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Resiliency Analysis in Residential Consumer with Photovoltaic Generation and Battery Energy Storage System ⋆

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Abstract: The number of connections with distributed generation has been growing steadily in Brazil, however, there is still a problem associated with it, the intermittence. Although a consumer with photovoltaic solar system (PVSS) is able to generate energy even when the grid is unavailable, the load is still susceptible to power outages given the intermittence of the source, one possible solution for this is the use of energy storage elements to supply part of the load, or even all of it when needed. In this study is analyzed, under the economic viability point of view, the impact of using a Battery Energy Storage System (BESS) coupled with a PVSS to supply a residential consumer in the event of power outages.

Resumo: O número de conexões com geração distribuída vem crescendo constantemente no Brasil, no entanto, ainda sim existe um problema associado, a intermitência. Embora um consumidor com um sistema solar fotovoltaico (SSFV) seja capaz de gerar energia mesmo quando a rede se encontra indisponível, a carga ainda sim está suceptível à falta de suprimento de energia dado a intermitência da fonte, uma possível solução para isto é o uso de elementos armazenadores de energia para abastecimento de parte da carga, ou toda ela quando necessário. Neste estudo é analisado, sob o ponto de vista de viabilidade econômica, o impacto do uso de um Sistema de Armazenamento de Energia com Bateria (SAEB) junto a um SSFV para o atendimento de um consumidor residencial em caso de quedas de energia.

Keywords: Distributed generation; Outages; Battery; Economic viability; Photovoltaic solar system.

Palavras-chaves: Geração distribuída; Faltas de energia; Bateria; Viabilidade econômica; Sistema solar fotovoltaico.

1. INTRODUCTION

The pandemic caused by COVID-19 virus in the beginning of the first half of 2020 generated a huge impact in the global economy, and in the people's routine as well. Social isolation is one of the main implications in the routine of people, it also increased the dissemination of remote work, or, home office. Such impacts also ended up reflecting in the power sector, according to (ANEEL, 2020), among some of the main impacts, under the distribution point of view, there are the loss of liquidity in payment flows due to a reduction in the consumption of electricity, an increase in the default on payment of invoices and the evolution of technical and non-technical loss indicators.

Regarding the impact in the load consumption, in Brazil there was a significant reduction in the amounts of consumption, mainly for commercial and industrial consumers, in contrast, the residential sector showed an increase in consumption due to social isolation policies. According with (EPE, 2020b), the residential consumption

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reached, in April of 2020, 6% of increase in comparison to the same period in the previous year, meanwhile the industrial and commercial consumers showed reductions of 12,4% and 17,9% respectively.

With regard to the impact in the electricity generation, according to (EPE, 2020a), in comparison to the first semester of 2019, the generation in 2020 had a decline of 5% in the total generated energy, with the biggest reductions occurring in PCHs (small hydroeletric plants) and CGHs (hydroeletric generating plants). In contrast, renewable sources such as solar photovoltaic (PV) and biogas had an increase of 25,5% and 6,3% respectively.

Based in the presented context, there is an increase in consumption in the residential sector due to the social isolation, and among these consumers some practice home office which in turn makes the supply of electricity without interruptions even more important, i.e., the resiliency topic becomes more significant.

Although the PV generation also presented an increase it is still not enough to guarantee the fully supply of a residence in case of an outage occurrence, either due the intermittence problem or due the outage event being able to occur in a period without generation, such as the night. A possible solution for this is the use of storage elements to help in the continuity of supply, this study considers the electrochemical storage type with use of Lithium-Ion batteries.

There are several studies searching to solve the outage problem by using Distributed Energy Resources (DERs). In (Yang and Walid, 2012) it is studied the trade-off between outage probability and battery capacity, the paper uses a statistical model to characterize different types of uncertainties in generation and uses Matlab to solve the convex optimization problem of the study case to find the trade-off, the findings showed that the outage probability decreases exponentially with respect to the square of the storage capacity.

In (Gantz et al., 2012) the authors search for an optimal mix and placement of Energy Storage Systems (ESS) in a distribution grid to minimize the costs of blackouts, the authors also used Matlab and OpenDSS to run the simulations. Still regarding ESS to help power distribution networks, in (Tercan et al., 2018) the authors deal to prevent outages in consumers connected to the grid, especially those who experience frequent outage events.

