Optimizing Energy Production Through BESS Integration in Photovoltaic Power Plants in Brazil

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Abstract

Electricity generation in Brazil is predominantly carried out using renewable energy sources. According to EPE, in 2024, renewable sources accounted for 88.2% of the national electricity matrix. Wind and solar, known as variable energy sources, together account for 23,7% of all the energy generated in the country. Despite the strong presence of renewables in Brazil, these sources have been facing a scenario of uncertainty due to significant operational constraints, particularly affecting wind and photovoltaic power plants in the Northeast region. These constraints worsened after the failure of the National Interconnected System (SIN) in August 2023, which caused a 41% reduction in energy transfer from the Northeast to the Southeast/Central-West regions. Therefore, an immediate solution is essential for the growth of intermittent sources, aiming to reduce the amount of energy wasted due to SIN restrictions. One solution is the integration of batteries alongside generation. With this objective, this study will model and analyze the results of integrating a Battery Energy Storage System (BESS) into a photovoltaic plant, thereby reducing its operational constraints. The results show that integrating a 30 MW/150 MWh BESS into photovoltaic plants in Brazil's Northeast effectively mitigates curtailment by storing excess midday generation and dispatching it during evening peaks (6 p.m. to 10 p.m.). Overall, PV-BESS systems provide a reliable solution to enhance dispatchability and grid adequacy in Brazil's renewable energy sector.

Keywords: PV Power Plant, BESS, curtailment.

1. Introduction

The problems caused by the release of greenhouse gases into the atmosphere are widely known, such as the increased frequency and intensity of extreme weather events, heatwaves, droughts, and floods (IPCC, 2021), which also result in losses in agricultural productivity (Ortiz-Bobea et al., 2020). The use of fossil fuels currently accounts for 75% of all greenhouse gas emissions (Mikuli et al., 2019). The energy transition toward an electricity matrix based on renewable sources is an excellent solution to this problem (IPCC, 2011). Brazil is a country that stands out significantly in the production of electricity from renewable sources. In 2023, 89.3% of all electricity produced in the country came from renewables (EPE, 2024). EPE also highlights solar energy, with an annual production of 50.6 TWh—a value 54.8% higher than in 2022—demonstrating the rapid growth of this source in Brazil (EPE, 2024). Wind energy also experienced significant growth of 17.4% compared to the previous year, having generated 95.8 TWh of electricity in 2023 (EPE, 2024). Despite the significant growth in installed capacity from renewable sources and the critical role these plants play in the country's energy production—as well as their contribution to reducing greenhouse gas emissions—owners of power generation assets have been facing major challenges due to operational constraints in the Brazilian electrical system, which have increased since the transmission system failure on August 15, 2023 (ONSa, 2023).

The Brazilian electrical system is divided into four subregions: North, Northeast, Southeast/Central-West, and South, with the highest demand located in the Southeast/Central-West subsystem, which accounted for more than 56% of all electricity consumed in the country in 2024 (ONSa, 2025). On the other hand, solar and wind power generation is predominantly located in the Northeast subsystem (ONSb, 2025), with 92% of all wind and 32% of photovoltaic energy production in 2024. On August 15, 2023, an incident in the SIN (National

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Interconnected System) caused the interruption of 22,457 MW out of the 71,000 MW being supplied at the time—that is, 31% of the entire Brazilian load was left without power. The event caused the electrical disconnection of the North and Northeast subsystems from the Southeast/Central-West and South subsystems (ONSa, 2023). Following the 2023 blackout, the operation of the Brazilian electrical system was redesigned. Previously, the transfer limit from the Northeast and North systems to the Southeast/Central-West system was 13,600 MW, but after the August 2023 event, these limits were re-evaluated for operational safety reasons and reduced to 8,000 MW—a decrease of more than 40% (ONSb, 2023). These restrictions impacted the energy production of renewable power plants, which, due to the nature of renewable resources, are intermittent and do not store energy. According to Brazil National System Operator (2025), the average power restriction by 2024 is 1,447 MW. In May 2025 alone, ANEEL restricted the operation of photovoltaic plants on 6,830 occasions, of which 6,519 were due to a lack of load to be served and 311 were restrictions related to the operational security of the transmission system (ONSc, 2025).

