and other sensitive factors to assess their effect on the NPV. From this eliminate risky ventures or set the rent to reduce the risk while ensuring affordability for the users.
6. Conduct risk analysis considering alternative energy sources e.g. cost of grid access, cost of fossil fuels such as kerosene/diesel to assess the likelihood that the proposed system will remain competitive over the payback period.

### 2.1. Socio-economic data collection

The village, which is the focus of this study, is Lemolo B in the County of Nakuru in Kenya (latitude:  $-0.006861$ ; longitude:  $36.041456$ ), see Fig. 1. It is located in a semi-arid region of Kenya, with approximately 247 households. The village has a new primary

<sup>2</sup> PVSyst is an industry-standard software package for simulating and sizing solar PV systems [<http://www.pvsyst.com>].

school funded by World Teacher Aid and a kiosk selling basic goods. The nearest town, Mogotio, is 13 km away via a rough dirt track. The nearest source of clean water is a river 11 km away. Clean water can also be bought in Mogotio at a cost of \$0.29 for 20 L. Most people were obtaining their water from a local, rain-fed pond that is also used by animals. However, a charity was looking to install a water tank in the village, to be refilled by a water bowser, at the time of the research. The village has two diesel-powered poshomills which charge \$0.03/kg for milling maize. Each household requires 2–3 kg of maize to be ground every day.

A survey of Lemolo B was undertaken to ascertain energy use and socio-economic factors in the village. A sample of 30 households was interviewed, representing about 12% of the community. Although caution needs to be taken in drawing conclusions from a small sample size, the data gathered offers useful insights into the economic activities and energy usage of the community. In addition, service value tests (SVT) were performed with different groups (women, youth, and elders) in the village to gather evidence for community and household consensus and prioritisation for energy services provision. Following on from the results of the study and the initial technology selection, system design and financial model development a second iteration of interaction with the community took place to present the results to ensure that the energy intervention met their expectations.

## 2.2. Technology selection

In contrast to many other countries in the developing world, Kenya already has a strong and vibrant solar market [21]. There are therefore many different brands of solar module, battery and charge controllers available in Kenya. The literature shows that for fee-for-service or credit schemes users tend to stop payments if the systems fail [10]. Therefore, careful selection of the technology to be used will be vital to the success of the project.

Batteries and compact fluorescent lights have been shown to be the most frequent cause of system failure in SHS [10,18]. These items are expensive and difficult to source in communities and so have led to systems being under-utilized or even abandoned [18]. More general causes of system failure have included issues with component incompatibility, faulty installations [17], as well as a lack of adequate maintenance for installed systems [16,18]. These factors have been exasperated by extremely rapid deployment of SHS in some countries in recent years without sufficient regulatory safeguards for standards in place [23,27].

The idea behind the system was to have a central energy hub where the PV modules, central battery store and balance-of-system (BoS) would be located. This would charge the user's battery, which would then be used for lighting and phone charging at their home in the evening. In selecting the modules for the energy centre, the system size requirements, the price, performance and reliability were all considered. Available home lighting systems were narrowed down to those with Lighting Africa approval [28] and those that still offered a warranty when charging centrally. It was further decided to source all the equipment in Kenya in order to support the local economy and to make it easier to have it repaired or replaced in case of any breakdowns, ensuring greater service reliability.

In addition to the lighting, a number of options for providing economic activity using solar power were considered:

- Solar Poshomills<sup>3</sup> for grinding maize with 750 W DC motor.
- Egg incubators, 20 W DC, peak 80 W such as model YZ-48 (48 eggs).

- Solar refrigerator, e.g. the 1651 Sundanzer refrigerator.
- Solar powered water purification systems requiring a 20 W module and 17Ah battery; to purify up to 1000 L per hour.

## 2.3. System sizing

In order to make the system as flexible as possible, it was decided that each separate sub-system would be individually sized. This allows the village to decide which services they would like to choose and the number of services can be selected based on the willingness and ability to pay.

