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Techno-economic Feasibility of Distributed PV plus Battery Systems for Residential Prosumers under Net-metering in Brazil

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ABSTRACT

This paper addresses the techno-economic viability of rooftop PV systems with batteries in Brazil for low voltage prosumers under net metering. Besides the traditional metrics NPV and LCOE, two additional indices adequate for battery systems are considered: the LCOS that measures cost, and the LVOS – Levelized Value of Storage, defined in this paper to assess the value that storage adds to a PV system. The study is conducted in software SAM of NREL, which allows to simulate systems performance over their lifetime and include the effect of equipment and parts replacement, degradation, and other operational aspects. Systems under net metering and TOU tariffs located in two Brazilian state capitals, one with very good solar radiation and high energy tariffs and the other with worse conditions, are assessed. Results suggest that the inclusion of storage can provide acceptable returns over investment only when justified by technical reasons.

Keywords: distributed PV generation plus batteries, techno-economic assessment of battery systems, levelized value of battery storage, PV plus battery under net metering.

NONMENCLATURE

Abbreviations	
LCOE	Levelized cost of energy
LCOS	Levelized cost of storage
LVOS	Levelized value of storage
NPV	Net present value
PV	Photovoltaic
ROI	Return over investment
TOU	Time of use
Symbols	
E_{dis}	Energy discharged by the battery
C_{inv}	Battery investment cost
C_{loss}	Cost of battery losses
C_{rep}	Replacement cost of the battery
C_T	Total cost
d	Discount rate
N	Years in the study
n	Index

1. INTRODUCTION

Distributed photovoltaic (PV) systems installed on low voltage consumers premises have significantly grown in the last years. These initiatives contribute with the diversification of the electricity matrix and, at the same time, promote self-consumption and reduce the energy bill. However, the variable nature of PV energy causes operational problems in distribution systems [1]. The inclusion of battery energy storage with the systems allows to mitigate renewable energy variability effects. Nevertheless, even under current decreasing battery costs, the economic viability of PV systems plus batteries is not demonstrated yet [2] [3].

This paper contributes with a techno-economic assessment of grid-connected rooftop PV systems with battery storage for low voltage prosumers under net metering in Brazil. To assess projects in localities with high human development index, in which citizens could afford PV plus battery systems adoption, and with different tariff and climatic conditions, the study is conducted for two cities located in different geographic Brazilian regions. The methodology is based on software

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SAM developed by NREL-National Renewable Lab. [4], that gives technical and economic performance of the projects. Additional economic assessment metrics are used to complement the analysis of the effect of storage adoption on system viability.

2. METHODS

A techno-economic analysis should consider system performance during its lifetime, since equipment and parts replacement, degradation and other operational aspects can impact the results [5]. To this end, in this paper software SAM, which allows to define a performance and a financial model for a renewable energy project, is used to conduct the study.

2.1 Economic metrics

The most used metric to evaluate and compare costs of renewable energies is the LCOE - Levelized Cost Of Energy. A similar metric is defined for energy storage, the LCOS – Levelized Cost Of Storage, that measures the average net present cost of a storage device in relation to the discharged energy over lifetime. In this paper, expression (1) that considers batteries investment cost, losses cost and replacement cost, is adopted for LCOS.

To assess return over investment, usual economic metrics are used: net present value (NPV), return over investment (ROI) and discounted payback.

Furthermore, an additional metric is defined in this paper, the LVOS – Levelized Value of Storage, to assess the value that storage adds to a PV system that belongs to a prosumer, as given by expression (2).

The software SAM implements the cash flow of the project in accordance with the financial model adopted by the user and calculates the traditional economic metrics NPV, LCOE and discounted payback period. Metric ROI is calculated directly from NPV and the initial investment value. The other metrics adopted in this paper, LCOS and LVOS, are calculated using results given by SAM by applying expressions (1) and (2).

$$LCOS = \frac{\sum_{n=0}^{N}(C_{n,inv}+C_{n,loss}+C_{n,rep})/(1+d)^n}{\sum_{n=1}^{N}E_{dis}/(1+d)^n} \tag{1}$$

$$LVOS = \frac{\sum_{n=0}^{N}((E_{dis}*Tariff)_n-C_{n,T})/(1+d)^n}{\sum_{n=1}^{N}E_{dis}/(1+d)^n} \tag{2}$$

In (1), investment costs (C_{inv}), costs of losses (C_{loss}) and replacement cost (C_{rep}) of batteries are discounted to present time, when applicable. The annual discharged energy (E_{dis}) is obtained from SAM. The cost of losses is calculated using the annual energy lost in the battery given by SAM; its value should consider the price of energy during charging periods.