The data presented above clearly demonstrate that the rapid growth of intermittent renewable energy sources in Brazil has surpassed the transmission capacity of the National Interconnected System (SIN), resulting in curtailment events, particularly during peak photovoltaic production periods. This imbalance is further exacerbated by the fact that the development of generation assets is occurring at a significantly faster pace than the construction of transmission infrastructure. The expansion of transmission lines is contingent upon centralized planning by the Energy Research Office - EPE, which identifies where grid expansion should occur. Following this planning phase, transmission projects are auctioned to private sector entities responsible for their construction. In contrast, the deployment of photovoltaic and wind power plants, especially those targeting the free energy market, is led entirely by private developers and driven by market demand. Consequently, the existing framework for transmission planning and development is unlikely to resolve the issue of curtailment in the short term, as the expansion of Brazil's transmission system is not expected to keep pace with the growth of renewable generation.

One potential solution to reduce the volume of energy wasted due to curtailment is the storage of electrical energy using electrochemical batteries (Saboori et al., 2021). These systems, commonly referred to as Battery Energy Storage Systems (BESS), can be integrated either at the transmission level or directly alongside photovoltaic power plants. In this study, we simulate the integration of BESS with photovoltaic power plants located in the Northeast region of Brazil, which currently face daily dispatch constraints imposed by the National System Operator (ONS).

To address key operational challenges in the Brazilian power system, this paper aims to contribute through the following objectives:

1 – Identify the periods of greatest photovoltaic dispatch restriction by analyzing the ONS's monthly constrained-off reports;

2 – Model and optimize the dispatch of photovoltaic energy from a representative plant in the Brazilian Northeast through the integration of BESS;

3 – Determine the appropriate battery capacity relative to the plant's power rating to minimize curtailed energy and improve system efficiency.

2. Literature Review

Brazil's electricity sector is undergoing a profound transformation driven by the rapid growth of variable renewable energy (VRE), particularly photovoltaic (PV) and wind power. In 2023, renewables accounted for 93% of total electricity generation in the National Interconnected System (NIS), with hydropower remaining dominant (58.9%), followed by wind (13.2%), biomass (8%), and solar PV, which reached an impressive 50.6 TWh (EPE, 2024). The expansion of PV generation has been especially remarkable, with a 68.1% increase in installed capacity between 2022 and 2023. This growth underscores the country's leadership in renewable integration but also reveals operational challenges related to variability, low dispatchability, and limited predictability of PV generation (IEA, 2023; Esswein Jr. et al., 2025).

The literature consistently highlights the role of BESS in addressing these challenges. Esswein Jr. et al. (2025)

demonstrate that PV plants integrated with BESS can contribute to firm capacity provision, making them suitable for capacity markets even though the current regulatory framework excludes them. Dettmar et al. (2024) reinforce this argument, showing that BESS enables time-shifting of solar energy, smoothing generation profiles, reducing reliance on fossil backup plants, and providing valuable grid services such as frequency regulation and reserve capacity. These benefits place BESS as a key enabler of large-scale renewable integration in Brazil.

International experiences provide strong evidence of BESS viability. The Hornsdale Power Reserve in Australia (100 MW/129 MWh, later expanded to 150 MW/194 MWh) demonstrated the effectiveness of storage for frequency regulation, arbitrage, and system reliability, saving over AUD 130 million in its first two years of operation (HPR, 2021). Similarly, the United States and Europe have witnessed rapid deployment of utility-scale storage, with global capacity reaching 85 GW in 2023 (IEA, 2024). These experiences confirm that hybrid PV+BESS configurations contribute significantly to grid resilience and energy market efficiency (IRENA, 2019).

In Brazil, the relevance of storage is amplified by the rising incidence of curtailment. Curtailment refers to the reduction or limitation of renewable generation when supply exceeds demand or when transmission bottlenecks occur. The National System Operator (ONS, 2025) identifies curtailment as an increasingly frequent phenomenon, especially in the Northeast, where renewable penetration has outpaced transmission capacity. The August 2023 disturbance revealed the need for stricter operational limits, leading to higher curtailment levels. By 2024, renewable restrictions reached 12,675 GWh, with projections indicating further growth through 2029 if structural measures are not adopted.

