Feasibility Study of PV & Li-Ion Battery Based Micro-Grids for Bolivian Off-Grid Communities

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Abstract:

In the rural areas of Bolivia, where about a third of the people lacks access to reliable electricity, both a complex geography and a scattered population make the costs of extending the national grid prohibitively high. As an alternative, we evaluate the feasibility of an isolated micro-grid, composed by Li-ion batteries and Photovoltaic (PV) panels, for a Bolivian remote community living without access to electricity. We surveyed two remote rural villages to assess the potential electricity consumption patterns of the population once provided access to electricity. We estimated the average demand profile using the tool *LoadProGen*, and we collected local techno-economic and solar irradiation data of the zone. We employed such data as inputs in a robust linear programming-based optimization tool to determine the capacities of the Li-ion battery bank and the PV array that minimize the net present cost (NPC) of the system.

Keywords:

Isolated micro-grids, Solar energy, Optimization, LoadProGen, Li-Ion Batteries, Bolivia.

1. Introduction

Bolivia is one of the poorest countries in Latin America where the mountain chain of the Andes and the Amazonian tropical forest converge. This economic and geographic situation has created many challenges to the development of basic infrastructures across the country, especially regarding the electricity sector. Figure 1 shows that transmission and distribution networks reach only a portion of all the inhabited villages: approximately 32% of people living in rural areas lack access to reliable sources of energy [1].

From an economic and environmental point of view, the extension and densification of the main grid is not an option to achieve 100% of energy access in rural areas [3]. On the other hand, Bolivia has high solar radiation [4-5] (due to the proximity of the equator and the altitude), vast experience in solar technologies [6] and one of the biggest reserves of lithium in the world [7]. All these aspects combined make micro-grids based on photovoltaic (PV) panels and Li-ion batteries a suitable and convenient alternative to supply electricity to the most isolated areas in Bolivia.

However, exploiting solar energy for off-grid rural electrification faces some major challenges, especially due to the stochastic nature of the solar resource and eventual electricity demand (*viz.* load profile). These can have a serious impact on the sizing of the micro-grid, and the stability and reliability of the energy supply. In addition, as analysed in [8-9], an insightful analysis on how the electrification process impacts the electricity-user's behaviour is generally lacking when planning a micro-grid, as well as a generalized underestimation of the social aspect during the design phase.

In this paper, we rely on a bottom-up approach, first generating different energy load scenarios through the *LoadProGen* tool [10] and then, sizing the micro-grid using a robust linear programming (LP) model, with the objective of minimizing the net present cost (NPC). With this synergy, we propose a flexible procedure that considers the variability of both load and solar resource when assessing rural electrification projects. Following the current push towards open source modelling [11], the scripts for the optimization are made available in an open repository with the publication of this work.

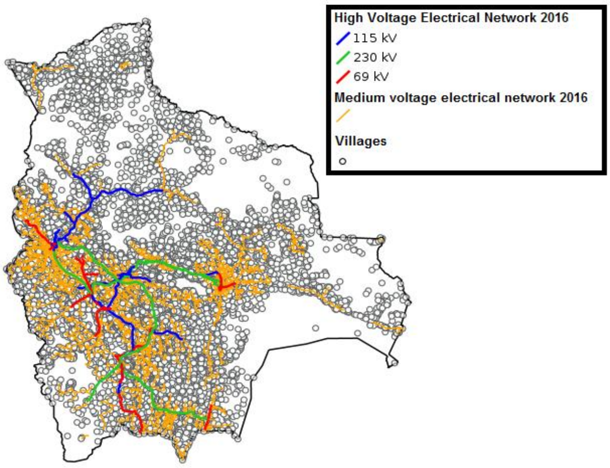

Figure 1. Localization of Bolivian villages and the transmission and distribution networks [2].

1.1. Methodology

To evaluate the feasibility of an isolated micro-grid, we conducted two local surveys in two Bolivian communities– one without access to electricity and the other with electricity. With this information, we determined the future electricity consumption patterns of the population currently lacking access to electricity, and derived local techno-economic information and solar irradiation data. Hereafter, 6 yearly demand profiles are estimated by relying on the software *LoadProGen* and the gathered data.

The simulation of the PV generation was realized using a five parameters model [11] implemented in the *Modelica* language and calibrated with manufacturer data from commercial PV arrays. The a-causal approach of this modelling language allows using more complex and accurate models by disregarding the numerical aspect of the solution of the problem. Temperature and solar irradiation profiles are the main inputs of the model.