The systems were sized using *PVSyst's* stand-alone mode. This program requires the user to supply solar radiation data, system orientation, an hourly load profile and information on the far and near-shadings. It proposes a preliminary system size taking into account acceptable loss of load and required days of autonomy of the system and allows the user to select appropriate battery and panel technology. The user also specifies the system losses including soiling loss, ohmic losses, array mismatch losses, angle of incidence losses, thermal loss factors and module efficiency loss. It then calculates the yield of the system, the state of charge of the battery over the year and any shortfalls in supplied energy.

A number of different solar radiation databases were consulted to provide the most appropriate input solar resource, these included PVGIS (both the Helioclim and Climate-SAF databases), Meteororm 6.1 (internal to *PVSyst*), Meteororm 7 and NREL's openEI database. The first four are based on interpolation of satellite data for a given location (in this case Lemolo B). The NREL data uses its METSTAT model with surface observed cloud being the main input. The nearest observation station to Lemolo B is Nakuru ~40 km due south. A typical metrological year for Nakuru was downloaded from this database. Comparing the five sources, it became clear that the PVGIS Climate-SAF model gave the lowest solar insolation. It was decided to size all the systems based on this data. This does risk the system being significantly oversized (and hence more expensive than necessary) for years with higher solar insolation but it is important to meet the needs of the community at all times.

The village is located very near to the equator in the southern hemisphere and so the orientation for optimum overall yield is 0° tilt and azimuth due north. The loads are constant over the year and the system will need to be sized to meet these loads during the months with lowest solar insolation. Therefore, it is better to tilt the panels to maximise the yield for the month with the lowest solar insolation. The optimum angle varies with the solar radiation database used; from 20° for Meteororm 6.1 to 5° for PVGIS Climate SAF. Losses due to soiling also need to be considered, particularly in these semi-arid lands. Soiling losses can be mitigated by tilting the panels off horizontal to assist run-off during rain. It was decided to use a tilt angle of 20° and azimuth due north for all calculations.

*PVSyst* allows the user to specify hourly load data but does not allow finer detail than this. In some cases, particularly the poshomill and fridge where the loads are likely to peak for short time periods rather than run at constant power for longer time periods, this could lead to inaccuracy in sizing the system. In order to try and mitigate these effects, each system was sized using load profiles with different hourly inputs but the same overall daily load, and the system was chosen to ensure the loads could be met at all times.

The losses specified were taken to be the default values in *PVSyst* as these seemed reasonable for this system. The acceptable loss of load depended on the system being sized. All of systems were sized to ensure that the minimum state of charge of the batteries at any time in the year would be 50% and for most of the year it would be better than 70%. This improves the battery lifetime and reduces the system cost overall. Critical systems such as the egg incubator,

<sup>3</sup> The name posho comes from a type of flour made from maize.



home batteries and lantern charging were designed with 0% acceptable loss of load. This required them to have three days of autonomy to allow for cloudy or rainy days. For the fridge, it would have required an extra day of autonomy to ensure 0% loss of load. This was found to be too expensive so it was decided to increase the loss of load to 1%, relying on the excellent thermal properties of the fridge to compensate. It also proved too expensive to have three days of autonomy for the poshomill. It is a non-critical load so it was designed to have only two days autonomy in order to reduce the overall system cost, resulting in an increased loss of load of 3%. The systems were also sized to account for panel degradation over the lifetime of the project, ensuring the required load could be met throughout the lifetime.

#### 2.4. Financial model

One of the major barriers to successful off-grid rural electrification projects is finding the right financial model. In a 2001 review, Nieuwenhout et al. [10] discussed the main types of finance used for SHS systems in the developing world: donations, cash sales, consumer credit and fee-for-service. They found that the major problem with donated systems was that users were not aware that there would be maintenance costs, and were not willing to pay for them. When users had to pay for a portion of the capital cost it was found that they were more likely to make repairs and save for replacement parts e.g. batteries. Credit schemes were found to be more acceptable to users but it was difficult to persuade creditors to provide loans to rural communities. Cash sales were only accessible to the relatively better off people in these communities. Fee-for-service options gave the providers an incentive to maintain the systems, which benefitted all parties.