Curtailment not only reduces operational efficiency but also imposes financial losses on developers, undermining Brazil’s decarbonization goals. PV+BESS projects can mitigate these impacts by absorbing surplus generation during off-peak periods and releasing it during demand peaks, thereby enhancing both system adequacy and project economics (Dettmar et al., 2024). This dual role positions storage as a strategic complement to renewable expansion.

From a technological standpoint, lithium-ion batteries dominate the global storage market due to their high energy and power density, round-trip efficiencies of 90–95%, and declining costs, which have fallen by nearly 90% in the past decade (Preger et al., 2021; Choi et al., 2021). Sub-technologies such as NMC (Nickel-Manganese-Cobalt), LFP (Lithium-Iron-Phosphate), and LTO (Lithium-Titanate-Oxide) provide different trade-offs in terms of lifetime, thermal stability, and cost structure. Beyond lithium, sodium-based batteries, such as sodium-sulfur (NaS), offer long-duration storage with lifespans of 15–20 years and round-trip efficiencies around 80–85% (Spoerke et al., 2021). Flow batteries, particularly vanadium redox flow batteries (VRFBs), present unique advantages such as decoupled power and energy capacity, virtually unlimited cycling, and high safety, though at higher upfront costs (Zhang et al., 2024).

In conclusion, the literature converges on the idea that PV+BESS systems are critical to the modernization of Brazil’s power sector. They can reduce curtailment, provide firm capacity, enhance flexibility, and align Brazil with international best practices in renewable integration. However, unlocking this potential requires regulatory evolution to incorporate hybrid systems into capacity auctions and ancillary service markets.

3. Methodology

The methodological framework of this study builds on Esswein Jr. et al. (2025), integrating technical and economic analyses to evaluate the feasibility of PV+BESS projects in Brazil. The approach involves resource characterization, system design, simulation of energy production and storage operation, and financial assessment, complemented by curtailment mitigation analysis based on ONS (2025) data. Through this methodology, the study provides a comprehensive evaluation of PV+BESS integration in Brazil, bridging technical, economic, and regulatory perspectives. The findings support policy recommendations for including hybrid projects in future capacity auctions and enhancing system adequacy.

3.1. System Modeling and Economic Scenarios

This study models the dispatch of photovoltaic energy from a representative power plant located in the

Brazilian Northeast, with emphasis on the integration of a BESS. The primary objective is to determine the appropriate battery capacity relative to the plant's power rating to minimize curtailed energy and enhance overall system efficiency. The photovoltaic systems were carefully designed and optimized according to the solar irradiance characteristics of each region. The optimization process focused on maximizing energy production while minimizing clipping losses and shading effects. These outcomes were achieved by adjusting parameters such as the power plant layout, the DC/AC ratio, and the ground coverage ratio.

Meteorological data in the simulation process. The analysis utilized Typical Meteorological Year (TMY) datasets from the NREL National Solar Resource Database (NSRDB). The TMY employed in this study was constructed from hourly data spanning 1998 to 2017 (NREL, 2024), providing a reliable long-term representation of solar resource conditions. The dataset includes essential variables for photovoltaic modeling, such as direct normal irradiance (DNI), global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), wind speed, atmospheric pressure, and relative humidity. These parameters were incorporated into the simulation framework to ensure realistic modeling of site-specific performance and environmental conditions.

Each plant configuration was simulated under four distinct setups: (i) a ground-mounted photovoltaic system with a fixed-tilt structure; (ii) a ground-mounted photovoltaic system with an east-west single-axis tracking structure; (iii) a ground-mounted photovoltaic system with a fixed-tilt structure integrated with a 30 MW/150 MWh BESS; and (iv) a ground-mounted photovoltaic system with an east-west tracking structure integrated with a 30 MW/150 MWh BESS. For the scenarios without energy storage, simulations assumed all electricity was sold in the Brazilian spot market at hourly prices. In contrast, the BESS-integrated scenarios considered participation in the capacity reserve market in addition to selling surplus energy on the spot market. Overall, four main simulation sets were performed, each including specific variations in plant configuration, capital expenditures (CAPEX), operational expenditures (OPEX), and revenue streams.