Finally, the collected generation and demand data are used as inputs in a robust linear programming-based optimization tool determining the nominal capacities of the Li-ion battery bank and the PV array by minimizing the Net Present Cost (NPC) of the system.

2. Modelling

The analysed supply system comprises a load supplied with electricity through a PV array connected to an inverter and a battery bank. Figure 2 shows the system layout. The main optimization variables are the energy flows between the different components (i.e. the dispatch of the battery) and the nominal capacities of the PV array and the battery Bank. As part of the optimization process the energies flow from both energy sources and the lost load in the system are optimized. The LP optimization is implemented in Python language using the Pyomo Library and CPLEX as the selected solver. The time step of the load and irradiation data is 1 hour and the optimization horizon is 1 year.

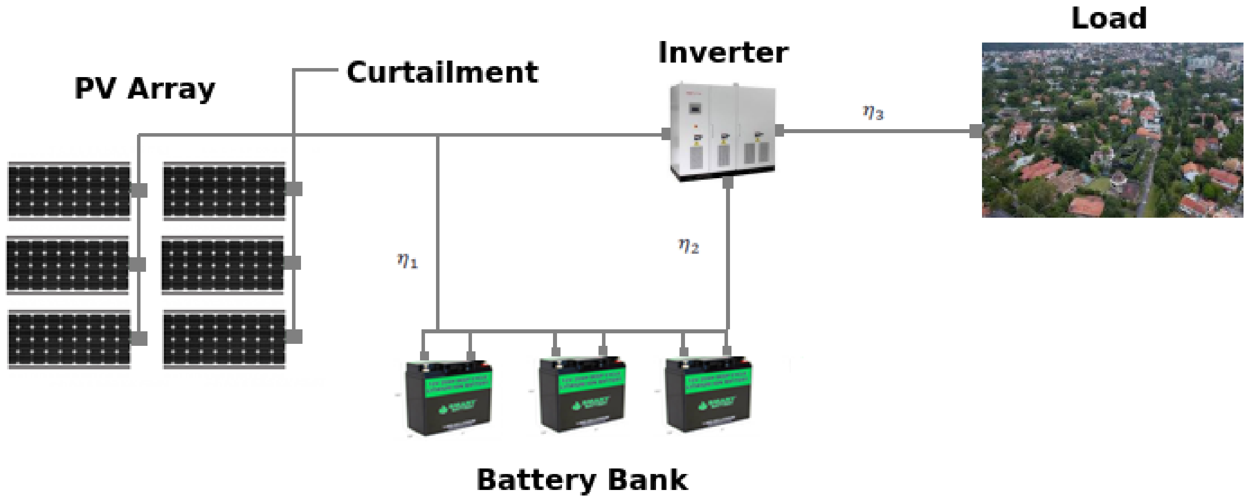

Figure 2. The considered micro-grid typology.

2.1. System characteristics

2.1.1. Solar irradiation

Because historical PV generation data is not available for the selected areas, it had to be estimated from weather data. The available data is the direct and diffuse irradiation on a horizontal surface. We therefore, relied on the isotropic sky model [12] to derive the value of the total radiation on a tilted surface, as explained in equation (1).

$$I_{T\beta}(j,t) = I_b(j,t) * R_b + I_d(j,t) * \left(\frac{1+cos\beta}{2}\right) + I(j,t) * \rho_g * \left(\frac{1-cos\beta}{2}\right) \qquad \forall j, \forall t \qquad (1)$$

Where $I_{T\beta}$ (W/m^2) is the total irradiation on the tilde surface with angle β (^{o}). I_b (W/m^2) is the direct irradiation on the horizontal surface, R_b is the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface, I_d is the diffuse radiation on a horizontal surface, I (W/m^2) is the total irradiation on the horizontal surface, ρ_g is the albedo of the reflected surface, t is the period, and j is the scenario analysed.

2.1.2. PV array

To calculate the energy yield of one PV module, i.e. $E_{pv,m}$ (Wh), we relied on a simulation tool written in the *Modelica* language. The PV array is modelled with the equivalent circuit as presented in Figure 3.