In (2), to calculate the value that storage adds to the project, the discharged energy should be valued at the energy price during discharge periods. C_T are the total costs in the numerator of (1).

2.2 Batteries performance simulation issues

Battery degradation is an important aspect on economic viability assessment. The modes of degradation include calendar ageing, capacity throughput, ambient temperature, state of charge, depth of discharge and current rate [5]. Software SAM includes a general voltage model whose parameters can be taken from datasheets, a thermal model and lifetime models. The thermal model considers an energy balance within the battery, heat transfer to and from the room, and heat generation due to internal resistance. There are two lifetime models, the calendar degradation and the cycle-dependent model implemented by the rainflow counting algorithm. For the later one, many battery datasheets provide cycling information as a function of the depth-of-discharge (DoD), which can be input to SAM. For lithium batteries there is available a calendar degradation model that depends on temperature.

3. CASE STUDY DESCRITPTION

This paper analyses the feasibility of PV plus battery systems for residential consumers in two Brazilian state capitals: Belo Horizonte (BH) and Curitiba (CRTB). Belo Horizonte is in the Southeast region and combines two characteristics that make it very favorable for PV generation and net metering: it has very good solar radiation and the second highest low voltage electricity tariff in Brazil. Curitiba is in the South region, with a PV potential approximately 37% lower than BH. Moreover, low voltage tariffs are 26.4% lower than in BH. These cities are good examples of high and low attractiveness.

3.1 Proposed scenario

The prosumers are under TOU (Time-Of-Use) tariffs and net metering. Load, PV and batteries are behind-the-meter. Batteries are expected to add value to the system due to their ability to shift energy over time: prosumers use batteries to storage the generated PV energy to be used later, during high TOU tariffs. Therefore, storage should prevent load to consume energy from the grid during most expensive peak periods, when there is low or no PV generation.

A comparison under two net metering compensation schemes is presented: NM-FC net metering full compensation and NM-EC net metering energy compensation. The schemes give different value to the PV energy exported to the grid. The full compensation scheme considers the full tariff while the energy compensation scheme valuates exported energy at the energy parcel of the tariff, which is approximately equal to 30% of the full tariff.

3.2 Consumption profiles

A typical residential daily load curve of Brazilian residential consumers in one-hour intervals is used.

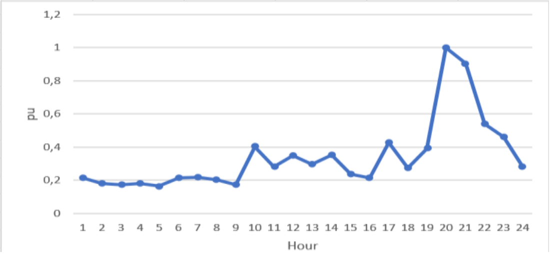

Fig. 1. Normalized daily residential load curve.

Annual consumption is assumed constant over the 25 years of the study. The average consumption seasonality of the regions is used to modulate monthly consumption over one year.

3.3 PV plus battery system

The "Detailed PV" AC-connected topology in SAM is adopted, as shown in Fig 2. DC-connected is not considered because the use of an integrated inverter that accounts for PV system and battery control is not widely available commercially yet.

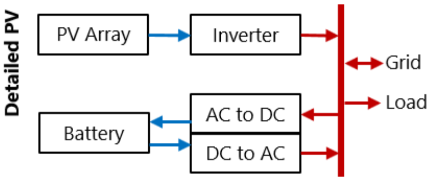

Fig. 2. Behind-the-meter system configuration [4].

Batteries chosen are ion-lithium, since currently most of new home energy storage systems use batteries based on one of the available ion-lithium technologies [6]. Sizing of the batteries should consider the depth of discharge (DoD) recommended for the technology, degradation and the overall technical efficiency.