The authors in (Hovanessian et al., 2018) consider a residential consumer in island state coupled with PV generation and storage, it is then proposed a smart load management based on the battery storage capacity and considering PV generation uncertainty. In (Gupta et al., 2020) the residential consumer is also studied along with the commercial, the authors propose an optimal sizing of PV and Battery Energy Storage System (BESS) to deal with lack of supply. (Zhang et al., 2019) also consider the residential consumer, however, as a community living in a building, and propose a coordinated BESS schedule and an adequate shift in load consumption to increase the use of renewable energy and to better sustain outages.

In (Fedotov et al., 2019) the use of storage is studied to limit the effects of short-term power outages, the BESS is used as a source of reactive power to stabilize the voltage on the buses of an industrial substation considering an outage event, in this case the BESS is activated before the relay and the simulink tool from Matlab is used to perform the simulations.

Finally, the use of storage is also applied to balance the grid power in (Ito et al., 2018). To completely or partially avoid outages in (Zhang et al., 2016), where is also considered scenarios with different degrees of sophistication of feeder automation.

This paper is divided as follows, Section 2 presents the methodology, components and assumptions used. Section 3 presents the study cases and in Section 4 is presented the conclusions of this work.

2. METHODOLOGY

This study is divided in two different scenarios, each one is coupled with a Lithium Ion BESS and a Photovoltaic Solar System (PVSS) under the White Tariff (WT), as presented in (ANEEL, 2016), the WT is better covered in section 2.1:

- The first scenario considers that the outage can happen multiple times per year, in this study are considered five faults per year with four hours of duration each.
- The second scenario considers the occurrence of a critical 24-hours outage that can happen one time per year.

The used software to perform the simulations is Homer Grid, it allows to evaluate among multiple hybrid energy system configurations the one with the best economical design by mixing different resources and based in the Net Present Cost (NPC) of the project. Some features of the software are that it can optimize a project based in demand charge reduction strategy, it has an accurate tariff modeling, a robust storage model, a solid database for solar and wind data, among other capabilities (LLC, 2020). The proposed methodology is presented as:

(1) Determine the best topology system that can fully supply the load given an outage occurrence considering different battery reserve percentages for fault events.
(2) A no BESS scenario is used for comparison, in order to evaluate the impact of the BESS use.

The battery reserve is a percentage of how much usable energy will be reserved in the BESS for outage events, in this study is considered a minimum State of Charge (SoC) for the battery of 10%, so a battery reserve of 10% means the battery can only use 80% of its nominal capacity in normal operational days and 90% in outage days.

The total NPC is the HOMER's main economic output, it is a value that ranks all the system configurations, the lower the better. This value is based in the present value of all system costs that can incur over the project lifetime, minus the present value of all revenues it earns over its lifetime. The costs can include capital costs, replacement costs, Operation & Maintenance (O&M) costs, emissions penalties, and the costs of buying power from the grid. Revenues can include salvage value and grid sales revenue. In this study the main constraints for the optimization are presented in (1) and (2).

$$OpC \geq GAC + CPL \tag{1}$$

$$Unmet_{load} = 0 \tag{2}$$

The first constraint is that the project must respect an minimum yearly operating cost (OpC) that has to be greater than the annual Grid Availability Cost (GAC) plus the annual Cost of Public Lightning (CPL). The GAC refers to the cost of using the utility grid (ANEEL, 2016) and CPL is the cost charged by each city for the public lightning. In this study is considered a minimum OpC value of R$ 537,60. The second constraint refers to the Critical Load (CL), where the unmet load value must be equal to zero, in others words, the CL must be fully supplied.

2.1 Components and Resources

Load. The residential consumer data represents a biphasic load, it is divided in two parts, one called CL and another Non-Critical Load (NCL), the CL represents 50% of the total load, and the total load has an average consumption of 11,72 kWh per day. Figure 1 presents the daily profile for a random day.

