The Role of Second Life Li-ion Batteries in Avoiding Generation Curtailment in Utility-scale Wind + Solar Parks in Brazil

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***Abstract* — Utility-scale hybrid wind (WD) + solar photovoltaic (PV) generators have been demonstrated to present high levels of complementarity in the Brazilian Northeast, where the wind resource is more abundant at night, and single-axis PV has a smooth peak during the day. The use of discarded, second-life Li-ion batteries from electric cars further reduces the potential mismatch between generation and demand, and at the same time improves the economic viability of electromobility. This paper evaluates the curtailment reduction potential of adding 100 MWh of second-life Li-ion batteries to a hybrid 95 MW wind + 60 MW solar PV power plant in the Brazilian Northeast.**

***Index Terms* — photovoltaic systems, hybrid power systems, energy storage system, wind system, complementarity wind and pv.**

I. Introduction

One of the main concerns with the increasing penetration level of renewable energies in the electric system is the effect of their variability due to the stochastic nature of both the solar and wind resources [1]-[2]. To mitigate these effects energy storage systems are becoming widespread, especially with the cost reductions experienced by Li-ion batteries in the context of electromobility [3]-[4]. The electric vehicles industry is expected to sell around one million vehicles in 2020 [5]**.** When electrical vehicles batteries reach 80% of their nominal capacity due to use and aging, they no longer satisfy the electric vehicles requirements and then, usually, they are collected to be recycled [6]. However, these batteries are still useful for stationary applications, such as reducing the impact of the variability of renewable energy sources [7], in what is called a battery's second-life. The electric car industry can greatly benefit if the energy industry can give the discarded Li-ion batteries another 5-8 years of use before they are finally discarded or recycled.

In the context of an ANEEL (Brazilian National Agency of Electrical Energy) R&D project, together with a 95 MW wind power plant (WD), a pilot photovoltaic (PV) plant was built to study the application of different PV technologies, as well as to evaluate the complementarity between wind and solar resources in the Brazilian Northeast [8]. In this study, we analyze the role of a second-life Li-ion battery energy storage system (BESS) in avoiding the generation curtailment, derived from a 100 MW substation limit, where both generators are connected.



Fig. 1. 95 MW wind power plant (left) and 2.2 kWp single-axis PV tracker (right).

II. System Description

This study uses data from the 95 MW WD plant together with data from a 2 kWp CdTe single-axis tracker PV plant whose nameplate installed capacity was extrapolated to represent a 60 MWp single-axis tracker PV power plant at the same site. Both systems are connected to a local 100 MVA substation. Fig.1 shows the wind power plant (left) and the PV system (right) in Brotas de Macaúbas-BA (12°S, 42°W), in the Brazilian Northeast.

III. Methodology

The aim of this study is to evaluate to which extent a BESS could avoid energy losses due to overloading the substation if both the WD and PV plants (combined nameplate capacity of 150 MW) operate close to nominal output power. Additionally, we evaluate the impact of different capacities of the BESS in order to maintain the total power output (WD + PV) at 100 MW. We used a model adapted from [9], which can be modeled using equations 1 and 2.

$$E_{BESS} = E_{BESS} + C_{BESS} \cdot \eta_{BESS} \quad (1)$$

$$E_{BESS} = E_{BESS} - \frac{D_{BESS}}{\eta_{BESS}} \quad (2)$$

Where η_{BESS} is the BESS efficiency, which includes the inverter efficiency and electrochemical conversion. The η_{BESS} was fixed at 85% and the depth of discharge was fixed at 80%. These values are based on [10]. The dispatch strategy based on [11] is presented in Fig. 2. If the total power generation is