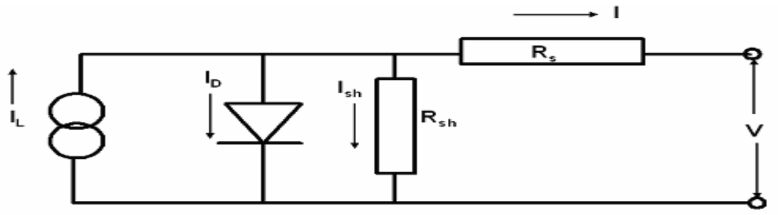

Figure 3. Equivalent circuit of a PV: adapted from [11]. I_l is the light current, I_D is the current in the diode, I_{sh} is the current in the shunt resistance, R_s is the series resistance and R_{sh} is the shunt resistance

The principal advantage of this methodology is the use of detailed electrical relationships that allow considering the influence of the voltage on the PV yield. In this work, we consider a perfect maximum power point tracking (MPPT) controller, which maximized the generated power. The final parameters of the model are the short circuit current, the open circuit voltage, the current at the maximum power point, the voltage at the maximum power point, the slope of the I-V curve at the short circuit point, the slope of the I-V curve at the open circuit point and the nominal operation cell temperature. The values of these parameters for more than 10,000 different commercial PVs are available in the SAM PV library [13].

Besides $I_{T\beta}$, the temperature in the photovoltaic cell T_c(°C) is also needed in the model and can be estimated with equation (2). where T_{amb}(°C) is the ambient temperature.

$$T_c(j,t) = T_{amb}(j,t) + \frac{NOCT-20}{800} * I_{T\beta}(j,t) \quad \forall j, \forall t \tag{2}$$

The production of the whole array is written E_{pv} (Wh) and is provided in equation (3). It takes into account N_{pv}(units) as the number of PV installed and the efficiency η_{inv} (%) of the inverter.

$$E_{pv}(j,t) = \eta_{inv} * E_{pv,m}(j,t) * N_{pv} \forall j, \forall t \tag{3}$$

2.1.3. Battery Bank

The battery bank is modelled through equation (4), where SOC_{bat} (Wh) is the state of charge of the battery. The energy into and out of the battery are denoted by $E_{bat,ch}$(Wh) and $E_{bat,dis}$ (Wh).Finally the charge and discharge efficiencies are given by as η_{ch} (%) and η_{dis} (%).

$$SOC_{bat}(j,t) = SOC_{bat}(j,t-1) + E_{bat,ch}(j,t) * \eta_{ch} - E_{bat,dis}(j,t)/\eta_{dis} \quad \forall j, \forall t \tag{4}$$

Equation (5) ensures the optimal operation and life time of the battery bank by maintaining the SOC above the minimum depth of discharge DOD (%) and below the nominal capacity of the battery C_{bat} (Wh).

$$C_{bat} * DOD \leq SOC_{bat}(j,t) \leq C_{bat} \; \forall j, \forall t \tag{5}$$

The charging and discharging powers $P_{bat,ch}$ and $P_{bat,dis}$ are limited by equations (6) and (7), respectively.

$$P_{bat,ch} = C_{bat}/t_{bat,ch} \tag{6}$$

$$P_{bat,dis} = C_{bat}/t_{bat,dis} \tag{7}$$

Where $t_{bat,ch}$ (hours) is the minimum time that the battery takes to fully charge and $t_{bat,dis}$ (hours) is the minimum time that the battery takes to completely discharge.

Equations (8) and (9) limit the energy from and into the battery bank, where Δt (hours) is the time step of the optimization.

$$E_{bat,ch}(j,t) \geq -P_{bat,ch} * \Delta t \forall j, \forall t \tag{8}$$

$$E_{bat,dis}(j,t) \leq P_{bat,dis} * \Delta t \forall j, \forall t \tag{9}$$

2.2. Objective function

The optimization is expressed as a linear programming (LP) problem. The objective function minimizes the sum of the multiplication of the net present cost NPC (USD) of each scenario and their probability of occurrence Po (%) as stated in (10) and (11).

$$ObjectiveFuntion = \sum_{j=1}^{J} Po(j) * NPC(j) \, \forall j \tag{10}$$

$$\sum_{j=1}^{J} Po(j) = 1 \, \forall j \tag{11}$$

The NPC of each scenario is given by (11), where YCC (USD) is the yearly constant cost of the project, n (years) is the lifetime of the project, v_T is the total investment cost and e (%) is the discount rate.

