The potential of energy storage systems associated with PV generation to postpone investments in capacity expansion

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Abstract. Postponement of infrastructure investment is often regarded as a potential benefit of distributed PV generation. However, PV has questionable impact on the postponement of investments for infrastructure capacity increase. This paper evaluates under which conditions and to which extent distributed photovoltaics and energy storage systems are able to aid the distribution system in terms of alleviating the loading of feeders. The methodology consists of a sensitivity analysis, in different demand and generation scenarios, on the impacts that photovoltaic generation and energy storage systems would have in alleviating distribution feeders. In each scenario, the synergy between energy storage and PV generation is evaluated by estimating the amount of energy storage capacity needed to reduce the peak demand to a desired level. Results show that the existence of PV generation may reduce the storage capacity needed (and consequently the cost) to achieve a desired peak demand reduction only if proper conditions are found in the demand curve.

1. Introduction
Photovoltaic (PV) generation is regarded as one of the most prominent forms of distributed generation (DG). In Brazil, for instance, according to the Brazilian Electric Energy Regulatory Agency (ANEEL), it accounts for over 90% of all the DG in the country [1]. The intermittency of the primary resource, however, creates limitations to the deployment of distributed PV and to the benefits that PV generation may bring to the distribution grid. The stochastic nature of the primary resource could be mitigated by introducing resources for storing the excess generation and reinjecting it in moments of peak demand. The use of flexible resources would reduce the necessity to curtail DG production or implement disincentives to inject energy into the grid. One of the issues from using flexible resources and DG to tackle infrastructure reinforcement are the risks involved, for such procedure is not part of more familiar procedures already in use by the distribution system operator (DSO). Even though it is possible to reduce peak demand by using DG and flexible resources, restrictions regarding the sitting and the sizing need to be accounted for and on many occasions the DSO has no control over it. The synergy between DG and energy storage systems (ESS), for example, and their capacity to aid the distribution grid by alleviating the loading of feeders have been the object of research over the last years [2–8]. However, it is important to mention that this synergy depends on the meeting of some conditions, being intrinsically case specific.

This paper evaluates under which conditions and to which extent distributed PV and ESS are able to aid the distribution systems by alleviating the loading of feeders, and therefore helping to postpone
infrastructure expansion. Though storage does not need to be done necessarily with batteries and the methodology used in this paper applies to any form of storage or virtual energy storage downstream of a distribution feeder (such as batteries, water reservoir, heat storage, etc.), this work focuses primarily on the use of battery energy storage system (BESS). The methodology consists of a sensitivity analysis of the impacts that PV generation and BESS downstream of a feeder would have in scenarios with different demand profiles and PV penetration levels in order to evaluate the amount of energy storage capacity needed to alleviate distribution feeders to a desired amount. The remainder of the paper is outlined as follows: section 2 presents the methodology for the sensitivity analysis, section 3 presents a sensitivity analysis, section 4 presents the discussion and considerations about the synergy between BESS and PV generation and section 5 presents the conclusions and the final remarks.

2. Methodology for assessing the complementarity of BESS and PV
PV generation alone has questionable impact on the postponement of investments for infrastructure capacity increase, as the reduction of the peak demand could not be guaranteed due to the intermittency of the PV generation or the actual moment when the peak occurs. Therefore, the actual capacity of the feeder would have to remain the same as in the case in which no PV generation is added.

The addition of PV generation, however, influences the potential for peak reduction when energy storage is added mainly in two different ways: by actually decreasing the peak demand due to the coincidence between demand and storage-stabilized generation; or by lowering the net load factor (LF), which would allow more flexibility to manage energy and further deployment of energy storage. However, given the current scenarios of costs, the latter is more theoretical than practical.

The analysis carried out in this paper consisted on evaluating the sensitivity of the necessary storage capacity (NSC) to variations in the desired peak reduction (DPR) for the feeder, the amount of PV generation under the feeder and the demand profile. Figure 1 presents the overall approach used in this paper to evaluate the amount of energy storage needed to achieve a DPR on a feeder with a given net demand curve. Hourly irradiation values and nominal installed PV capacity are used to estimate the PV generation. Then, the PV generator production along with the hourly demand values and the DPR are used to estimate the amount of useful energy storage needed to steadily reduce the peak demand. In the analysis, all the values are expressed in per unit (p.u.) values and referred to the peak demand of the demand curves.