The simulations were conducted using the System Advisor Model (SAM), a computational platform developed by the National Renewable Energy Laboratory (NREL) with comprehensive technical and economic analysis capabilities. SAM was applied to simulate the technical performance of the plants. The process involved inputting meteorological data, selecting photovoltaic modules and inverters, and defining the electrical configuration and site layout as specified for each project. Subsequently, the outputs from SAM were integrated with Python routines to allow more efficient data analysis. Post-processing of the results focused on both economic indicators—such as annual revenue, internal rate of return (IRR), and net present value (NPV)—and technical parameters, including energy profiles, loss of load probability and curtailment analysis.

The operational period simulated extends from 2027 to 2046. Two economic perspectives were considered: (i) a photovoltaic plant without batteries, where all electricity is sold at the spot market price, the Price of Settlement of Differences (PLD), based on historical PLD data from 2021 and 2024 corrected for inflation; and (ii) a photovoltaic plant integrated with a 30 MW/120 MWh BESS. For the second case, the annual revenue includes additional remuneration for providing firm capacity, with the ability to deliver 120 MWh per day (4 hours x 30MW). Moreover, energy dispatch is shifted from morning and afternoon periods to evening peak hours (6 p.m. to 10 p.m.), when demand and prices are typically higher. Based on the results of Brazil's 2023 Capacity Reserve Auction, the additional remuneration amounts to approximately R$814,000 per MW annually, reinforcing the economic viability of BESS integration in photovoltaic systems.

3.2. Economic Analysis

The economic evaluation was structured to analyze the financial performance of photovoltaic plants with and without battery energy storage integration. In the base case, the photovoltaic system operates without batteries, and all electricity generated is sold directly in the Brazilian spot market. Hourly prices are represented by the PLD, which served as the benchmark for revenue projections throughout a 20-year simulation period (2027–2046). Historical PLD data from the years 2021 and 2024, adjusted for inflation, were adopted to represent distinct hydrological conditions—2021 as a wet year and 2024 as a dry year. These two years capture the variability and volatility of the Brazilian market, reflecting how precipitation cycles influence spot pricing and the increasing impact of intermittent renewable generation, particularly solar photovoltaics. Moreover, the 2024 price curve captures the influence of the significant penetration of photovoltaic generation in the Brazilian Northeast submarket, making the simulations more realistic for the dynamic conditions of today's Brazilian electricity market.

In the alternative scenario, the photovoltaic plant is integrated with 30 MW/150 MWh BESS. In this case, revenues include not only energy sales to the spot market but also additional remuneration for providing firm capacity to the grid, equivalent to a guaranteed supply of 120 MWh per day. Moreover, the dispatch strategy shifts generation from low-value morning and afternoon hours to high-value evening peak hours (6 p.m.–10 p.m.), when demand and prices are historically higher. Based on the Capacity Reserve Auction, the additional remuneration for capacity provision was estimated.

Capital expenditures (CAPEX) for equipment and services were derived from quotations obtained directly from suppliers active in the Brazilian market. To account for unforeseen costs not captured in the initial design, a contingency margin of 15% was added to the total investment. The financial structure assumed full equity financing (100% equity), without leverage. Operational expenditures (OPEX) were modeled separately for each configuration: R$14/kWp per year for fixed-tilt photovoltaic plants, R$32/kWp per year for single-axis tracking systems, and R$20/kW per year for the BESS. In addition, a land lease cost of R$15,000 per hectare per year was included to reflect ongoing site-related expenses.

The fiscal treatment of energy sales was incorporated explicitly. Under Brazil's actual profit taxation regime, a tax burden of 34% was applied, covering corporate income tax (IRPJ) and social contribution on net income (CSLL). Alternatively, for projects under the presumed profit regime, a tax rate of 7% was adopted, consistent with official values reported by the Energy Research Office (EPE, 2021). For the calculation of Net Present Value (NPV), a weighted average cost of capital (WACC) of 9% was assumed, reflecting current financing conditions for renewable energy projects in Brazil. Together, these parameters provide a robust framework for assessing the financial viability of BESS integration in photovoltaic power plants under varying market and policy conditions.