In 2012 a new business, M-KOPA, was launched in Kenya allowing households to buy their own SHS in instalments over a year using mobile phone payments [29]. Customers get an 8 W solar panel with two LED lights, a portable solar radio, phone charger and one portable LED torch. The products are guaranteed for a period of two years. This scalable business model is proving very popular with over 150,000 homes connected in Kenya, Tanzania and Uganda in the first two years of business. However, there is no information about the possibility of increasing the size of the systems installed or about replacing broken parts, which leads to questions about the long-term benefits and sustainability of the model.

The model used in this project involves charging individual households a weekly rent for use of home batteries and solar lanterns. The rent should be comparable to what an average household spends on kerosene lighting to ensure it is affordable and therefore sustainable. It needs to cover the capital cost and the on-going operations and maintenance (O&M) costs as well as the cost of periodically replacing the batteries. Within this model there are two options for the system providers: they can retain ownership of the system and continue to generate income by running the system beyond the payback period; or they can incorporate a larger return on investment in the pricing structure and effectively offer a credit service to the village for eventually purchasing the systems. At this point responsibility for battery replacement and operations and maintenance would fall to the village where a legally representative group a 'Village Energy Committee' (VEC) would take on the ownership.

For the income-generating services, the latter model is most appropriate. The VEC will pay the system provider a weekly or monthly fee for the exclusive use of the systems chosen. This fee will cover the capital cost (including the building costs), servicing and maintenance costs and any battery replacement costs within the payback period, in addition to an attractive rate of return for the

investor. After the agreed payback period ownership, and responsibility for maintenance and battery replacement, would fall to the village. The VEC will be responsible for running and managing the systems and levying a fee on individual users. Any profit could be used by the village to expand the available energy services, develop other services in the village, or perhaps even provide microfinance to village entrepreneurs.

The novelty of this model lies in providing income-generating activities, which not only helps in the development of the village but, by increasing the purchasing power of the village, also creates a market for further services. It is flexible in that it allows the village of Lemolo B to choose which system elements they can afford and also allows incremental increase of the services. It should not depend on subsidies or grants and should provide an attractive rate of return for investors.

#### 2.5. Technoeconomic, sensitivity and risk analyses

A technoeconomic analysis was performed to determine the lifetime costs of each system considered and an appropriate price for the service offered. The capital cost of the components for each system was determined by contacting suppliers in Kenya.<sup>4</sup> In addition, solar installers were requested to provide quotations for the balance of systems items, for installing the systems and for servicing packages. In all cases provision was made to replace the batteries in the battery bank at least every five years. The cost of a technician was also factored into the calculations.

There are two options for the building to house the energy centre: a permanent structure built locally or a prefabricated structure delivered to the site. The cost of converting a shipping container to an energy hub was ~\$8,428, while the cost of building a permanent structure locally was ~\$6370 [30]. Therefore, a locally built structure was chosen. The cost of the building was spread among the different services according to how much space was required for mounting the solar modules and for housing the batteries and BoS equipment.

The key performance indicators (KPIs) that were considered when evaluating the financial viability of the system were NPV, IRR, years to break-even and LCOE. They were calculated using the following equations:

$$NPV = -C_0 + \sum_{t=1}^n \frac{A_t}{(1+d)^t}$$

$$LCOE = \frac{C_0 + \sum_{t=1}^n \frac{B_t}{(1+d)^t}}{\sum_{t=1}^n E_t}$$

where  $C_0$  is the total initial capital cost,  $A_t$  is the project's cash flow (revenues – annual costs) in year  $t$ ,  $B_t$  are the annual operating costs,  $E_t$  is the annual energy used, and  $d$  is the discount rate. The IRR is equal to the discount rate that results in an NPV of zero and the years to break even is the value of  $t$  for which NPV is zero. This simple model does not consider the cost of project financing as in our case the source of capital is not known in advance and will be investor-dependent. More sophisticated technoeconomic models include this, such as that described by Bertolini et al. [36] and it could be considered for future work.

