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Loss-of-load probability analysis for optimization of small off-grid PV-battery systems in Bolivia

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Abstract

This study evaluates the use of energy storage technologies coupled to renewable energy sources in rural electrification as a way to address the energy access challenge. Characteristic energy demanding applications will differently affect the operating conditions for off-grid renewable energy systems. This paper discusses and evaluates simulated photovoltaic power output and battery state of charge profiles, using estimated climate data and electricity load profiles for the Altiplanic highland location of Patacamaya in Bolivia to determine the loss of load probability as optimization parameter. Simulations are performed for three rural applications: household, school, and health center. Increase in battery size prevents risk of electricity blackouts while increasing the energy reliability of the system. Moreover, increase of PV module size leads to energy excess conditions for the system reducing its efficiency. The results obtained here are important for the application of off-grid PV-battery systems design in rural electrification projects, as an efficient and reliable source of electricity.

Keywords: Photovoltaic; Energy storage; State of Charge; Renewable Energy; Rural Electrification; Li ion batteries.

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1. Introduction

During the last two decades, significant progress has been made in Bolivia regarding electricity access. Nevertheless, 28% of the total rural population has still no access to electricity [1]. Rural electrification in developing countries is closely related to poverty reduction and economic development [2, 3]. Therefore, the Bolivian government, as member of the SE4ALL initiative, has established the challenge to achieve 100% access to electricity by the year 2025 as part of the “Agenda Patriotica 2025”, a development strategy proposed by the government [4]. Although the plans to extend the electrical grid to achieve this goal, remote and disperse communities still need to be electrified, mainly using local renewable energy sources such as high sun irradiation which is the case for the Altiplanic highlands region in Bolivia.

The analysis of the system’s energy reliability can be determined based on energy supply interruption (i.e. condition of blackouts). The reliability study for off-grid PV systems is based on the system’s energy balance estimation over long time periods using a simulation process with radiation and consumption data as inputs. The comparison of different system designs operating under the same conditions was found to be very useful to choose an optimal design. This comparison can be performed using energy reliability studies [6, 7].

Although most of the studies focus on the evaluation of the impact of renewable sources intermittence on the lead-acid battery type lifetime, ageing of lithium-ion type batteries are not well understood yet [8, 9]. The evaluation of off-grid applications in remote and disperse areas where high irradiation is available need to be addressed in order to deliver systems with efficient and optimal design. This not only assures the sustainability of most rural electrification projects but also have a great significance on the adoption of renewable power technologies as reliable alternatives to the traditional ones.

This study discuss and evaluate SOC profiles calculated for three different remote and disperse rural applications; household, school and health center. The PV-battery system power output was simulated based on climatic and geographical data of the Altiplano region of Bolivia. Moreover, annual SOC profiles data were obtained from this simulation and are further used to evaluate the energy reliability of the system for 12 different PV and battery sizes and the three different applications and scenarios.

The paper is organized as follows: In section 2 we started by estimating the electrical load profile (consumption) for three applications, then a method to calculate the power output from the PV is proposed using solar irradiation, weather and geographical data from the Patacamaya region; finally, the calculation procedure for the battery state of charge based on the power output and load calculated previously is presented. In section 3 we present the results and discussion section by comparing four PV-battery designs for each of the three applications, to analyze the reliability level computed among them, also, a detailed analysis of the calculated SOC curves is performed in a daily base. Finally in section 4 the conclusions are presented.