3.3. Curtailment Data Analysis

To better understand the operational challenges in the Brazilian power system, this study undertook a comprehensive data collection. The analytical framework is grounded in official data sourced from both the Brazilian National System Operator (ONS) and the Chamber of Electric Energy Commercialization (CCEE). The primary objective was to qualitatively and quantitatively assess the full impact of generation curtailment, with a specific focus on the Northeast submarket where this phenomenon is most pronounced. This data-driven approach was essential to accurately understand the scale of the problem.

By leveraging historical and projected curtailment volumes from these official sources, the analysis aims to quantify the tangible benefits of integrating a BESS. The collected data allows not only for a precise measurement of the current system-level need for energy storage but also helps to establish a clear growth profile for this necessity in the near future. The resulting dataset was used to construct realistic curtailment scenarios within the simulation environment, enabling a direct quantification of the BESS's efficacy in mitigating energy losses. This methodology is critical for evaluating the economic and systemic value that BESS provides by capturing and re-dispatching high-value, previously unutilized energy, thereby strengthening the financial case for its deployment.

4. Results and Discussion

This chapter presents the comprehensive results derived from the techno-economic simulations of 4 representative utility-scale photovoltaic power plants in the Brazilian Northeast, as detailed in the preceding methodology. The findings are structured to provide a multi-stage analysis, beginning with the contextual market dynamics and progressing to a granular assessment of the plant's performance under various configurations. The initial section of this chapter establishes the operational baseline by characterizing the energy market profile of the Brazilian Northeast. The results will demonstrate the magnitude and frequency of curtailment events. These curtailment figures establish a foundational metric for assessing the performance of the BESS, quantifying the amount of economically significant energy that is otherwise lost. Subsequently, the results of the analysis of the photovoltaic plant's technical performance. The results will clearly illustrate how the storage system not only captures curtailed energy but also facilitates strategic energy arbitrage, shifting generation from low-price midday hours to high-price evening peak periods (6 p.m. to 10 p.m.), thereby fundamentally altering the plant's interaction with the grid. Finally the economical assessment is presented, these results quantify the financial performance, presenting annual revenues derived from spot market sales and, for the BESS-integrated scenarios, the substantial additional income from participation in the capacity reserve market. Indicators such as Internal Rate of Return (IRR) and Net Present Value (NPV), demonstrated how the BESS transformed the project from a simple energy commodity producer into a provider of valuable grid services.

Each region of Brazil has different hourly energy prices, which causes economic results to vary across the country. The region focused on in this study is the Northeast, so Figure 1 presents the annual average values for the base years: 2021 and 2024. The climate in Brazil exhibits a typical climate pattern, with alternating hydrological variations. Therefore, these years were selected precisely to represent the contrast between a year of high precipitation and a year of low precipitation.

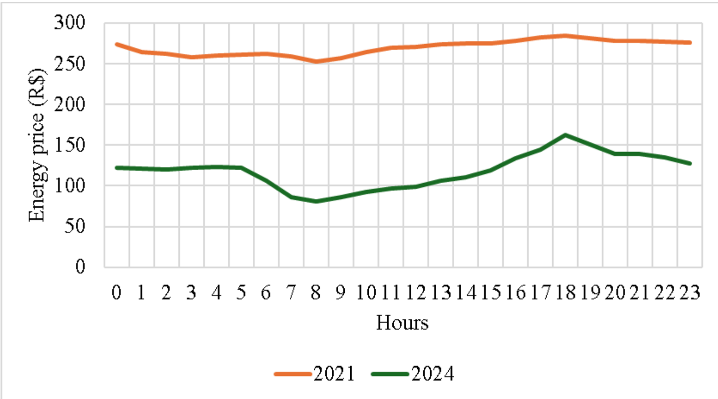

Figure 1: Annual average hourly energy price (BRL) in the Northeast region of Brazil in 2021 and 2024.

Analyzing the magnitude and frequency of hourly curtailment events at the site under study allows to establish a metric for evaluating system performance, quantifying the energy that would otherwise be wasted. There are different types of operational constraints for photovoltaic power plants: EUR (External Unavailability Reason), RCR (Reliability Compliance Reason), and ER (Energy Reason). Figure 2 shows the annual number of these hourly curtailment events in the Northeast.