Calculations of Net Present Value (NPV) were performed for a payback period of 10 years and a discount rate of 15%. The payback

<sup>4</sup> The suppliers contacted included the Centre for Alternative Technologies Kenya, Chloride Exide, SunTransfer Systems, African Solar Power Systems Ltd., Davis & Shirtliff, Powerpoint Ltd., and Kenital Ltd.

period was chosen to ensure an affordable rent for the VEC while providing enough time to ensure an attractive return for investors. The discount rate chosen was due to the significant risk in serving this low-income community. The following factors must be taken into account in setting the discount rate: most of the solar equipment is imported from overseas and therefore the discount rate must reflect the currency fluctuations (in the last ten years it has varied from below 60 Ksh to over 100 Ksh to the US dollar [31]); the high inflation rate in Kenya (currently standing at 6.62% [5] but varying considerably in the last five years from 4% to 20% [32]); and lending interest rates of ~15% [33]. In all cases the weekly rent from the individual households or from the VEC was informed as far as possible by current prices paid by the community; those for water, maize milling and lighting are outlined in Section 2.1. The upper bound on rent for the income generating services is dictated by what the community could make from running these services.

The sensitivity analysis was performed by varying the value of the capital costs (from -60% to +50% of expected), discount rate (from -50% to +100% of that used), weekly rent charged (from -50% to +60% of suggested weekly rent), operations and maintenance (O&M) costs (from -50% to +60% of expected value) and frequency of battery replacement (from -60% to +60% of expected) for each service and calculating their effect on the NPV. For the water purification, the sensitivity of the NPV to number of litres of water purified from -40% to +100% of expected was also determined. In addition, for the poshomill, a sensitivity analysis on the price per kg of maize milled was performed by varying the hours of use (from -50% to +20% of expected), kg processed per hour (from -80% to +17% of expected) and weekly rent (from -30% to +50% of suggested). For the batteries, solar lamps and egg incubator, the potential financial losses due to system oversizing were determined by repeating the calculations with other sources of solar insolation data. Finally, a simple probability-based risk analysis was performed for the batteries and solar lamps based on the varying cost of kerosene and how that might affect the villagers' willingness-to-pay.

### 3. Results and discussion

#### 3.1. Socio-economic survey

The main employment for residents in Lemolo B is farming or casual labour and over 75% of the households surveyed have no other income sources. Four of the households surveyed had solar home systems, 63% used paraffin lamps, 17% used bottle lamps and 20% used only fires for household lighting meaning a fifth of the community currently does not have money to pay for lighting. Of those that pay for kerosene, the average monthly expenditure was \$4.24, with a range from \$1.96-\$14.70. (To put this expenditure in context, the average income for smallholder farmer households in Kenya in 2009 was \$211 per month [37].) Over half of the households surveyed reported having one mobile phone and a similar number also own a radio. Mobile phones can be charged in

Mogotio. There is also some limited mobile phone charging at the kiosk, which has a solar home system.

Through the SVT, the community was asked to suggest, and rank in order of popularity, services that would improve the village and the lives of its inhabitants. There was a broad range of suggestions, the most popular of which included improved lighting, mobile phone charging, television/radio, improved roads, a health centre, clean water, improved education facilities and electric cookers. Other suggestions included a fridge, an egg incubator, a hairdryer, ironing, irrigation and security lighting. An analysis was conducted on the near-term economic benefit and the ease of delivery via solar power of these suggestions and the following services were selected: improved lighting, mobile phone charging, fridge, egg incubator, maize milling and water purification.

The number of batteries and solar lanterns provided depends on the interest shown by the community and their ability to pay. The village survey indicated that 33% of households spend between \$1.96 and \$3.92 every month on kerosene and 40% spend \$4.41 and over. At the time of the survey the average price of kerosene was ~\$0.78 per litre, since then the average price of kerosene has fallen to ~\$0.59 per litre which means expenditure is currently 25% less [5]. Allowing for the uncertainty in kerosene price, some caution due to the limited survey sample size and experience of earlier projects [14], it was decided to provide enough lighting for ~40% of households in the first instance. This amounts to 60 batteries and 35 solar lanterns and can be expanded if there is further demand.

#### 3.2. System design

Table 1 shows a summary of the technical requirements for each individual system designed using *PVsyst* with the parameters defined in Section 2.3. Suitable modules, batteries and charge/load controllers to meet these requirements were selected from the range available in Kenya.

