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

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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.

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;

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Nomenclature

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

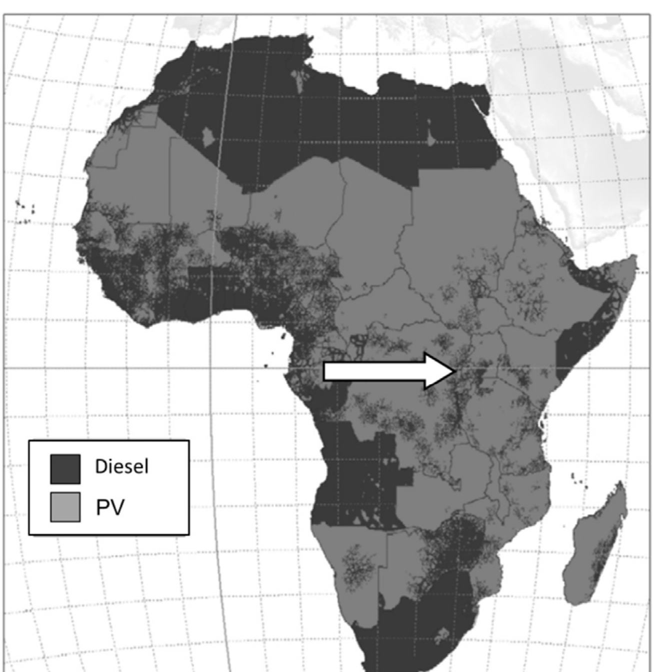

Fig. 1. Regional differences in the feasibility of PV and diesel across Africa. The arrow marks the location of Rwanda [3].

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.