Furthermore, to assess the system's ability to supply the desired power to the grid, the number of hours with load loss is analyzed. Figure 3 shows the load loss events in the system located in the Northeast region during the simulated year of 2027.

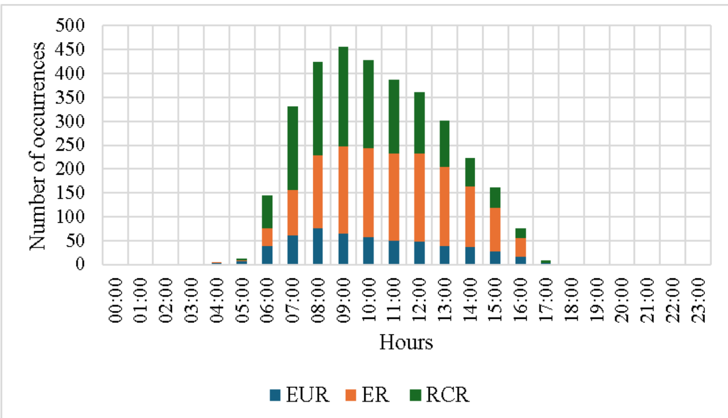

Figure 2: Annual number of curtailment occurrences per hour in the Northeast region

Figure 3: Frequency Distribution of Loss of Load Probability in 2027

To analyze the plant's performance, different tests were conducted with different configurations and operating modes. The estimated energy generated in the Northeast region for each season in 2027, for example, can be seen in Figure 4.

The operation of the hybrid PV-BESS plant, in turn, was programmed to prioritize battery charging, storing 120 MWh per day. This stored energy is delivered to the grid every four hours, starting at 6:00 PM, in installments of 30 MWh per hour. Excess energy, after the battery is fully charged, is also injected into the grid. Figure 5, therefore, shows the estimated energy injected into the grid in 2027 for this defined plant operating configuration.

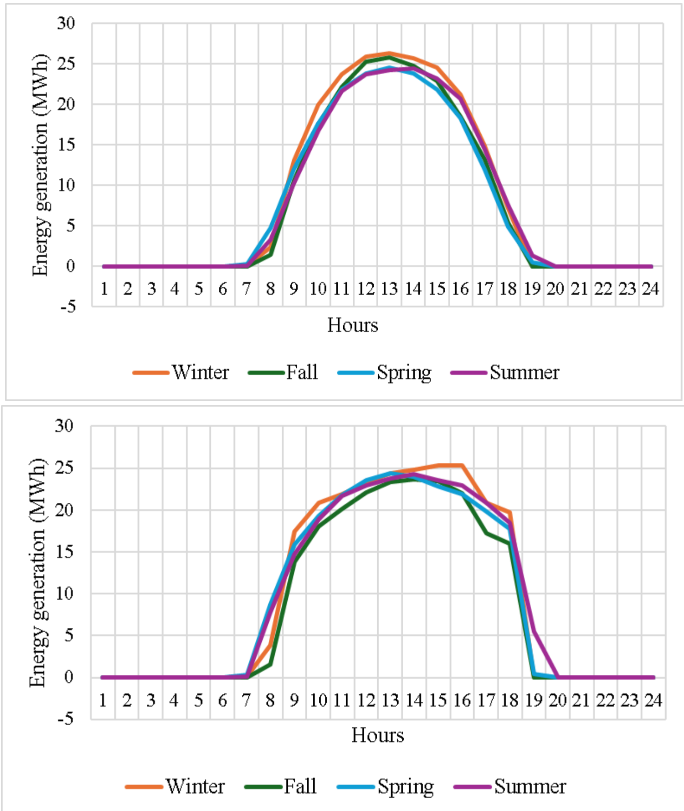

Figure 4: Monthly hourly average power generation PV during the seasons in 2027: (a) Fixed til, and (b) Tracker