Figure 1. Overview of the methodology.
2.1. Determination of the necessary storage capacity
The useful storage capacity is considered to be the total amount of energy required to reduce the maximum demand to a desired level. The NSC to meet the DPR for each day of the year, \(d\), is given by:

\[
NSC(d) = \int_0^T a(t) \times [D(t) - (1 - DPR)]dt
\]  

(1)

where \(T\) is the day period, \(D\) is the demand and \(a\) is a dummy variable given by:

\[
a(t) = \begin{cases} 
0, & D(t) < MaxDem \\
1, & 1 > D(t) \geq MaxDem 
\end{cases}
\]  

(2)

The size of the BESS is considered as the maximum \(NSC\) found along the year. It is also considered that the BESS would only perform one cycle during the day, given the specific application (peak shaving).

3. Sensitivity analysis
For the estimation of the PV production, simulations were carried out using annual measured irradiation data for the city of São Paulo with hourly resolution taken from a measurement station at the Laboratory of Photovoltaic Systems of the University of São Paulo. Moreover, three load profiles were used in the simulations for representing typical consumption profiles of residential, commercial and industrial customers. The criteria for creating them is based on the technical procedure NT-2018 used by the São Paulo Utility [9] to estimate the sizing of transformers. Figure 2 shows the typical daily profiles for residential, commercial and industrial demands used in the simulations (from now on referred to respectively as RDP, CDP and IDP). The load profiles present distinct periods for their respective peak, which may influence the results due to the different correlation levels with the PV generation profile.

To provide a notion of the impacts that the PV generation would cause in each of the demand curves, figure 3 present the net demand for a clear sky day, considering different levels of PV generation penetration.

![Figure 2. Typical demand profiles.](image-url)
Figure 3. Impact of PV generation on the demand curves on a clear sky day for (a) the RDP, (b) the CDP, and (c) the IDP.

In the case of the RDP, shown in figure 3 (a), the PV generation would not produce reduction in peak demand regardless of the amount of the PV generation due to the evening peak. In figure 3 (b), for the CDP case, and it is observed that PV generation may produce a considerable peak demand reduction, which eventually saturates at 0.8 p.u. Moreover, the peak demand reduction becomes quite small for values past 0.75 p.u. of PV generation penetration. In figure 3 (c), for the IDP case, it is observed that PV generation may produce a considerable peak demand reduction, due to the coincidence of demand and generation.

Although PV generation may result in peak demand reduction in a clear sky day, when the variability of the resource is considered throughout the year, the peak reduction cannot be guaranteed. Table 1 presents the amount of peak demand reduction due to the insertion of PV generation alone in the annual simulation. According to the results, only in the IDP case there is a small reduction of the maximum demand due to the insertion of PV generation. This reduction in IDP case would require a high penetration of PV generation and, still, the configuration would not be reliable without an amount of dispatchable output.

Table 1. Peak demand reduction due to the deployment of PV generation.

| PV generation penetration level (p.u.) | Peak demand reduction |
|---------------------------------------|----------------------|
|                                       | RDP  | CDP  | IDP  |
| 0.25                                  | 0%   | 0%   | 1%   |
| 0.50                                  | 0%   | 0%   | 2%   |
| 0.75                                  | 0%   | 0%   | 3%   |
| 1.00                                  | 0%   | 0%   | 4%   |
| 1.10                                  | 0%   | 0%   | 5%   |
| 1.20                                  | 0%   | 0%   | 5%   |
| 1.30                                  | 0%   | 0%   | 6%   |
| 1.40                                  | 0%   | 0%   | 6%   |

Even though PV generation may not be enough to produce significant decrease of the peak demand, it may reduce the number of hours per year that the demand spends at the peak (or close to the peak). In order to illustrate this, figures 4, 5 and 6 present the fraction of the time spent above each loading level, respectively for the RDP, CDP and IDP cases. In figure 4, it is noticeable that the PV generation does
little to reduce the number of hours above a given level. Throughout the loading range considered, the insertion of PV generation made almost no difference in loading reduction, and even when it did reduce the loading, this reduction showed little sensitivity with the PV generation penetration.