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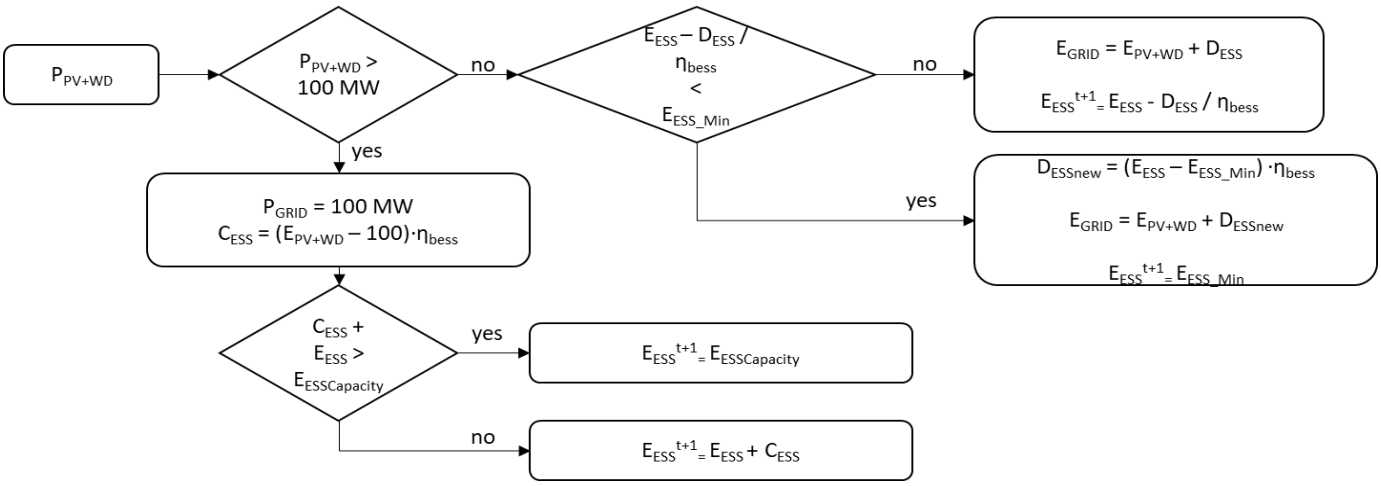


Fig. 2. Energy dispatch flow chart, based on [11].

greater than the 100 MW limit, then the exceeding energy is stored at the BESS. If the BESS is full or is going to reach its maximum capacity, the exceeding energy is discarded (WD or PV output curtailment). If the total power generation is less than 100 MW and the BESS has energy enough to provide the energy shortfall without reaching its minimum state of charge, the BESS provides the missing energy to guarantee the 100 MW. However, if the BESS does not have enough energy, it provides energy until it reaches its minimum state of charge.

IV. Results and Discussion

The average day, presented in Fig. 3, is calculated by the mean of all points for that hour and minute over the year. This analysis enables an overview in the complementary nature of the WD and PV power plants. As can be noted in Fig. 3, the wind plant has a night-time maximum, while the PV plant peaks during the middle of the day as expected, indicating a good complementarity between the two resources. For the average day presented, the Pearson Correlation Coefficient is -0.7, indicating a good temporal complementarity between the two sources [12]-[13]. In addition, this analysis shows that, on average, the total power output does not exceed the 100 MW limit. However, it is important to note that the average day tends to soften extreme values and hide important peaks as we have already shown elsewhere [8].

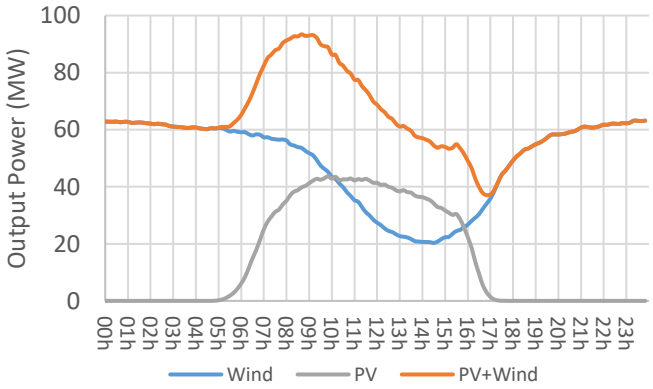


Fig. 3. Average day of the Wind, PV and Total generation.