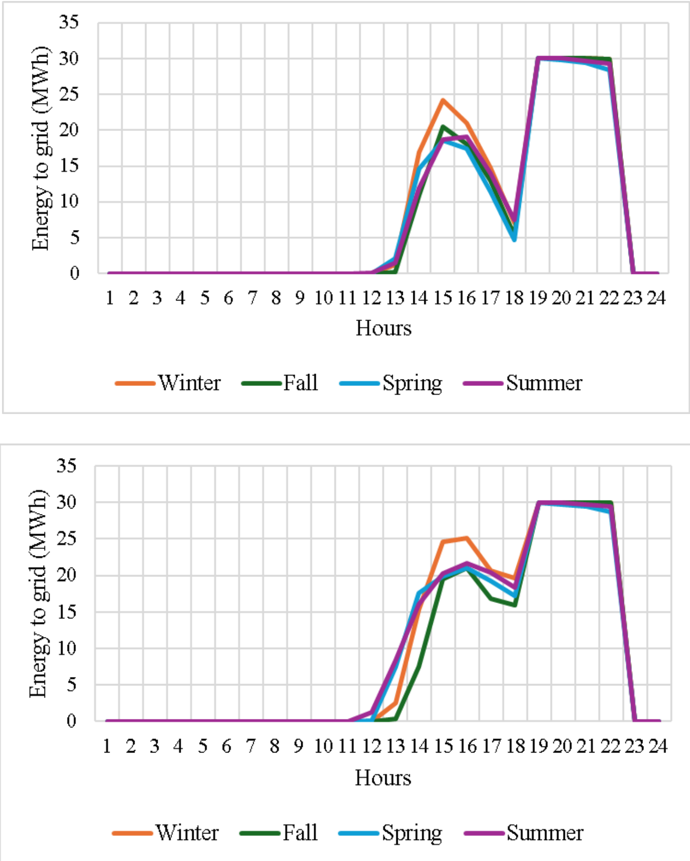

Figure 5: Annual hourly energy to grid PV during the seasons in 2027: (a) Fixed tilt, and (b) Tracker

The load curve represents the variation in energy demand over time and is essential for assessing the balance between generation, storage, and consumption. In the context of a PV-BESS plant, it allows for the identification of periods of surplus, which can cause curtailment, and deficit, which indicate load losses. Thus, the load curve guides battery operating strategies, contributing to better utilization of the generated energy and greater system efficiency. Figure 6 presents the monthly average hourly load profile during the seasons of the base year, 2024.

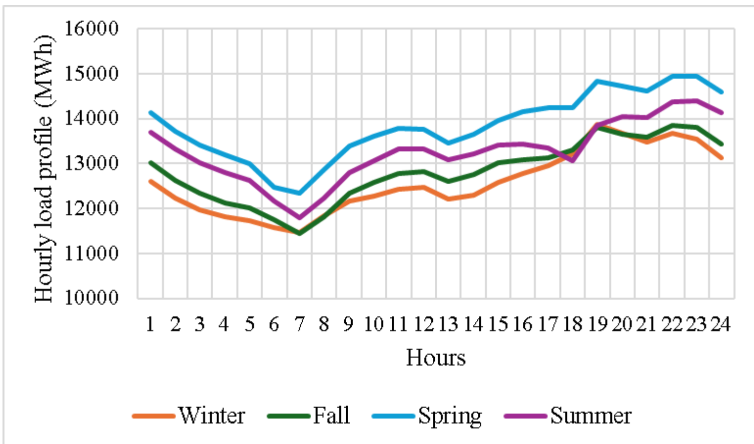

Figure 6: Monthly analysis of the average hourly load profile

Figures 7 and 8 present hourly analysis of photovoltaic generation, BESS dispatch, and curtailment events, highlighting the operation of the photovoltaic-BESS hybrid plant described above. The graphs show that photovoltaic generation peaks around noon (approximately 10:00 AM to 3:00 PM), while grid dispatch follows the plant's operation.

It can be observed that during periods of excess photovoltaic generation, a high number of curtailment events occur. To mitigate these losses, the integrated BESS system plays a crucial role by capturing energy that would otherwise be wasted and storing it in the battery. This energy is then strategically dispatched during four hours when the number of outages is lowest, the hourly energy price is highest, and photovoltaic generation declines. In this way, the plant can supply energy during peak demand periods, achieving energy arbitrage and increasing the economic value of the energy generated.