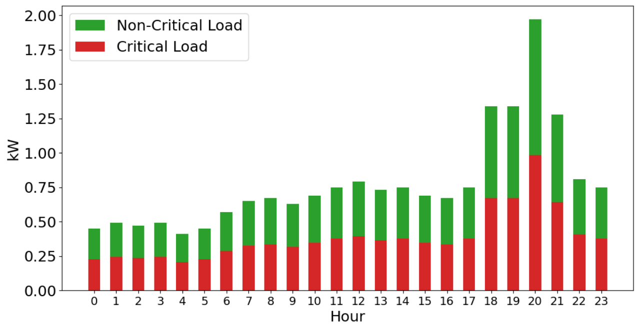

Figure 1. Residential load profile.

Continuity Indexes In Brazil, in order to maintain the quality in the distribution of electricity the National Agency of Electrical Energy (ANEEL) requires that energy utilities maintain a standard supply continuity, to achieve this it then uses collective indicators of continuity such as the Equivalent Duration of Interruption per Consumer Unit (DEC) and the Equivalent Interruption Frequency per Consumer Unit (FEC), the equations for each one are provided in (ANEEL, 2018). DEC is the average value of how much time a consumer stays without electricity for a given period, this parameter is the same as the System Average Interruption Duration Index (SAIDI). FEC represents the average value of how many times the consumer experience an interruption in the power supply, also referred as System Average Interruption Frequency Index (SAIFI). In Table 1 is presented the yearly DEC and FEC values for the energy utility of the region of Santa Maria/RS.

The values in Table 1 show that the consumers in this area experience an average value of 14,01 hours per year without supply with a mean frequency of occurrence of 6,25 times.

Table 1. DEC and FEC for the area of study.

Brazil - 2019	
DEC	14,01
FEC	6,25
Number of consumers: 2.875.122	

Distributed Energy Resources. In each study case is considered the use of a PVSS coupled with a BESS to supply entirely the critical load, and, if possible, part of the non-critical load. Table 2 presents the DER's specifications. The prices for the storage element are based in (Mongird et al., 2019), for the PVSS is considered a common commercial value per kWp for the Brazilian market and for the hybrid inverter, in this case a Schneider Conext SW2524, is also considered an average market value. All components are used from the software library and prices are given in Brazilian reais (R$).

Table 2. DER's specifications.

Both cases		
Component	Specifications	Base price (R$)
PV	1 kWp	5.548,16
Inverter	1 kW	2.937,33
Case 1 - One major outage		
BESS LG Chem	3,3 kWh/63 Ah	13.115,00
Case 2 - Multiple short outages		
BESS LG Chem	6,4 kWh/126 Ah	25.436,16

Data Resources. All resource data such as solar radiation and temperature are obtained using the *Resources* tool of Homer Grid that utilizes the NASA's database.

Utility Tariffs. The White Tariff is based in (ANEEL, 2016) and the used prices refers to a local utility of Santa Maria - RS/Brazil. This tariff has three different price periods, the on-peak (18:00 to 21:00 - higher price), intermediate (one hour before and one hour after the on-peak - medium price) and the off-peak period (remaining hours - lower price), all price values already consider the incidence of taxes. Table 3 presents the WT setup.

Table 3. Tariff specifications.

White Tariff			
R$/kWh	On-peak	Off-peak	Intermediate
	1,567	0,749	1,029

Economic Inputs. Both the study cases consider a 10 year project horizon, under a real discount rate of 5,88% per year, and the salvage value, or scrap value, of each system component are not taken into consideration.

3. STUDY CASES

In this study there are two different outage situations and the topology of the system in each one is the same, however, with different capacities for each component. Figure 2 presents the topology for the study cases.

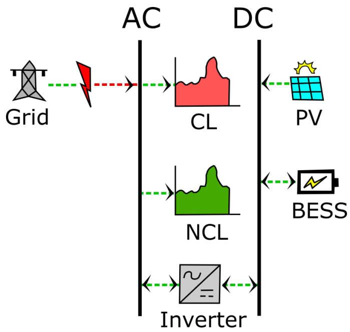

Figure 2. System topology.