The actual substation size (100 MVA) leads to a curtailment loss equal to 2.7%. To mitigate these losses, one could expand the actual substation or install a BESS to store the exceeding energy and use the stored energy when necessary. Fig. 4 shows the curtailment values for different substation sizes. It is evident that adding a PV plant that represents 60% of the substation size, the required expansion is about only 30% of the substation original size.

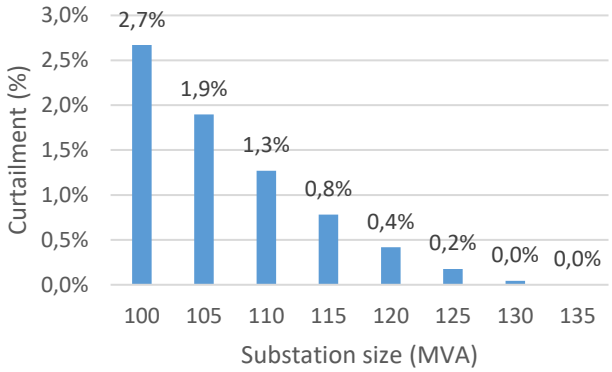


Fig. 4. Curtailment losses for different substation sizes.

For the BESS analysis, we analyze two main losses: curtailment loss – the loss due to excess generation –, and the efficiency loss – the loss due to the BESS energy conversion. As shown in Fig. 5, the increase in the BESS capacity leads to lower curtailment losses, but also leads to an increase in the efficiency conversion losses. However, the total losses decrease exponentially with the increase of the BESS capacity. While the curtailment losses decrease at a rate of -0.23 percentage points (p.p.), the efficiency conversion losses increase at a rate of 0.07 p.p for each 10 MWh of BESS capacity.

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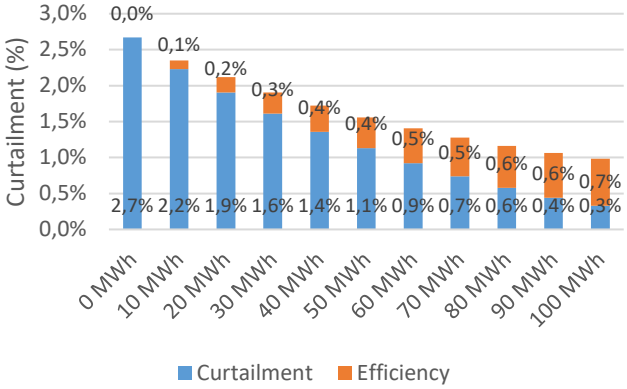


Fig. 5. Curtailment and conversion efficiency losses for different BESS capacities.

Considering a target load as 100 MW, the Loss of Load Probability (LOLP) [14] was calculated to determine how the BESS affects the hybrid plant dispatchability. The result is presented in Fig. 6, and it shows that the LOLP decreases by 5 p.p. from no storage to 100 MWh of storage capacity, showing that the dispatchability is slightly increased by the BESS, and it tends to become constant at around 48%.

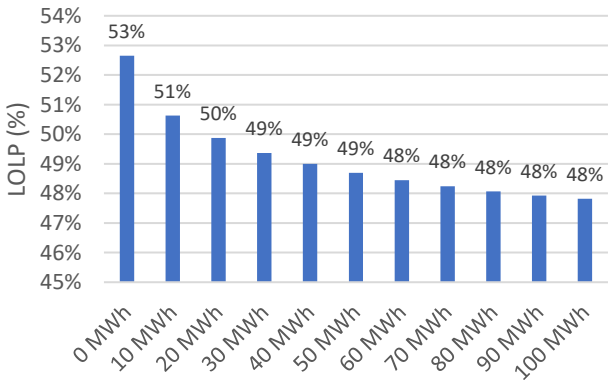


Fig. 6. LOLP for different BESS capacities.