A number of lighting systems were considered in detail. The systems finally selected were the Fosera PSHS 7000 battery lighting system and the Sundaya Ulitium 200 solar lamp. The Fosera system comes with a LiFePO4 7 Ah battery (usable capacity: 3.6 Ah), two 180 lm (lumens) LED lamps and mobile charging cables. It can also be used to power 90 lm lamps or a 45 lm torch, a Fosera radio system and a fan; each battery can power up to four loads at a time. Multiple batteries can be connected in parallel to increase system power. The battery has an in-built charge controller to protect from overcharge and over-discharge, thereby extending the lifetime of the battery. If the battery is used with the two lamps provided, a single charge can power the lamps for up to 6 h. The Sundaya Ulitium 200 is a single 240 lm LED lamp with an in-built battery, charge controller and low voltage disconnect; the lamp is dimmable to 120 lm and 25 lm. The lamp can provide 6 h at 240 lm, 12 h at 120 lm or 60 h at 25 lm. These systems were selected on the basis of their flexibility, high brightness lamps and their price.

A single system for charging 30 batteries concurrently can be seen in Fig. 2. Three 250Wp panels (Canadian Solar CS6P-250P) are

**Table 1**  
Summary of technical requirement for each individual system offered.

Sub-system	System Size [Wp]	System Voltage [V]	Battery Capacity [Ah]	Charge Control	Maximum Load Current [A]
Home Batteries	750	24	300	PWM	40
Solar Lamps	250	24	150	MPPT	15
Poshomill (a)	1500	24	400	MPPT	45
Poshomill (b)	1800	24	800	MPPT	70
Egg incubator	300	12	200	MPPT	45
Fridge	135	12	150	MPPT	15

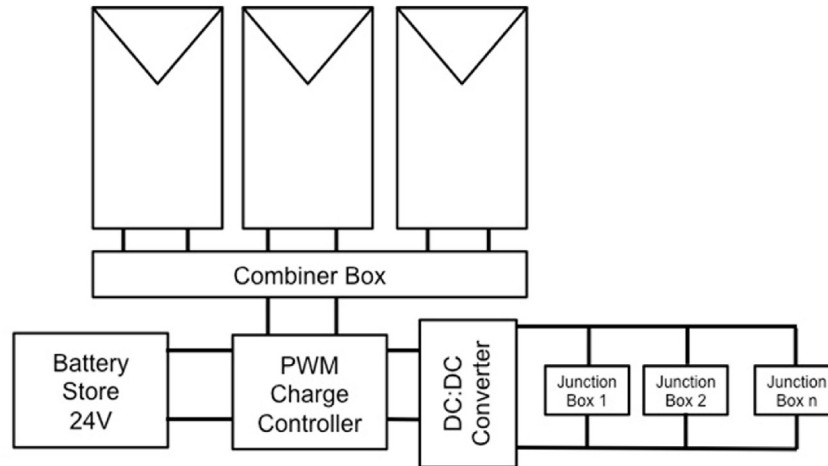


Fig. 2. Schematic of system for charging home batteries.

wired in parallel (26.7 V and 25 A) and fed to a 40 A Pulse Width Modulation (PWM) charge controller. The charge controller charges the 300 Ah battery bank (four 12 V 150 Ah batteries connected two in parallel and two in series) and provides a steady 24 V to the load. The load comprises five junction boxes in series (~4.8 V available to each junction box) connected to the charge controller via a DC:DC converter to ensure the correct voltage at the batteries.

There is a hub available commercially for charging up to four solar lamps at a time. These hubs can be connected in parallel to charge more than three lamps at once from a single panel. They require the voltage to be between 16 V and 24 V and the current to be at most 0.5 A. Therefore, a single 250Wp (24 V, 8.3 A) panel can charge up to 35 lamps at once with 9 hubs connected in parallel.