3.1 Case 1 - Multiple short outages

In this scenario, the *Reliability* tool, from the software is used, it allows to model random short faults that may occur multiple times per year. Both the number of faults and the duration of each one are based in power supply indicators of the local utility, similar to the values presented in Table 1. In this study are considered the occurrence of five faults per year, each one with four hours of duration, totaling 20 hours per year without energy supply.

In this step a filter is applied in order to search for a setup that also satisfies the constraint from (1), this filter is applied in the yearly OpC, and for this consumer it has to be greater than 537,60 R$/yr, that is the annual GAC plus the CPL. The constraint (2) is applied directly on the Unmet Load parameter of the software and has to be equal to zero. The simulations are run considering both constraints and for different battery reserve percentages (10% to 100%) in order to find the best solution ranked by NPC. The best alternative found is presented in Table 4.

Table 4. Case 1 - Best project.

Components	NPC (R$)	IC (R$)	RF (%)
PVSS (3,4 kWp) Inverter (1,88 kW) BESS (0%)	41.260,00	36.974,00	70
	CoE (R$/kWh) 0,89	SPb (yr) 9,6	Total BS (R$) 28.594,00
Grid Only NPC - R$ 32.880,00. CoE 1,04 R$\kWh			

The project in Table 4 ensures that the system is able to supply the load even with the occurrence of faults. The used BESS is a LG Chem 3,3 kWh and for this project the best solution is not to reserve a percentage of the battery for outage events, as indicated by the 0% value in parenthesis in the Components column. The found project OpC is R$ 579,03 per year.

The value at the bottom of the table (R$ 32.880,00) represents the NPC of the system considering the supply only by the grid (grid only case), where the fault is also taken into account and during these periods the grid is then unavailable. The project, with the DERs, has an NPC of R$ 41.260,00, which is significantly higher than the grid only case, however, it is the best solution to supply the CL, and if possible part of the NCL when the grid is offline.

In Table 4 is also presented the Cost of Energy (CoE) of the system, which represents the average cost per kWh of useful electrical energy produced by the system, note that for the found project this value (0,89 R$/kWh) is quite lower than the grid only case (1,04 R$/kWh). The system also manages to generate R$ 28.594,00 in utility bill savings by the end of the project, these savings come from energy charge reductions strategies, through the arbitrage or renewable arbitrage service.

Finally the project presented a Renewable Fraction (RF) of 70%, which represents the portion of the energy delivered to the load that originated from renewable power sources, however, the high upfront cost of the project, or the Initial Capital (IC) ended up being very expensive, totaling R$ 36.974,00 with a Simple Payback (SPb) of 9,6 years, which is very close to the end of the project lifetime. In Figure 3 is presented a yearly heatmap of the load along with the outage occurrences.

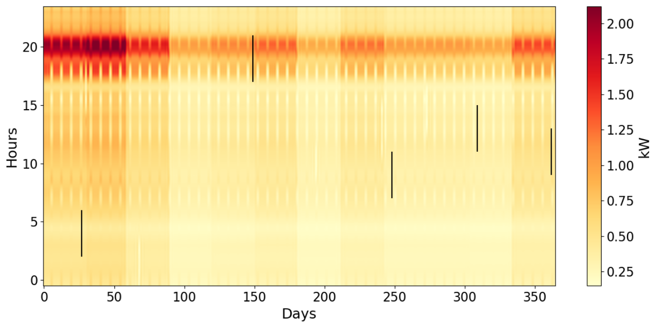

Figure 3. Residential load profile and the outage occurrences.

The black lines in Figure 3 are the fault occurrences, with four hours duration each. The figure also shows that the load has its highest demand values in the peak period of the tariff (18:00 to 21:00) during the year. The outage events are presented in Table 5.

Table 5. Case 1 - Outage occurrences.

Day	Jan. 27	May 30	Sep. 1	Nov. 6	Dez. 29
Period (h)	02 - 06	18 - 22	08 - 12	12 - 16	10 - 14

For the chosen system the software found an average battery throughput of 3,02 kWh for an outage day and 4,08 kWh for a normal operational day. This parameter indicates how much energy is cycled through the battery, in this case, less energy is cycled during the outage because due to the grid being unavailable the BESS only can be recharged by the PVSS output, and if the outage occurs in a period without generation the BESS doesn't charge at all. Another major point is that, in this case, the system can use a wider range of energy from the battery in normal operation because there is no battery reserve. Figure 4 presents the daily DER's dispatch considering the outage event.