We highlight that in this study we did not consider a power charge/discharge maximum limit to the BESS, in other words, the BESS can fully charge/discharge (respecting the depth of charge and maximum capacity) in a single 10 min interval. Fig. 7 shows the energy flow for the day with the highest curtailment loss (8.83% without BESS) with a BESS of 100 MWh. The light blue area represents the energy dispatched to the grid; the dark blue and green areas represent the BESS charge and discharge, respectively; the areas in red and gray represent the losses due to curtailment and BESS efficiency, respectively; and the orange line represents the total energy generation.

It can be noted that a BESS with capacity of 100 MWh was charged in a period of four hours. The maximum charge and discharge power observed for this day were 33 MW and 29 MW (33% and 29% of nominal capacity respectively).

V. Conclusions

According to the results presented in this study, we conclude that for a hybrid 95 MW wind + 60 MWp single-axis tracker PV plant, the curtailment losses, imposed by a 100 MVA substation limit decrease exponentially with the increase of both the substation size and the battery energy storage system capacity. It was noticed that for an addition of a PV plant that represents 60% of the substation size, the required expansion is about only 30% of the substation original capacity. The curtailment losses start at 2.7% for a system without storage and decrease up to 1.0% for a storage system with a capacity of 100 MWh. Moreover, we observed that even with a battery capacity of 100 MWh, the hybrid WD+PV system does not maintain the output in 100 MW for long periods, with the LOLP stabilizing at 48%. For the day with the highest curtailment losses (8.83%), the system maintained output in 100 MW for a total period of 16 hours and 40 minutes. The benefits of adding a BESS are not restricted to the plants dispatchability, and includes ancillary services and energy arbitrage which are not in the scope of the present analysis, but which must be evaluated in order to make the best of any investment in storage [15].

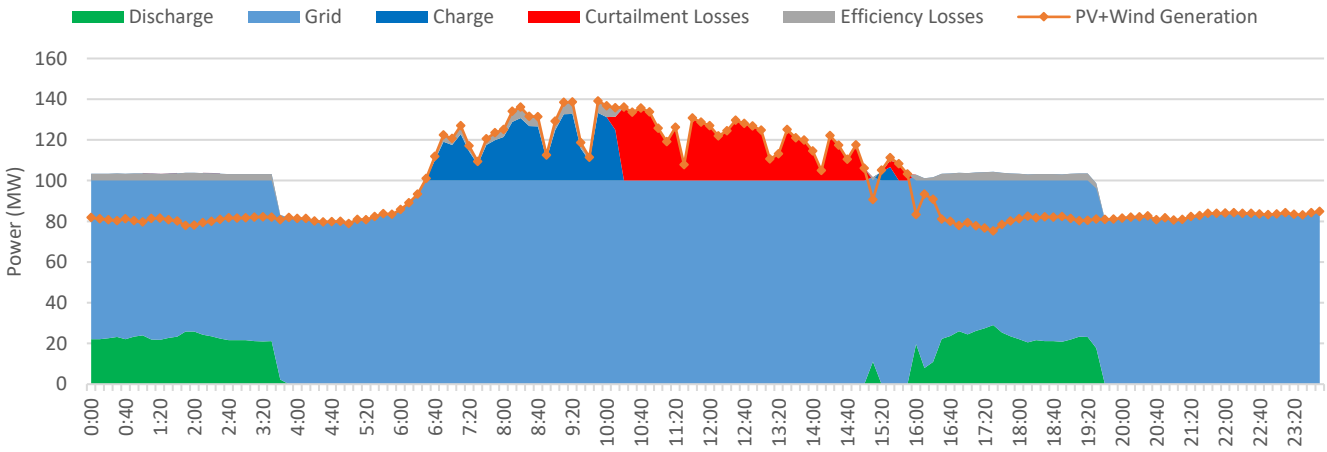


Fig. 7. Energy flow for the day with the maximum curtailment loss.

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