The poshomill is expected to grind up to 30 kg of maize per hour using the 1HP 750 W DC motor. Two options were considered. The first (a) serves up to 50 households, meaning 4 h of operation are required every day. This load can be met by five 300Wp modules connected in parallel (32 V, 41.8 A) feeding a 60 A maximum power point tracking (MPPT) charge controller and a 24 V 400 Ah battery bank comprising four 200 Ah batteries (wired two in series and two in parallel). The available MPPT charge controllers at this rating do not offer load control so a separate 45 A load controller will connect the poshomill to the battery bank. In the second option (b) daily operation was maximized, assuming 7 h of operation per day, thereby serving up to 100 households. This load could be met by six 300Wp modules connected in parallel feeding a 70 A MPPT charge controller and a 24 V 800 Ah battery bank comprising eight 200 Ah batteries (wired two in series and four in parallel). The load controller was unchanged.

The system for the egg incubator comprises a 300Wp module feeding a 50 A MPPT charge controller and a 12 V 200 Ah battery; it also required a separate load controller. The fridge system requires a small enough module (135Wp) to be compatible with the Blue

Solar 15 A MPPT charge controller, which incorporates load control (it can tolerate a maximum of 200Wp at 12 V). All of these sub-systems are variations of the set-up shown in Fig. 2; their schematics can be found in the [supplementary material](#). The water purification system is much smaller and bought complete from the supplier so there was no need to design a system for this.

### 3.3. Technoeconomic analysis and pricing model

All of the systems except for the poshomill were found to be financially viable. Table 2 summarises the key results for each system. The battery system is the most profitable. By charging each user \$1.08 every week, an IRR of 25% could be achieved and the capital costs would be fully paid back after just 5.5 years. At ~\$4.66 per month, this rent is close to the average spend on kerosene and is well within the budget of 60 households in the village so it should be possible to rent all the batteries. It would be feasible to charge just \$0.98 per week and still have an IRR of 21%, however, the solar lamps system is more expensive and there needs to be a reasonable price differential between them. The solar lamps require a minimum weekly rent of \$0.69 in order to make a reasonable return for investors, IRR of 18%. At this price, it takes 7 years to pay back the capital costs. This price is justifiable because although there is only one light and no mobile phone charging, the light is brighter than those offered by the battery system and it has three brightness settings.

The remaining systems will be rented to the VEC rather than individual users. For these systems, the aim was to produce an IRR of ~20% for investors. In order to do this the rent that needs to be charged is \$15.19 per week for the egg incubator, \$15.68 per week for the fridge and \$24.99 per week for the water purification. Comparing the price of an egg and a hen shows that this rent will allow the VEC to make a profit from running the egg incubator of up

Table 2  
Results of technoeconomic analysis and pricing model for different systems.

System	Home Batteries	Solar Lamps	Poshomill 1	Poshomill 2	Egg Incubator	Fridge	Water Purification
Capital Costs [\$]	9155	3507	6758	8264	2705	2836	5137
O&M Costs [\$/yr]	245	123	245	245	123	123	49
Weekly Rent [\$]	1.1	0.7	24.7	34.8	15.2	15.7	25.0
NPV [\$]	3681	427	-2339	-2007	535	514	1012
IRR [%]	25	18	4.4	7.5	20	19.7	20
Years to Break Even	5.5	7	>10	>10	6	7.3	6

to \$1205.40 per year, depending on the number of eggs hatched. (The local price of an egg is \$0.10 and of a fully-grown hen is \$2.94.) The cost of purifying water with this system is \$0.01–0.02 for 20 L (depending on volume purified each day) and is much cheaper than buying clean water from Mogotio; it should be affordable for even the poorest in the village. The VEC could increase the price to make a profit for other activities and services. It is not clear how the VEC plans to use the fridge but even if they decide against using it for income generating activities, it should be possible for them to pay the rent on it from the profits made from the egg incubator and water purification system.

It was not possible to make the solar powered poshomill service profitable at a price comparable to the existing diesel-powered poshomills in the village. Of the two systems considered the second one, which maximized the use of the poshomill, was more economical. In order to make the investment attractive (IRR~20%) the weekly rent charged would require a price of \$0.04/kg for the larger system and \$0.05/kg for the smaller system, which is uncompetitive. Pricing at \$0.03 Ksh/kg (the same as the diesel poshomills) resulted in an IRR of just 4.4% and 7.5% for investors, which is far too low to be attractive. The calculations were rerun using the data with the highest solar insolation (Meteonorm 7) and showed that a charge of \$0.03/kg and \$0.04/kg respectively would be required to break even, meaning the system was still not financially viable.