In Figure 4, though the CDP would not appreciate reduction in peak demand due to the insertion of PV generation alone like the IDP (as presented in Table 1), the PV generation would contribute to reduce the number of hours in which the demand curve is above a given level. For instance, a 0.25 p.u. PV generation would reduce the number of hours in which the demand curve is above 0.95 p.u. by more than 50%. In this context, combining storage and PV generation may result in configurations that would have a better performance than generation-only or storage-only.

In Figure 6, it is noticeable that the PV penetration greatly reduces the number of hours above a given level. The introduction of a PV generation of 0.25 p.u. would reduce the number of hours greater than 0.95 p.u. by 95%, which suggests improved potential for the use of BESS. Throughout the loading range considered the reduction seems to saturate past 0.5 p.u. of PV generation.
3.1. Useful storage capacity requirements

As presented in the previous section, depending on the demand curve there may be synergy between the PV and BESS to reduce the peak demand. This subsection evaluates the requirement in terms of energy storage capacity to reduce the annual peak demand of the demand curve, considering the three above mentioned demand curves and different values of PV penetration.

As expected from the previous analyses done to the RDP case, there is little synergy between PV generation and BESS to reduce the peak demand. Figure 7 (a) presents the NSC for a given DPR for different values of PV generation. As expected, the curves present almost no sensitivity with the PV generation for most of the range considered for demand reduction. Only close to 0.3 p.u. of DPR the curves cease to overlap. Figure 7 (b) shows the data of figure 7 (a) from a different perspective and shows the percent reduction in terms of storage capacity that the existence of PV generation would allow to achieve a given DPR (the values are compared to the NSC in the situation where no PV generation exists). In this situation, the only contribution that the PV generation would provide for this application is lowering the net LF at the point of common coupling.

Figure 8 presents the impact that different values of PV generation would cause on the NSC for a given DPR in the CDP case. In figure 8 (a), it is noticeable that for DPR up to 0.05 p.u. the amount of PV
generation has little sensitivity with the NSC. This happens because the demand levels over 0.95 p.u. occur at moments in which the solar generation is low. Since the energy needed to flatten the demand to 0.95 p.u. is somewhat shifted from the PV generation, it would not influence the NSC needed. Past a DPR of 0.05 p.u., the PV generation starts to influence considerably the NSC, reaching more than 60% reduction in some cases, as presented in figure 8 (b). This implies that the presence of PV generation downstream of the feeder would decrease the amount (and hence the cost) of the BESS for the same peak reduction. It is also noticeable that most of the reduction in NSC occur for the first units of PV generation and past 1 p.u. of PV generation the reduction of energy storage capacity seems to saturate.

Figure 8. Impact of PV generation on the storage capacity for the CDP case. (a) NSC required as a function of the DPR for the RDP and (b) NSC reduction in relation to the scenario in which no PV generation exists.

Figure 9 presents the impact that different values of PV generation would cause on the NSC for a given DPR for the IDP case. Unlike the CDP case, in the IDP case the curves do not necessarily start at zero for no amount of energy storage, as presented in figure 9 (a), which means that the PV generation alone may reduce some of the peak demand (as presented in table 1). Also, the amount of PV generation influences the NSC even for small peak demand reductions, different from the behavior presented in the CDP case. The sensitivity with the amount of PV generation increases as the DPR increases. Due to the existence of low energy density local maximums in the IDP, the curves present a smaller inclination for demand reduction values up to 0.15 p.u., when compared to the other two demand profiles. Past a DPR of 0.17 p.u., the PV generation starts to influence considerably the size of the BESS, reaching considerable reductions between the curve without the PV generation and the curve with 1.5 p.u. of PV generation, which suggests that the PV generation has the potential to reduce the NSC needed for peak shaving. Similar to the CDP case, past 1 p.u. of PV generation the reduction of NSC seems to saturate, as presented in figure 9 (b).
3.2. Least cost configuration considerations

The cost analysis compares the cost of the different configuration of the PV-energy storage pair for a given DPR presented in the previous section (figures 7, 8 and 9). In order to make the results more general, the comparison is made by assessing the influence that the cost relation (CR) between 1 p.u.h of energy storage and 1 p.u. of PV generation would have in the least cost configuration to achieve a given DPR. In this way, the conclusions drawn from the analysis are valid regardless of the actual values attributed to the PV and NSC.