In Figure 4 during the beginning of the outage (02:00) all the load is supplied by the BESS, in this period there is no PV generation and the Grid Purchases (Grid P) are equal to zero. In Figure 4 a positive value for the BESS means charging and a negative value means discharging. By the end of the outage (06:00) the PV generation becomes available, although the generation is this particular day is lower (peaking at 1.76 kW) than the usual, it is still, along

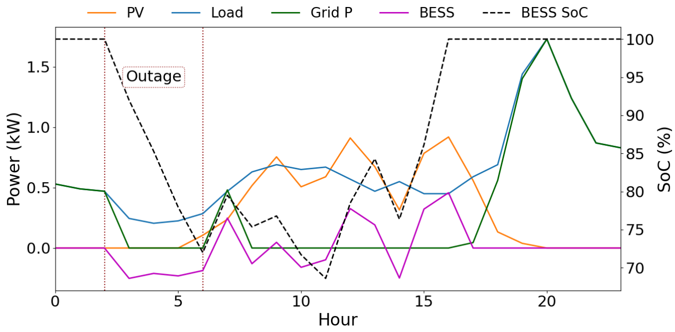

Figure 4. Outage day - Daily DER's dispatch.

with the BESS dispatch, enough to supply most part of the load.

At hour 16 the BESS uses the excess PV generation to recharge its energy and achieves its full SoC, it then preserves the SoC to the next day operation. By the end of the day as the PV output decreases the grid is activated to serve the load. The last step is to evaluate the chosen system without the BESS. The found results are summarized in Table 6.

Table 6. Case 1 - No BESS scenario.

Components	NPC (R$)	IC (R$)	RF (%)
PVSS (3,4 kWp) Inverter (1,88 kW)	32.035,00	23.874,00	62,6
	CoE (R$/kWh) 0,612	SPb (yr) 7,1	Total BS (R$) 24.719,00

In Table 6 the total NPC of the system without the BESS presents better economic results (in comparison to the values in Table 4), both the total NPC of the project and the IC are, respectively, 22,35% and 64,57% lower, however, although economically better, the system is still unable to fully supply the load. The system also presents a SPb of 7,1 years and a CoE evaluated at 0,612 R$/kWh, that are significantly better than the values in the project with the BESS.

In contrast, the project with the BESS showed better results in terms of total bill savings and RF, accounting for improves of 21,27% and 11,82% respectively. The RF improve is due the increase in use of renewable energy by the storage element, and the increase in bill savings comes from the arbitrage services provided also by the BESS. However, although better, these improvements are not enough to make the project economically viable. Finally, the project without the BESS presented an NPC lower than the grid only scenario (NPC at the bottom of Table 4), which represents an economically viable option, however, the system is technically not viable given that it can not supply the entire load during the short outages.

3.2 Case 2 - One major outage

In this case the *Resiliency* tool from Homer Grid is used, it allows to model a critical outage (random or not) of 24 hours or more. In this study it will considered one fault per year with 24 hours of duration. The best alternative that satisfies all the constraints is presented in Table 7.

The results in Table 7 guarantees that the system is capable of serving the CL under the occurrence of an

Table 7. Case 2 - Preliminary results.

Components	NPC (R$)	IC (R$)	RF (%)
PVSS (3,2 kWp) Inverter (1,67 kW) BESS (35%)	52.454,00	48.097,00	70,8
	CoE (R$/kWh) 1,20	SPb (yr) –	Total BS (R$) 28.507,00
Grid Only NPC - R$ 32.865,00. CoE 1,04 R$/kWh			

outage, however, in this case the best option was to reserve a percentage of the battery energy for outage events, the found value is 35%, which means that the usable energy in normal operational days is only 55% of the BESS, given that here is considered a 10% of minimum SoC. Note that now there is a different project to serve the load, with other power capacities for the PVSS and the inverter, also, the BESS used is a LG Chem 6,4 kWh. The chosen day for the outage is the 27th of January.