The adopted 'Detailed-PV' model in SAM ensures good representation of the produced PV energy. The PV modules are north oriented with a tilt angle equal to the local latitude. PV generation reduction due to modules degradation is modeled.

Dimensioning follows the criteria:

- PV system is designed to supply consumption during sun-hours and peak hours.
- The battery charges during sun-hours and discharges during peak tariff hours, which are after sun-hours. Therefore, its capacity is calculated considering the consumption during the three hours of the peak tariff period and the DoD recommended for the technology. Notice that higher DoD means that more of the battery's capacity can be used, and the bank is smaller than with a lower DoD. The trade-off is the shorter lifetime. Battery power is defined considering the load curve peak power during peak tariff intervals.

3.4 Battery dispatch

SAM allows to define battery dispatch manually. Table 1 describes de adopted dispatch rules. Periods refer to the TOU tariff described in section 3.6. Batteries are charged using only the generated PV electricity.

Table 1 – Battery dispatch

Period	**Charge**	**Discharge**
Off-peak tariff	From PV*	Not allowed
Intermediate 4 p.m.	From PV*	10%
Peak tariff	From PV*	100%
Intermediate 8 p.m.	From PV*	100%

*Charging from the grid is not allowed.

3.5 Electricity tariffs

Low voltage TOU tariffs in Brazil are defined with three intervals, as described in Table 2. One can notice that in BH peak rates are 35.6% higher than in CRTB and off-peak tariffs are 26.4% higher.

Table 2 – Low voltage residential electricity tariffs

Tariff - Site	**Characteristics**	**Value (R$/kWh)**
TOU – BH	Peak, 3hrs: 5, 6, 7 p.m.	1.972
	Intermediate: 4, 8 p.m.	1.267
	Off-Peak	0.854
TOU – CRTB	Peak, 3hrs: 5, 6, 7 p.m.	1.4542
	Intermediate: 4, 8 p.m.	0.9432
	Off-Peak	0.6757

3.6 System costs

Typical rooftop PV system costs from the market research conducted by [7] are adopted.

Ion-lithium battery costs considering both capacity and power are taken from [6]. A projection of cost reduction over the years is made to calculate battery replacement cost.

Table 3 presents systems cost data together with additional data needed for simulation.

4. RESULTS

The 'Detailed PV' model and the 'Residential owner' financial model of software SAM are used to simulate systems performance and conduct the study. Table 4 presents the results obtained. The replacement capacity threshold assumed for the ion-lithium batteries is 90%. Costs over the 25 years of the study are calculated at year zero with a discount rate of 6.5%.

One can observe that the battery bank is replaced once in project life in both cities, in year 14 and year 17. The round-trip efficiency obtained in the simulations is 88.2% in all cases.

Energy bills with system are lower than bills without system in all cases, as expected. In BH, energy bills with system represent 34% and 42% of bills without system for NM-FC compensation and NM-EC compensation, respectively. Economies in energy bills, when calculated for CRTB, are less attractive, as expected due to lower tariffs and solar radiation. One observes that the economy decreases when one moves from full compensation to energy compensation in both localities. It is important to separate economies among those related with battery usage, with PV generation directly given to load and with energy compensation in the net metering scheme. Table 4 shows that economies associated with batteries and PV generation direct to load account for at least 78% of the total economy.

Costs of losses in the battery are calculated using yearly energy losses in the battery, which are given by SAM, valued at the off-peak TOU tariff. Since the battery is allowed to charge exclusively from PV generation, i.e., during off-peak tariff intervals, tariff values during this period are chosen to value the losses. On the other hand, to calculate the value of the energy discharged from the battery to the load, the peak value of TOU tariff should be used, since discharge is allowed only during those periods. One observes that the value of discharged energy in CRTB is 41.17% lower than in BH.

The NPV obtained in all cases is positive. However, the ROI that relates the project return with the investment is lower than the unit in all cases, and it is remarkably low in CRTB. The discounted payback is acceptable in BH but it is very high for CRTB. The LCOS is lower than the peak-TOU tariff only for BH.

One can observe that the LVOS obtained for BH is positive, but it is negative for CRTB. This means that tariffs in CRTB are not enough to overcome battery cost.