$$NPC(j) = Inv_T + \sum_{n=1}^{N} \frac{YCC(j,n)}{(1+e)^n} \quad \forall j, \forall n \tag{12}$$

Inv_T is calculated by (13), where the unitary cost of the PV and Battery are given by $Cost_{pv}$ (USD) and $Cost_{bat}$ (USD). The percentage of Inv_T that is financed by a bank (or any another entity) is represented by Fun (%)

$$Inv_T = \left(N_{pv} * Cost_{pv} * C_{pv} + C_{bat} * Cost_{bat}\right) * (1 - Fun) \tag{13}$$

The YCC is calculated in (14) where the OM_{cost} (USD) is the cost of operation and maintenance of the micro-grid, $Finan_{cost}$ are the constant payment for the loan to pay the Inv_T, $Replace_{cost}$ is the cost to replace the battery bank after the end of their life time and LL_{cost} (USD) is the cost for the load that the micro-grid cannot supply .

$$YCC(j) = OM_{cost} + Finan_{cost} + Replace_{cost} + LL_{cost}(j) \quad \forall j, \forall t \tag{14}$$

The OM_{cost} is given by (15) where OM_p (%) is a percentage of Inv_T.

$$OM_{cost} = \left(N_{pv} * Cost_{pv} * C_{pv} + C_{bat} * Cost_{bat}\right) * OM_p \tag{15}$$

Equation (16) is used to calculate $Finan_{cost}$ where N (years) is the number of years in which the loan has to be paid back and the interest rate is r (%).

$$Finan_{cost} = Inv_T \times \frac{Fun \times r}{1-(1+r)^{-N}} \tag{16}$$

The LL_{cost} is calculated using the equation (17) and $VOLL$ is the cost that the inhabitants experience due to the lack of supply, i.e. the price of an alternative source of energy used instead of electricity from the micro-grid, such as diesel.

$$LL_{cost}(j) = \sum_{t=1}^{T}(j,t) * VOLL \quad \forall j, \forall t \tag{17}$$

The leveliced cost of energy LCOE (USD/W) of the project is calculated with the help of equation (18) with (W) $E_{d,a}$ as the annual demand of energy.

$$LCOE = \sum_{j=1}^{J} \frac{NPC(j) * Po(j)}{\sum_{n=1}^{N} \frac{E_{d,a}(j)}{(1+e)^n}} \quad \forall j \tag{18}$$

Equation (19) is used to calculate $E_{d,a}$ where the demand of energy in the system is represented by E_d (W).

$$E_{d,a}(j) = \sum_{t=1}^{T} E_a(j,t) \quad \forall j, \forall t \tag{19}$$

2.2.1. Energy balance

The energy balance is ensured by equation (18). Cu (W) is the energy produced by the PV that cannot be consumed or store by the micro-grid.

$$E_d(j,t) = E_{pv}(j,t) + E_{bat,ch}(j,t) - E_{bat,dis}(j,t) - Cu(j,t) + LL(j,t) \forall j, \forall t \tag{18}$$

Finally, LL is constraint with the use of equation (19) where LLP is the lost load probability.

$$LLP = \frac{\sum_{t=1}^{T} LL(j,t)}{\sum_{t=1}^{T} E_d(j,t)} \quad \forall j, \forall t \tag{19}$$

3. Case study

The community without access to electricity, chosen for our case study is: “La Brecha” (-19.506,-62.563) a Guarani[1] village that belongs to the municipality of Charagua in the department of Santa Cruz, Bolivia. It is located at 210 km from Santa Cruz de la sierra and has 181 households with approximately 973 inhabitants.

In order to have a deeper understanding of the energy demand of the Guarani people, a village with access to electricity was also surveyed: “El Espino” (-19.188, -63.560) is a community located 165 km away from Santa Cruz de la sierra that has an isolated micro-grid that provides electricity to 125 households.

3.1. Surveys

The Study was held in “La Brecha” from the 16 to 21 of September of 2016 and in “El Espino” from the 21 to 25 of November of the same year. Besides collecting the techno-economic information, the surveys focused on the social and behavioural aspects of the villagers, including their energy habits.