At the bottom of Table 7 is the NPC os the grid only scenario, where it is considered the occurrence of the major fault and the system is then supplied only by the grid. Note that this cost is different from the one in Table 4 given that now a different outage situation occurs.

Different from the multiple short outages case, now a battery reserve percentage is needed to satisfy the constraint (2), but although the chosen system do satisfies it, the NPC is significantly higher, almost 60%, in comparison to the grid only scenario and the system also presented a higher CoE value, the first constraint is satisfied by an yearly OpC of R$ 588,60 for this project.

This system does not present a simple payback value through the project lifetime but it is capable of generating total bill savings of R$ 28.507,00. In comparison to the previous case (Table 4), this project presents a higher IC cost, mainly due the use of a more expensive BESS (the LG Chem 6,4 kWh), however, the RF (70,8) in this case is a little better. Figure 5 presents the DER's dispatch for the outage day.

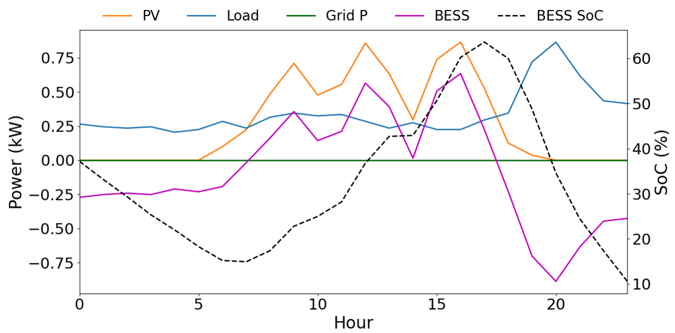

Figure 5. Major Outage day - Daily DER's dispatch.

In this scenario by the beginning of the day all the load supplied by the BESS, here the served load is just the CL, as the PV generation becomes available the BESS decreases its discharge and starts to be recharged by the excess energy from the panels. During the PVSS low production moments the BESS is also activated to supply part of the load and as the PV output decreases all the energy in the battery is used to fully serve the CL, reaching at the end of the day its minimum SoC. In order to compare the dispatch of the BESS, Figure 6 presents the daily behavior of the system for the same day but without the outage occurrence.

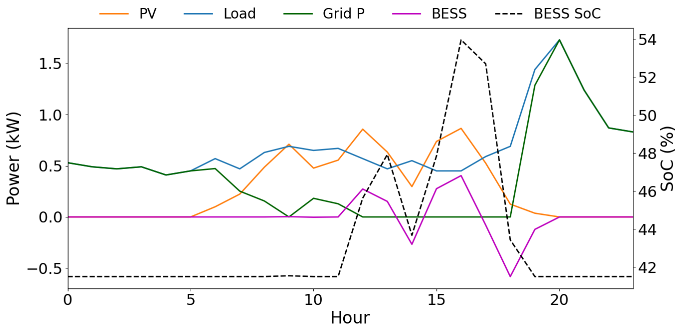

Figure 6. Normal operational day - Daily DER's dispatch.

In Figure 6 the BESS stays most of the time in idle state with around 40% of its SoC, note that this SoC is very closer to the minimum SoC allowed for normal operation. During the day the BESS uses the excess PV generation energy to recharge and by the beginning of the peak period of the tariff it supplies part of the load, however, the most part of the load is still served by the grid.

Note that in this scenario, due to the battery reserve for outage events, the system has a smaller portion of the battery energy to use in normal days. Also, the load in Figure 6 represents both the CL and the NCL. One last comparison is to evaluate the same system considering the outage occurrence but with the battery reserve percentage set to zero. Table 8 presents the overall results for both cases (with 35% of battery reserve and with 0%).

Table 8. Case 2 - Battery reserve comparison.

Project with 35% of battery reserve		
Quantity	Outage	Normal operation
Battery Throughput (kWh/day)	4,10	1,08
Project with 0% of battery reserve		
Quantity	Outage	Normal operation
Battery Throughput (kWh/day)	3,44	1,08
Capacity shortage hours	7	0
Unmet load (kWh)	1,29	0

In Table 8 the results considering 35% of battery reserve presents a higher battery throughput for the outage day (4,1 kWh) in relation to the same day but without the outage (1,08), that means the system ended up using more the BESS given that all the CL must be supplied and also the BESS has a larger SoC operating range.