It is interesting to analyze how economic metrics vary when the size of the battery bank varies. Fig. 3 shows results when the battery bank size varies, and the PV system remains fixed, in Belo Horizonte. One can notice that projects with smaller batteries are more attractive, since they have higher NPV and lower paybacks. On the contrary, economies in energy bills are higher for projects with greater battery banks. This result indicates that battery costs are still high, and the additional economies in energy bills due to bigger energy storage equipment are not enough to obtain better returns from investments on PV systems with batteries. Furthermore, NPV in Fig. 3 monotonically decreases with bigger batteries. This result suggests that the inclusion of energy storage cannot be motivated by economics, it must be justified by technical reasons. Therefore, if specific operating conditions, like reliability requirements of prosumers or limits imposed by the local distribution company on the energy exported to the grid, indicate the use of batteries integrated with PV systems, then, in some regions of the country they are viable.

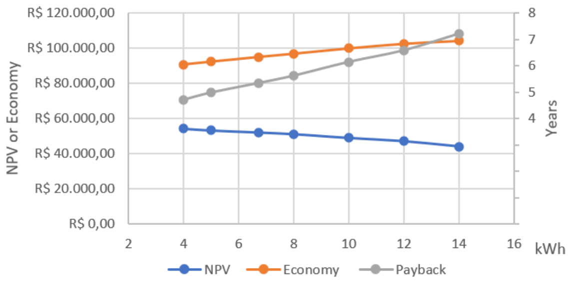

Fig. 3. Economic metrics as a function of the battery size, in BH.

5. CONCLUSION

The preliminary techno-economic assessment conducted in this paper indicates that, in general, battery storage currently does not add enough value to rooftop PV systems for low voltage prosumers in Brazil. However, under favorable conditions of solar radiation and high electricity tariffs there exist a reasonably return over investment. In this case, projects with smaller batteries are more attractive.

Results indicate that the inclusion of energy storage cannot be motivated only by economics yet, it must be justified by technical reasons.

It is important to observe that only economies due to energy shift under TOU tariffs were considered in the study. Additional results are being pursued by the authors, modeling other services that batteries can offer to increase prosumers revenue.

Table 3. Simulation data

Meteorological data	BH: [-19.9, -43.9] typical year in NSRDB [1]. Hourly CRTB: [-25.3, -49.3] typical year in SWERA. Hourly	
PV system	Nominal capacity PV modules Inverters	5 kWp Yingli Energy (China) YL250P-32b HoymilesMI_1000T_240V
Load data	Average annual consumption Peak hours /off-peak hours consumption Peak load	12,000.00 kWh 20% 4.41 kW
Batteries	Technologies Nominal capacity Average DoD AC/DC and DC/AC conversion	Lithium iron phosphate 12 kWh / 4 kW 60% 94%
Costs	PV system Batteries Total Total installed cost per capacity	R$ 24,200.19 R$ 23,792.94 R$ 47,993.13 9.60 R$/Wdc

Table 4. Results. Exchange rate: USD 1.00 = R$ 5.22

	TOU - BH		TOU - CRTB	
	NM-FC	NM-EC	NM-FC	NM-EC
Battery replacement	Once, at year 14		Once, at year 17	
Average annual energy, batt. to load (kWh)	1592.0		1258.5	
1st year annual energy, batt. to load (kWh)	1703.2		1384.1	
Bill w/out system in 25 yrs (R$)	155507.07		119806.57	
Bill with system in 25 yrs (R$)	52957.48	65138.29	58001.01	61726.74
Economy in 25 yrs (R$)	102549.59	90368.78	61805.56	58079.83
Economy due to: Battery discharge	37.80%	42.89%	36.89%	39.26%
PV energy to load	40.09%	45.50%	48.43%	51.54%
Compensated energy	21.11%	11.61%	14.68%	9.20%
Battery replacement cost at year 0, with discount rate 6.5% (R$)	5004.69		3921.84	
Battery cost of losses in 25 yrs. (R$)	2239.18		1411.23	
Value of energy from batt. to load in 25 yrs. (R$)	38761.37		22802.27	
NPV (R$)	47069.3	34888.5	7407.97	3682.27
ROI	0.981	0.727	0.154	0.077
LCOS (R$/kWh)	1.58		1.86	
Discounted Payback (years)	6.58	7.87	14.22	18.76
LVOS (R$/kWh)	0.39		-0.40	

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