3.1.1. La Brecha

La Brecha is a rural village where the main activity is farming and breeding with the purpose of self-consumption and sell in case of unexpected economic problems. The only access road is not paved and difficult to use during the rainy season (December to March). In La Brecha, 4 socio-economic classes have been defined for the present study:

- *High income (HI)*: workers holding a public office and get a fixed monthly salary. They can afford to make the investment for obtaining the connection to the grid or to pay the tariff for their energy consumption. In order to meet their energy demand these people has acquired small diesel gen-sets or PV systems.
- *High medium income (HMI)*: people that run business in the village (normally grocery stores). They can afford the fee to connect to the grid and the monthly payments for the energy supply. As HI, these people adopt small gen-sets or small PV systems to supply their electrical appliances with electricity.
- *Medium income (MI)*: The households of this class have relatives that work in the cities and send money for the support of the rest of the family. Depending on the particular family financial situation, these households might pay for the connection to the grid and the monthly cost of the electricity. For illumination they use candles and sometimes small PV systems, although some of them have gen-sets for special occasions.
- *Lower income (LI)*: The households in this class do not have a steady income and they subsist due to the yield of the crops of their fields and temporary jobs in the village. This segment of the population would have problems to acquire the amount necessary to pay for the installation of the electrical components to connect to the grid or the monthly tariff for the energy consumption. They use primarily candles to light their houses.

Besides the four social classes in La Brecha, there are public and productive organizations that currently use gen-sets or PV to meet their energy needs. A summary of the appliances used in these organizations at the moment of the survey is shown in Table 1.

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[1] The Guarani people are one of the 36 indigenous nationalities that coexist inside the plurinational state of Bolivia.

Table 1. Resume of appliances in La Brecha.

	HI	**HMI**	**MI**	**LI**	**Hospital**	**School**	**Student House**	**Computer centre**	**Church**	**Weaver association**
Indoor bulb	3	4	2	3	16	0	15	1	10	6
Outdoor bulb	2	3	2	0	2	0	3	0	7	5
TV	1	1	1	0	1	0	1	1		0
Radio	1	1	0	0	0	0	0	0	0	0
Phone charger	3	1	0	0	15	5	0	0	0	0
PC	1	0	0	0	2	9	0	2	0	0
Printer	1	0	0	0	0	1	0	0	0	0
Fridge	0	1	0	0	2	0	0	0	0	0
Speaker	0	0	0	0	0	0	0	0	1	0

3.1.2. El Espino

El Espino is a Guarani community, the access to the village is ensured by a paved road. The zone has some oil projects, which make the village less dependent on agriculture than La Brecha. Due to the economical and geographical situation of El Espino, a pilot micro-grid was installed in December 2016 with pre-paid meters. The information of the micro-grid is shown in Table 2.

Table 2. Information of El Espino micro-grid[14]

Variable	**Value**	**Unit**
PV	62	kW
Batteries	618	kWh
Gen-Set	65	kW
Cost of the Batteries and PV	320	Thousands USD
Cost of Gen-Set	55	Thousands USD

At the moment of the survey, the micro-grid had been operating for almost a year. This time period was sufficient for the villagers to purchase more appliances and change their energy behaviour. This is explained by a cheaper and more reliable energy supply, compared to individual gen-sets or home PV systems. We identified the same 4 socio-economic groups as in La Brecha, as well as similar public or private organizations. A summary of their appliances is shown in Table 3.

Table 3. Resume of appliance in "El Espino".

	HI	**HMI**	**MI**	**LI**	**Hospital**	**School**	**Computer centre**	**Church**
Indoor bulb	6	5	3	2	16	8	2	10
Outdoor bulb	2	2	2	1	2	6	0	7
TV	2	1	1	1	1	1	2	0
DVD	1	1	1	1	0	1	0	0
Antenna	1	1	1	1	0	0	0	0
Phone charger	5	4	4	2	15	5	0	0
Freezer	2	1	0	0	2	1	0	0
Stereo System	1	1	0	0	0	1	0	0
Mixer	1	1	1	0	1	0	0	0
PC	1	0	0	0	2	18	5	0
Printer	1	0	0	0	0	1	0	0
Radio	0	1	0	0	0	0	0	0
Speaker	0	0	0	0	0	0	0	1

3.2. Scenarios Construction

There are two levels of uncertainty in the electrification path of La Brecha: (i) the percentage of each socio-economic group members that will be able to connect to the grid and (ii) their willingness and capacity to buy more appliances, thus modifying the load curve, as stated in El Espino. In order to tackle these uncertainties, 6 possible scenarios are created using the available information and the results of enquiries with the leader of La Brecha and with local ONGs that operate in the area.