2. Methods

2.1. Load profile estimation

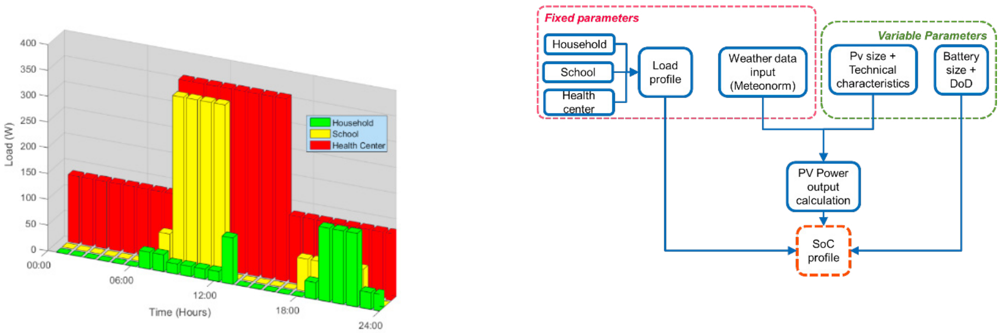
Electrical power consumption profiles were estimated for a household, school and health center in the rural Altiplanic region of Bolivia. Electricity consumption in rural areas is restricted to basic needs such as lighting, communication (radio and TV), phone charging, and in the case of health centers refrigeration appliances are considered. Meier et al. [10] describes the most common used appliances by households in the Altiplanic region and the amount of usage hours per day for radio and TV. Furthermore, for the case of school and health center the type and number of appliances were determined from reports of rural electrification projects previously executed in Bolivia [11]. The power consumption and usage time for a household, school and health center are shown in Table 1.

Table 1. Power consumption for Altiplanic rural users in Bolivia

Final use	Description	Power (W) [1]	Quantity [2]	Hours/day [3]	Total power (W) [1x2]	Wh/day [1x2x3]
Household	Compact Fluorescent Lamp	11	3	5	33	165
	TV	90	1	4	90	360
	Radio	20	1	4	20	80
	Phone Charger	10	2	3	20	60
School	Compact Fluorescent Lamp	11	6	5	66	720
	TV	90	2	4	180	720
	Computer	20	1	4	180	330
	DVD player	10	2	4	44	176
Health center	Compact Fluorescent lamp	11	4	8	180	1440
	Computer	180	1	8	44	352
	Refrigerator	130	1	24	130	3120

Battery sizes were estimated according to the energy needed to satisfy the load profile for two and three days of autonomy. The school load profile presents two days with no energy consumption during the weekends, therefore the battery will only perform charge processes. Fig. 1-a shows the estimated load profile corresponding to the proposed three applications.

Besides television, radio, and mobile phone charger, the most desired appliance among remote and disperse rural population is lighting. Therefore, the power consumption peaks during the morning and evening for household and school belong to the usage of TV, radio, DVD player, and computer, while lighting run as background load. The distribution of the usage hours were estimated following the energy consumption behavior of rural household in Bolivia presented by Espinoza et al. [12]. The benefits and importance of lighting among the previously mentioned appliances used in rural electrification, lies on education, health and environmental aspects of the rural community [5].



a) b)

Fig. 1. a) Estimated daily load profile for a school, health center, and household; b) State of charge calculation scheme

2.2. Climatic data and solar module simulation

Climatic data for the south-west Altiplanic highlands region in Bolivia close to Patacamaya's location (Latitude: 17°14'S; Longitude: 67°55'W; Altitude: 3789 m.a.s.l.) was obtained from a global climatic database, Meteonorm [13]. Among several climatic parameters, this database includes global horizontal radiation (W/m^2), diffuse horizontal radiation (W/m^2) and ambient temperature (°C). The PV module was assumed tilted 15° facing north to generate maximum power. Tilt correction was performed according to [14]. Simulation of the solar module power output was performed using a mathematical model used by [15].

2.3. State of Charge calculation

The battery SOC was calculated for a typical year with hourly resolution using data from the PV module power output model and the load profile, following the scheme showed in Fig. 1-b. Equations (1) and (2) were used to calculate discharge and charge processes respectively:

$$P_b(t) = P_b(t-1)(1-\sigma) - \left(\frac{P_{PV}(t)}{\eta_i} - P_l(t) \right) \tag{1}$$

$$P_b(t) = P_b(t-1)(1-\sigma) + \left(P_{PV}(t) - \frac{P_l(t)}{\eta_i} \right) \eta_b \tag{2}$$

where $P_b(t-1)$ and $P_b(t)$ represent the battery energy at the beginning and the end of the interval t, respectively, the load demand at the time t, the energy generated by the PV module at the time *t*, σ the self-discharge factor and η_b, η_i the battery charging and inverter efficiency, respectively as presented in [15].