### 3.4. Sensitivity and risk analysis

NPV is most sensitive to changes in the weekly rent followed by changes in the capital cost and discount rate as can be seen in Fig. 3 for the batteries. The same trend was found for the other systems. The O&M costs and battery replacement frequency have much less of an effect on the NPV except for the larger poshomill system where the batteries make up a large part of the capital cost and so the consequence of having to replace them frequently is a stronger negative impact on the NPV.

The capital cost is set by the system power and solar insolation. All of the systems were sized for the worst-case scenario, ensuring the power requirements could be met by the lowest solar insolation data for the entire lifetime of the system. Higher solar insolation

would allow capital costs to be reduced and/or more power to be drawn from the same system to, for example, charge extra batteries or solar lamps. Table 3 shows how many extra batteries could be charged by the same system for different solar insolation databases, along with the NPV for the expanded system and the potential lost revenue due to conservative system sizing. The most optimistic solar insolation data, Meteonorm 7, suggests the number of batteries being charged by the system could be increased by a third; resulting in a significant increase of revenue for the investor, or alternatively the possibility to reduce the rent charged to the user. In the real system, it would be valuable to measure the output of the solar modules and if the system is oversized, increase the number of batteries being charged daily.

The biggest risk to the profitability of the systems proposed is the willingness-to-pay of the villagers. For example, kerosene and diesel prices depend on the cost of Brent Crude Oil. It was \$80 a barrel in Nov 2014, fell to \$28 a barrel in Jan 2016 and was \$52 a barrel in April 2017. This means that households could be spending less on kerosene for lighting than they did and might find the proposed weekly rent too expensive. A calculation was carried out to determine the effect on the NPV of having to reduce the weekly rent in response to a fall in kerosene prices without being able to increase it if the price of kerosene increases. It was found that the NPV could fall from \$3681.07 to \$2554.44 for the home batteries and from \$427.26 to \$9.05 for the solar lamps. This indicates that it might be prudent to increase the rent for the solar lamps to \$0.74 per week, which would ensure a NPV of \$426.75 even if prices were forced down due to lower kerosene costs.

Another threat to the lighting system could be the arrival of grid electricity; the President of Kenya is making rural electrification a priority for his government [6] and grid electricity could be available at Lemolo-B in the next few years. The Levelized Cost of Electricity (LCOE) provided by the home batteries is \$2.72/kWh and by the solar lamps is \$2.67/kWh. In order to compare with grid electricity, an estimate of the LCOE of grid electricity was made. The connection cost to each house is \$147 [6] but in addition the households have to pay for electrical wiring and appliances such as light bulbs. The monthly fixed charge for grid electricity in Kenya is \$1.47 and in addition to the unit price there are government levies