The first set of 3 load profiles is created using only the information of La Brecha by changing the percentage of connections for the MI and LI segments. The second set of 3 load profiles is constructed with the information of El Espino's appliances and consumer behaviour, and the same percentage of connections as before. We note that, since the weaver association and student house are not present in El Espino, for forecasting the "future" appliances that such hubs will adopt once La Brecha will be electrified with the micro-grid, we derived such information by directly asking which appliances would buy if they had a reliable energy source.

The hypothesis that people in La Brecha will behave as people in El Espino is reasonable because they share similar culture, economic status and climate. Table 4 shows the different load profiles taken in to account for this paper. The detailed inputs to the LoadProGen are available as electronic annex to this paper[2].

Table 4. Load Scenarios.

	Sub Scenarios	**Percentage of connections HI**	**Percentage of connections HMI**	**Percentage of connections MI**	**Percentage of connections LI**	**Data from**
Scenario A	1	100 %	100 %	50 %	20 %	surveys made in La Brecha
	2	100 %	100 %	60 %	30 %	
	3	100 %	100 %	70 %	40 %	
Scenario B	1	100 %	100 %	50 %	20 %	surveys made in El Espino
	2	100 %	100 %	60 %	30 %	
	3	100 %	100 %	70 %	40 %	

A sample of the energy demand for two days is shown in 4-A. The peak consumption happens between 8 to 10 pm. The base energy demand between sub-sets is similar but there is a significant peak consumption in the subset with higher percentage of households, as shown in the load duration curve of all cases in 4 - B. La Brecha is situated in the southern hemisphere with a latitude of 19.5^{o}, and it has a yearly average radiation of 4.8-5.1 kW-h/m^2-day and the period of time with more radiation is between September and March, as shown in Figure 55.

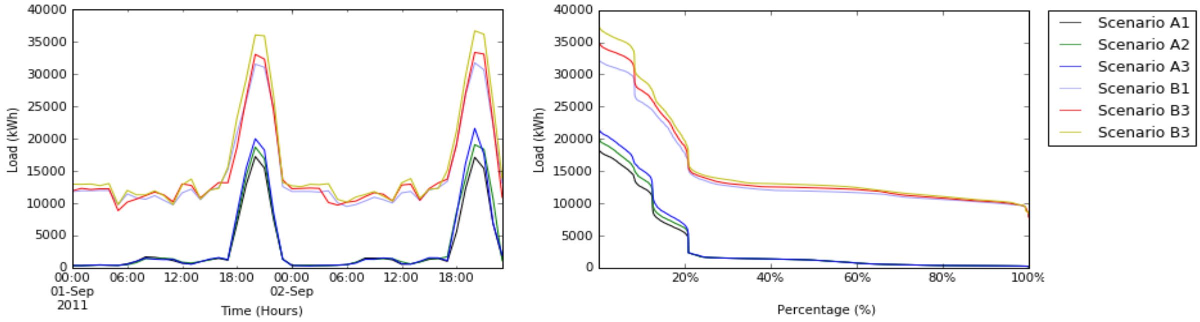

Figure 4. The energy profile of the 6 scenarios. B) Load duration curve for the 6 demand profiles

With two radiation profiles (Muyupampa and Gutierrez databases) and 6 load profiles, it is possible to construct 12 different scenarios as inputs of the robust optimization model. The Probability of Occurrence (PO) of each case is defined in **Error! Reference source not found.**.

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[2] https://github.com/Slbalderrama/LoadProGenInPutIres2017

Table 5. Probability of occurrence of each analysed scenario

Scenarios	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*Total*
Solar Profile Muyupampa	12.5%	10%	7.5%	10%	5 %	5 %	50%
Solar Profile Gutierrez	12.5%	10%	7.5%	10%	5 %	5 %	50%