3. Results and Discussion

Summarized over one year, Table 2 shows the time-fraction values at which the battery SOC remains at 20%. In other words, the time-fraction values corresponding to battery depletion or system's blackout.

Among several battery and PV sizes, only the three most realistic cases were identified for the reliability evaluation. Low Energy Reliability (**LER**, Bold in Table 2) stands for those cases with relatively high time-fraction values at SOC ⩽ 20%, this configuration corresponds to a smaller PV, but with a battery which should last during 3 days without charging (e.g. rainy and cloudy days); High Energy Reliability (*HER*, Italic in Table 2) stands for those cases with the lowest (close to zero) time-fraction values at SOC ⩽ 20%, and 3 day battery size; finally, Optimal Energy Reliability (OER, Underlined in Table 2) stands for those cases with low times-fraction values at SOC ⩽ 20% and 2 day battery size. Thus, the OER case would be the optimal due to the reduction in battery size without considerably increasing the time-fraction value at SOC ⩽ 20%, therefore a cheaper option.

Table 2. Time-fraction (as percentage) at which the SOC remains at 20% level (**LER**, *HER* and OER indicated).

Final Use	PV power (W)	1.5 kWh*	2.2 kWh**
Household	80	48.37	**49.25**
	160	1.12	*0.00*
School		3.4 kWh*	5.1 kWh**
	190	4.43	**3.53**
	380	0.02	*0.00*
Health center		9.8 kWh*	14.7 kWh**
	500	68.03	**67.75**
	1000	0.43	*0.00*

* Battery size intended for 2 days of autonomy.
** Battery size intended for 3 days of autonomy.

Increasing the size of the battery leads to smaller time-fraction with blackouts (e.g. SOC⩽20%). However, when the PV size and its power production is too small, a larger battery has no positive impact. Moreover, the lifetime of the battery is affected due to long periods remaining at high SOC which leads to harmful calendar aging. This is mainly due to side reactions happening in the electrodes/electrolyte interphase reducing the amount of cyclable lithium, thus, a reduction on the cell capacity [17].

Variation in design parameters (e.g. PV module and battery size) result in cases where the system reach zero or close-to-zero time-fraction values at SOC ⩽ 20% which seems to directly affects the energy reliability of the system. However, it is important to note that increasing the PV module size does not indicate the same cost as increasing the battery size.

3.1. Household

Figure 2-a shows a typical day load and SOC profile for a rural household. The load profile (green bars) shows two peaks, which take place in the morning from 6 AM to 12AM and the evening from 6 PM to 12PM. Power consumption is below 150W which is relatively low compared with an urban household.

The increment of battery size increases the electricity production to consumption ratio, this is the fluctuation amplitude of the battery's SOC. Furthermore, the value of this ratio determines if the battery is operated in either safe or harmful zone, which depends directly on the demand profile and design of the system for each case.

Although the **LER** case present a blackout in the system from 10PM to 8AM due to the small size of the PV module, the *HER* and OER cases shows a stand-by time-fraction in the same period of time, where the battery remains at 76% and 64% SOC respectively. The battery charge/discharge process is related to the cycling ageing process whereas the stand-by time-fraction at a certain SOC level is related to the calendar ageing.

a) b) c)