The results for the system with 0% reserve presented a lower battery throughput (3,44 kWh), however still larger than the normal day, and in this case the CL is not fully supplied, staying seven hours in shortage situation with an unmet load of 1,29 kWh. Note that even though there is an unmet load, the total hours without load supply is just 7 seven instead 24 there is the total outage hours that occurs. In this case, the BESS, even without a battery reserve, along with the PVSS, is still able to serve most part of the CL. Figure 7 presents the daily behavior of the system for the no battery reserve scenario.

In Figure 7 the BESS starts supplying the load by the beginning of the day, however, it also starts the day with

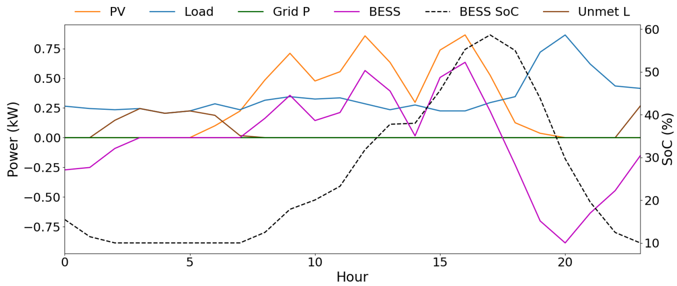

Figure 7. Major Outage day without the BESS reserve - Daily DER's dispatch.

a low SoC, which in turn limit the battery discharge, there is then an unmet load (Unmet L) event. As the PV output becomes available, besides serving the load it also recharges the BESS, as indicated by the dotted curve. The BESS reaches, for this day, its highest SoC value by the end of the PV production and starts to supply most of the CL in the peak period of the tariff, however, by the end of the day there is again another unmet load event when the BESS reaches its minimum SoC.

Finally, in order to asses the economic impact of the BESS in the PVSS, a final simulation in run without the BESS. Table 9 presents the found results.

Table 9. Case 2 - No BESS scenario.

Components	NPC (R$)	IC (R$)	RF (%)
PVSS (3,2 kWp) Inverter (1,67 kW)	32.777,00	22.661,00	60,5
	CoE (R$/kWh)	SPb (yr)	Total BS (R$)
	0,658	7,4	22.748,00

Similarly to Case 1, the results for the no BESS scenario showed better economic results, however, without being technically viable. Both the NPC and the IC presented costs, respectively, 37,5% and 47,1% lower. This time the system showed an SPb evaluated at 7,4 years with a CoE being at least half of the one in the original system. On the other hand, the system with the BESS presented higher levels of RF and total bill savings.

4. CONCLUSIONS

This study presented interesting results for the residential consumer when using the BESS, it showed in both cases that the BESS helped to increase the RF and presented good amounts of savings, however, at higher NPC's. In both cases the BESS use solved the outage problems, in the multiple short outages case the battery did no need the capacity reserve, however, in the major outage case it was needed at least 35% of reserve. In terms of NPC, in both cases the PVSS alone presented economically viable options given that the final NPC's were lower than in the grid only scenarios, however, these systems were not able to satisfy the constraints. With the addition of the BESS in each solo PVSS the constraints have been met but at higher NPC's, which in turn ended up making the projects unfeasible.

In resume, for this particular Brazilian consumer, the BESS showed to solve the outage problem, however, at a high price. Although using storage elements tends to increase the project price, it is still a good option to deal with lack of supply, and given the falling prices for PV panels and battery cells, these hybrid systems are expected to be more deployed in the future and considering that the Home Office may become more common, this type of system could receive more importance.

Among some further improvements for this particular study it could be taken into account reduced prices for the components and incentives for storage deployment, in order to find a threshold value were the complete system starts to represent a feasible option. It could also be considered an outage forecasting technique to deal with the battery dispatch, this way the battery reserve also could be used in normal days being able to generate more savings through the arbitrage service.

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