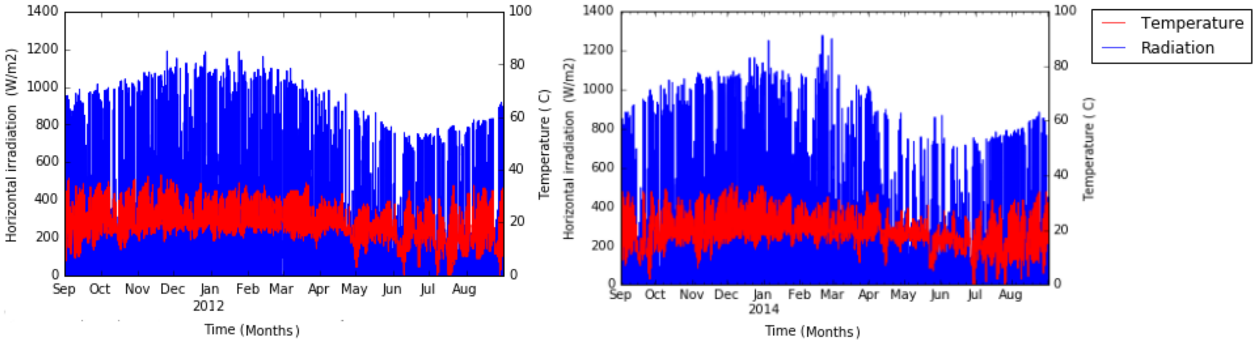

Figure 5. A) Radiation and temperature profile of the meteorological station of Muyupampa B) Radiation and temperature profile of the meteorological station of Gutierrez.

3.3. Micro-grid system characteristics

The technical characteristics of the PV inverter are selected with the information available from the hybrid plant of El Espino [14]. For the Li-ion battery due to the fast evolution of the technology, the characteristics and reference price are selected from recent evolutions in the sector [15] with increment of the wholesale price of 40 % due to installation and transport. All the technical and economical parameters of the project are provided in Table 6.

Table 6. Techno-economic parameters of the project.

Variable	**Characteristic**	**Unit**	**Value**
PV Panel	BYD 235_P6-30	-	-
C_{pv}	Nominal capacity	*W/unit*	*235*
$Cost_{pv}$	Cost of the PV	*USD/W*	*1.5*
η_{inv}	Efficiency of the inverter	*%*	*98.6*
η_{ch} and η_{di}	Efficiency of charge and discharge of the battery	*%*	*95*
DOD	Deep of discharge of the battery	*%*	*20*
$t_{bat,ch}$	Charge time of the battery	*h*	*4*
$t_{bat,di}$	Discharge time of the battery	*h*	*4*
$Cost_{bat}$	Cost of the battery	*USD/Wh*	*0.6*
$VOLL$	Value of lost load	*USD/W*	*0.0003*
LLP	Lost load Probability	*%*	*0*
N_p	Period of reposition of the battery	*Years*	*10*
Δt	Time period	*h*	*1*
Fun	percentage of Inv_T that is finance by a bank	*%*	*55*
n	Duration of the project	*Years*	*20*
e	Discount rate	*%*	*12*
r	interest rate	*%*	*6*
OM_p	operation and maintenance percentage	*%*	*1.5*

4. Results and Discussion

The main results of the case study are provided in Table 7. For the sake of comparison, the Levelized cost of energy (LCOE) is first computed by setting the value of LLP to 0 (i.e. the system must cover 100% of all needs at all times in each scenario). This case involves oversized nominal capacities to meet the demand and therefore prohibitive costs (Table 6). In practice the PV/battery system should not be designed to offer 100% reliability[16]. As an example, the isolated system of El Espino is designed to provide a share of renewable energy between 60 and 70%. As a comparison, in 2013 the closest connection point to the main grid was at 85 km [17] with a price of 15,000 USD dollars for the extension of the distribution network [14]. The cost of this extension of the grid project was 1,250,000 USD without taking in account the extra electrical material, the cost of fuel, maintenance and the extra capacity needed to serve the new demand. The dispatch in the micro-grid use of the PV generation during the day. In case the demand results as unmet, the battery energy is used to close the gap and the excess energy is stored or curtail, as shown in Figure 66.

Table 7. Optimal Size of the micro-grids components and economical values of the case study

Variable	Value	Unit
PV	278	kW
Batteries	845	kWh
NPC	1.01	Millions of USD
LCOE	0.003	USD/W