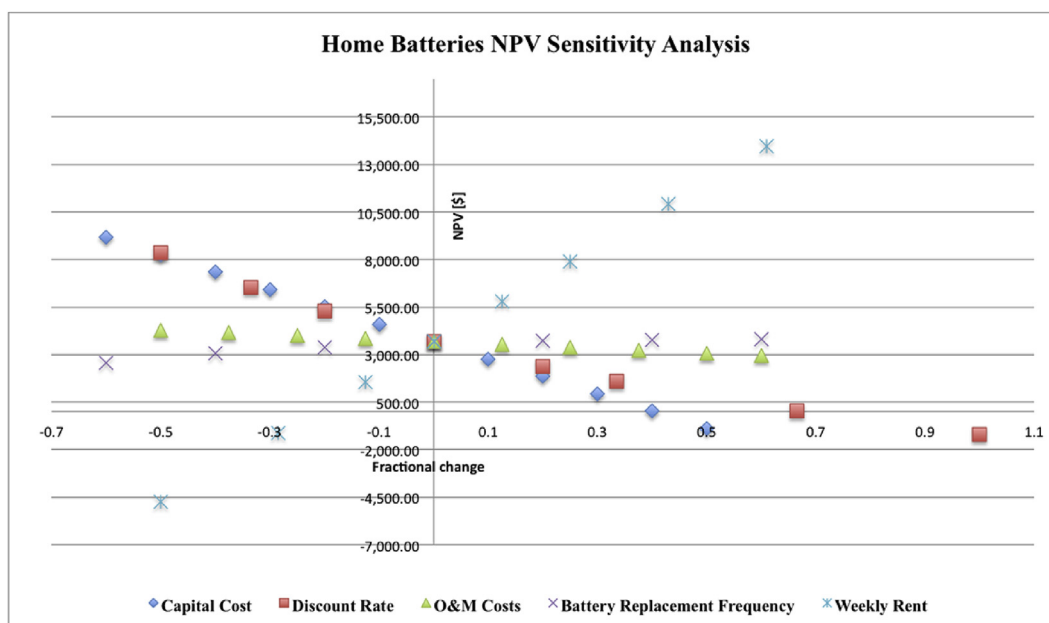


Fig. 3. Dependence of Net Present Value of home battery system on fractional change in key parameters.



**Table 3**

Dependence of NPV on different solar insolation (or meteo) databases. Higher solar insolation allows more home batteries to be charged from the same system, increasing the revenue and the NPV. In all cases the system was sized to ensure 0% loss of load throughout the lifetime.

Meteo Database	Number of Batteries	NPV [\$]	Lost Revenue [\$]	Lost Revenue [%]
PVGIS Climate SAF	60	3681.07	0.00	0.00
PVGIS Helioclim	60	3681.07	0.00	0.00
Meteonorm 6	70	5694.06	2012.99	54.7
Meteonorm 7	80	7609.04	3927.98	106.7
NREL - Nakuru	75	6749.55	3068.48	83.4

[34]. For the same amount of energy provided as the home batteries and the same discount rate and lifetime payback period, the LCOE for grid electricity in Lemolo-B is estimated to be ~\$3.45/kWh. Grid electricity in Kenya is generally unreliable with frequent power cuts, while the system here has been designed to provide reliable power. Therefore, even if grid electricity is made available in the near future, it is not likely to threaten the financial viability of this project.

#### 4. Conclusion

The aim of this study has been to design energy service provision for the village community of Lemolo B. It has been shown that it is possible to provide affordable and financially sustainable electricity services to this off-grid rural community in Kenya using a solar energy centre model without the need for subsidies or grants. The socio-economic survey indicated there was need for this energy intervention. In addition to lighting services, it is possible to offer income-generating activities to village communities in order to support their economic development. The financial model demonstrates cost is competitive with existing energy sources and with grid electricity, and offers a more reliable service than grid electricity or alternatives such as solar home systems. Furthermore, the socio-economic evaluation indicated it could be affordable. At the same time, it offers an attractive low-risk return for investors, making wide deployment across Sub-Saharan Africa more feasible. The sensitivity analysis indicated the importance of capital cost and battery replacement costs. Global forecasts on the purchase cost of PV modules and batteries are downward which should further reduce the effects of these sensitivities. Throughout the research consultation with the community has taken place to assist in the design of the 'energy centre' [35] and a future research will include performance data from monitoring and evaluation of the subsequently installed systems to benchmark performance against the model developed here.

In summary, the solar energy centre model offers affordable, reliable and flexible energy provision compared to other systems such as solar home systems and microgrids. There is less opportunity for energy theft than in microgrids where illegal lines have been added [11,18] in some schemes and there is system autonomy provided by an energy centre, which is missing in solar home systems. Like a microgrid, it can offer additional services such as income generating services, offering the communities a chance to lift their technoeconomic status. In addition, we have shown that all this can be provided with an attractive return for investors making it more likely to be a scalable model.

#### Acknowledgements

The authors would like to thank Anna Clements from Oxford University, UK and Dr Yong Wu from Wuhan University of Technology, China for useful discussions, and Dr Tom Betts for providing access to Meteonorm data. Furthermore, we would like to thank project team members, Dr Ed Brown, Dr Alison Mohr, Dr Jon Cloke, Evan Kimani, Dr Jon Leary, Arran de Moubray as well as the

community in Lemolo B. This work was part funded by UK Engineering and Physical Sciences (EP/L002612/1) Research Project: Solar Nano Grids.

#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.renene.2017.11.053>.

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