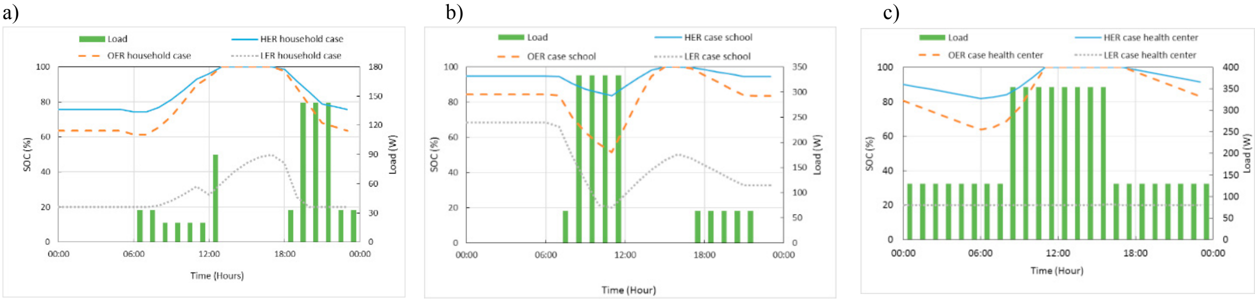


Fig. 2. Daily household (a), school (b) and health center (c) SOC and load profiles.

3.2. School

Fig. 2-b shows a typical daily SOC profile for a school. We observe SOC profiles presenting high technical reliability for the three cases. Although the **LER** case shows high reliability (see table 2), the OER case would represent the optimal case since the battery size is smaller and the variation of the SOC range is shorter, between 55% and 100%. Due to the particular load profile of a school we expect to observe a gradual decrease of SOC during the week which is recovered during the weekends.

3.3. Health center

Fig. 2-c shows a typical hourly SOC profile for a health center during an entire day. The **LER** case shows an SOC profile constantly around 20%, which means large periods of blackouts due to the small PV-panel size. The energy production is not enough to fulfill the demand. On the other hand, both *HER* and OER cases show SOC profiles values around 60% and 100% which means high energy reliability, this is partially due to the good synchronization between PV production and consumption profiles. However, the battery remains at 100% SOC for almost 6 hours during the day, therefore, the energy produced is not used, this leads to low system efficiency, and since it is not possible to sell the energy surplus the system becomes inefficient. Furthermore, the calendar ageing of the battery when it remains for prolonged times at high potentials (e.g. 100% SOC) is higher, causing unwanted ageing effects and impact on the life cycling. The usage of efficient and smart appliances, software and hardware, for distributed systems in rural electrification will increase in the future, due to the fast drop in hardware prices. The advanced software can enable grater control and integration of the system components. Such components can be used to storage energy. For instance, during surplus energy generation periods vaccine refrigerators could be used as energy buffer. Therefore, the saved energy allows the battery to recharge quickly, avoiding blackouts (e.g. SOC $\leqslant$ 20%).

3.4. Suppressed demand and usage fluctuations

The usage fluctuations are related to variation in daily solar irradiation, load profiles and suppressed demand. Daily solar irradiation depends on seasonal and weather conditions, thus, the impact on SOC profile can be predicted by using accurate climate data for the geographic region under study. Moreover, load profiles are hard to predict for a particular user, however, stochastic models can generate accurate enough profiles which along with demand side management can be used for the optimization process. Finally, suppressed demand defined here as any variation in the amount of electrical power or energy demanded by customers but not supplied by the power plant, a PV-battery system in this case, lead to undersized systems which can be avoided by including them in the optimization process.

4. Conclusions

The application of computational methods to calculate the SOC profiles for distributed systems applications can contribute to the systems design improvement and optimization. The analysis of the three different cases shows how this information can be used to identify the most suitable option to be developed. However, more efforts need to be assigned to the experimental validation of these profiles in order to gain deeper understanding on the impact of SOC profiles variation on the cycle life of the battery.

The simulations performed for a household, school, and health center shows two cases with acceptable energy reliability: this is, Optimal Energy Reliability and High Energy Reliability. Although the difference in performance is similar, the first one should be the adequate one for the system design, since its lower initial investment cost due to a smaller battery size. The school is the only case where a weekend factor has been considered. The assumptions made for the load profile in all the cases play an important role, moreover, the seasonal load variation is not being accounted for which could have a large impact.

As a conclusion, the implementation of stand-alone PV systems in rural areas should include a reliability assessment based on its SOC profile. For that, the cycle life of the battery, as a key component of the system, need to be evaluated trough extended laboratory and field work.

5. Acknowledgement

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