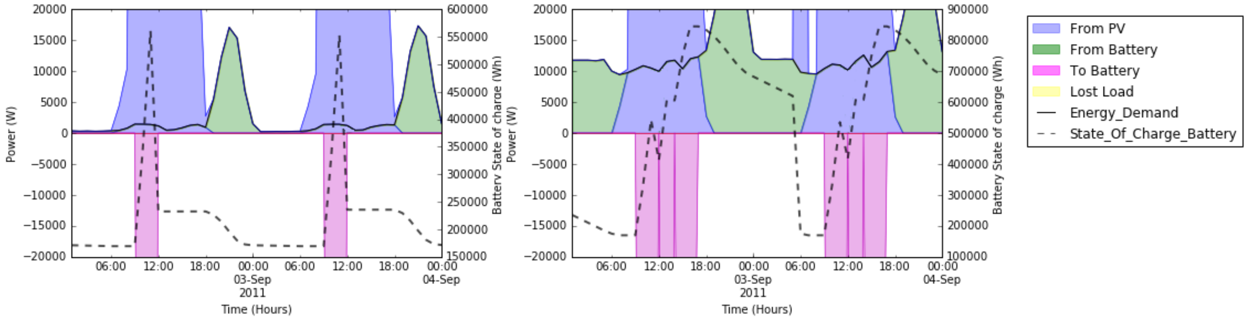

Figure 6. A) Energy dispatch from Scenario A1 muyupampa B) Energy dispatch from scenario A3 Muyupampa.

In order to make a better comparison with the isolated system of El Espino, we performed a sensitivity analysis by varying the *LLP* value as shown in Table 8. With LLP=30%, the values of the nominal capacity of the PVs and the NPC are similar to El Espino. The difference can be attributed to the fact that La Brecha comprises more households, and that the reference cost of El Espino's projects did not take in account the maintenance and a different battery technology (Acid-lead). The dispatch of energy in the sets with higher demand use the LL in times where supplying with other energies would increase the NPC of the system while in the sets wit lower demand there is not a need of using the LL due to the system capacity to cover the demand (Figure 7).

Table 8. Values of the size of the components of the micro-grid and economical values for each case for the sensitivity analysis of the LLP.

LLP (%)	5 %	20 %	30 %
PV(kW)	194	107	92
Batteries (kWh)	350	304	249
NPC (Thousands USD)	534	393	344
LCOE (USD/W)	0.0017	0.0012	0.001

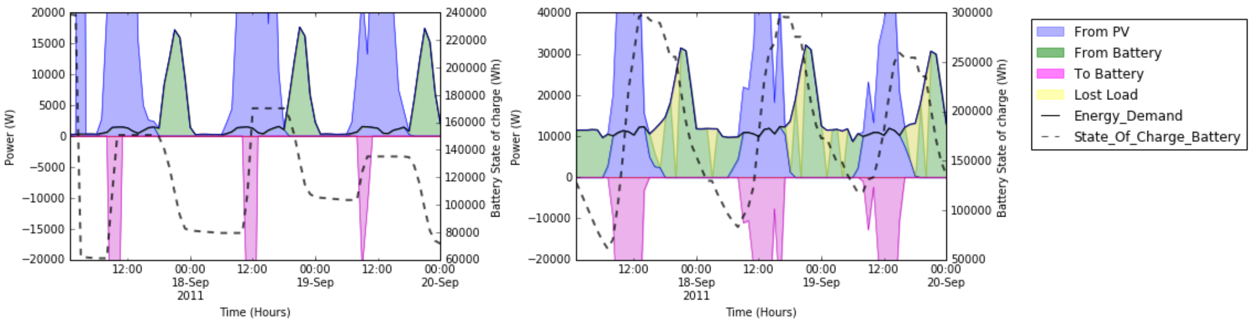

Figure 7. A) Energy dispatch from Scenario A1 Muyupampa and LLP of 20%   B) Energy dispatch from scenario A3 Muyupampa and LLP of 20%.

5. Conclusions

In this paper, a bottom-up approach to evaluate the feasibility of an isolated PV – Li-Ion battery based micro-grid for a Bolivian remote community is presented. This methodology relies on the use of local surveys and a stochastic demand profile generator to determine the load demand in rural villages. A robust linear optimization tool [17] is used to size the least expensive nominal capacity of the system. Results show that an isolated micro-grid may have a LCOE which ranges between 0.003 and 0.001 USD/W, depending on the loss of load probability (LLP) admitted in the system and the investment costs for PV and batteries. These high costs are in line with the cost of other alternative solutions for off-grid electrification in similar areas.

Future work will focus on the addition of a combustion source of energy to allow the modelling of energy systems with bio-mass or diesel energy sources, and to explore the coupling of electric and thermal demand. Also the study of the change in the behaviour of people in newly electrified villages and their increase in energy demand.

6. References

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