In the sensitivity analysis carried out for the RDP case and CR up to 4, disregarded of the size of PV generation and the CR, the storage-only configuration is the least cost option for peak demand reduction, as expected from the lack of sensitivity the peak and the PV generation for this case. In the CDP case, the storage-only configuration is not necessarily the least cost configuration depending on the value of the CR and the DPR. Figure 10 shows the sensitivity analysis carried out for the CDP and IDP cases, up to a CR of 4. In figure 10 (a), the storage-only configuration is the least expensive arrangement only for peak reductions up to 0.085 p.u., disregarded of the CR. When CR reaches 2, PV-storage configurations may become less expensive depending on the desired DPR.

![Figure 9](image9.png)

**Figure 9.** Impact of PV generation on the storage capacity for the IDP case. (a) NSC required as a function of the DPR for the IDP and (b) NSC reduction in relation to the scenario in which no PV generation exists.

![Figure 10](image10.png)

**Figure 10.** Least cost configuration. (a) for the CDP case and (b) for the IDP case.
In the IDP case, presented in figure 10 (b), the storage-only configuration is not necessarily the least cost configuration depending on the value of the CR and the DPR. The storage only configuration is the least expensive arrangement for CR up to 1.5 or for DPR below 0.13 disregarded of the CR. When the CR reaches 2, some PV-storage configurations become less expensive depending on the desired DPR. Tough in the industrial case PV-alone configurations may reach some levels of peak demand reductions, energy storage also has great potential in this profile due to the presence of low energy density peaks. Although currently the CR is close to the unit, when the upfront cost of both technologies is considered, the life cycle cost (LCC) of a BESS is not concentrated in the initial investment, like the LCC for PV generation. The LCC of BESS is highly dependent of its lifespan, which in turn relies on several factors. This makes it difficult to estimate the LCC of BESS, especially because it is a relatively new technology for the application of grid reinforcement, which aggregates risks to the investment. The lifespan of batteries is dependent not only of its calendric life, but also of the number of cycles, operating temperature and C-rate, maximum depth of discharge, among other factors, which may result in a LCC considerably different than the upfront initial cost. Since BESS for stationary application is supposed to operate for long lifespans, reduction of the performance and capacity are expected to occur, which may influence the operational costs of real business cases [9] and may even require some level of oversizing to ensure that the necessary amount of energy is available throughout the lifespan of the application. On the other hand, the upfront cost of BESS is expected to decrease in the coming years due to increases in technology maturity, specific energy, energy density and economies of scale. According to [10] in a projection of the cost reduction of utility scale BESS, battery storage is expected to have a more prominent decrease in the 2020 decade.

4. Discussion
Postponement of infrastructure investment is often regarded as a potential benefit of distributed PV generation. Though PV generation may influence the peak demand reduction, it would not be advisable to install PV generation alone as a way to reduce maximum demand and postpone grid reinforcement. The results suggest that this potential is low when PV-generation alone is considered because the peak demand reduction could not be guaranteed. The least cost analysis shows that considering PV generation solely for the purpose of reducing peak demand would only be cost effective if the CR were greater than 1.5 and the demand peak showed coincidence with the PV generation. Results of the simulations show that for CR equal to 2 or above at feeders with predominance of commercial or industrial demands, configurations using PV generation may reach lower costs than storage-only configurations depending on the desired DPR. For CR below 1.5, storage-only configurations are the least cost arrangements in every case considered. Since batteries show declining costs, it is more likely that the CR would fall to values below 1, which is already the case for residential and commercial consumers according to the costs for PV systems presented in [11]. However, PV generation has its main revenue stream at the energy trade (either self-consumption or feed in), therefore it does not need necessarily to find other revenue streams to be economically viable. The PV generation may contribute to reduce the size of the storage needed to achieve a particular DPR and, since the analysis presented in figures 7, 8 and 9 considers the useful storage, the cost reduction could be higher due to factors like the depth of discharge, loss of storage capacity (due to cycling) and discharge efficiency, which may require oversizing of the storage and, therefore, would drive the BESS cost up. Regarding specifically the use of BESS as infrastructure repowering, the planning of the DSO would have to account for the capacity derating and the nominal storage capacity would have to be greater than the one needed or additional storage would have to be deployed to assure that the purpose would be met throughout the distribution grid planning horizon. One advantage of using storage for capacity deferral is that it reduces the investment risks of a planned demand increase not realizing [12]. Depending of the demand profile, the decouple between PV generation and peak demand may render the PV generation not appropriate to reduce peak hours throughout the year. In the results, this situation is more prominent in the RDP case, in which there was no correlation between the use of PV and peak reduction (the overlapped curves in figures 4 and 7 (a)). However, there are still benefits that could come from the deployment of BESS along with PV generation in residential areas. For example, BESS could improve the value of the PV generation by increasing the amount of self-consumption of households
and also increasing the maximum penetration levels of distributed generation by providing support to the grid. Moreover, trends of cost reduction for both storage and PV, increasing electricity tariffs and even, in some countries, the disincentive to feed excess PV generation into the grid may make the use of PV generation with on-site or near-site storage (in the case of microgrids) a feasible scenario in the future.

In the case of commercial and industrial demand profiles, the effectiveness of using BESS for postponing investments is influenced by the PV generation. The existence of PV generation downstream of the feeder may reduce the NSC (and hence its cost) to achieve a given level of DPR. In the results, presented in figures 8 and 9, considerable reductions could be achieved by combining the two distributed resources. From the results, it is also noticeable that the reduction of the NSC saturates as more PV generation is deployed. In terms of the NSC, the first 0.5 p.u. of PV generation are the most cost effective in reducing it. Moreover, even if high values of PV penetration are not as effective in reducing the NSC and the peak demand, the same additional benefits stated for the RDP case could still be applied to the CDP and IDP cases.

Currently, the use of BESS for providing grid services, especially at the distribution level, are not economically viable on most locations. The revenue streams for storage in the distribution grid would be mainly trade and behind the meter applications like arbitrage, maximization of distributed generation self-consumption and reducing maximum contracted demands for some types of consumers (usually this would only apply to commercial and industrial consumers). In the case of the latter, many commercial and industrial consumers use diesel generation as peak plants in Time of Use Tariffs, which, currently, is more economically viable than using BESS [13], but it may become a viable market in the near future as the BESS prices drop. To increase the attractiveness of BESS, grid services would have to also constitute revenue streams, for example, in Poudineh et al. [14] a scheme to account for infrastructure reinvestment deferral by a “Contract for Deferral Scheme” is proposed in which the DSO would pay for the infrastructure deferral service in exchange for the guarantee that the distributed resource would be available in the time of need. Other alternative would be the use of price signals to tailor the operation of flexible resources owners even if the DSO does not have direct control over the storage.

5. Conclusion
This paper evaluated in which situations the presence of PV downstream of a feeder would help to reduce the size of energy storage systems for peak shaving application. Though PV generation may find synergy with BESS (reducing the NSC for a given DPR), proper conditions in the demand curve are needed for the storage capacity reduction to be appreciated, which makes the outcomes site specific. The results suggested that the potential to reduce peak demand was low when PV-generation alone is considered because the reduction could not be guaranteed even in the case where the demand shows correlation with the generation. When ESS is introduced, proper conditions should exist for the synergy to occur, mainly the coincidence between demand and generation and the existence of short duration peaks during the daytime. From the results, it is also noticeable that the reduction of the NSC saturates as more PV generation is deployed.

Currently, the use of BESS for providing grid services, especially at the distribution level, are still not economically viable on many locations. The revenue streams for storage in the distribution grid are still limited. It is expected that as the price drops, BESS may be used for substituting diesel generation for some applications like not exceeding contracted demands.

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