Table 1 summarizes the key economic assumptions adopted in the financial assessment and the resulting IRR and NPV outcomes for each system configuration analyzed. Financial revealed that systems integrating BESS significantly increased total investment costs while reducing the internal rate of return (IRR). The inclusion of BESS improves energy dispatchability and enhances revenue stability but increases capital and operational costs, reducing short-term profitability. However, the higher NPV indicates greater long-term value and resilience against market price volatility, particularly in submarkets with significant curtailment risk. Therefore, storage integration can be justified as a strategic investment for financial and operational optimization in the Brazilian energy market.

Table 1: Financial parameters and Results.

Mounting System	CAPEX/MWp	OPEX (year 1)/MWp	VPL	TIR
Tracker	R$ 2,765,608.22	R$ 74,803.29	R$ 45,562,556.35	14.25%
Fixed-tilt	R$ 2,406,452.88	R$ 41,922.87	R$ 61,056,836.24	15.87%
Tracker + BESS	R$ 13,487,568.64	R$ 197,348.12	R$ 99,453,813.80	11.29%
Fixed-tilt + BESS	R$ 12,569,792.26	R$ 158,075.32	R$ 91,717,278.78	11.15%

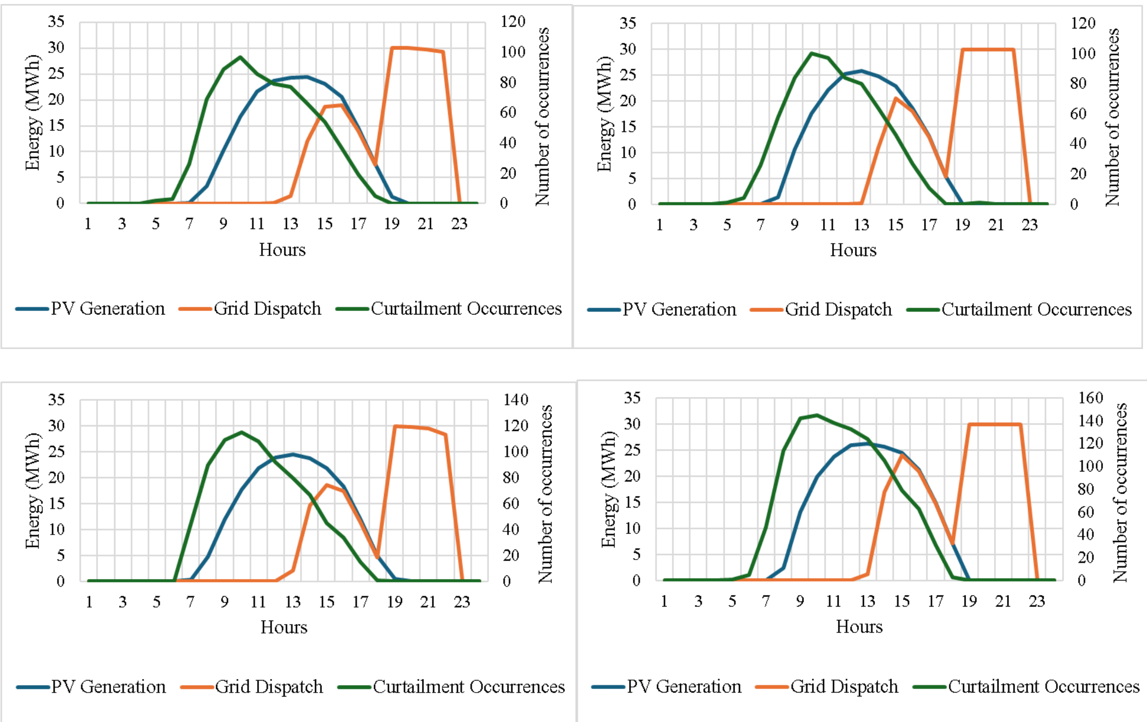

Figure 7: Hourly analysis of PV generation, BESS dispatch, and curtailment events under fixed-tilt conditions during the seasons: (a) Summer, (b) Fall, (c) Spring, and (d) Winter

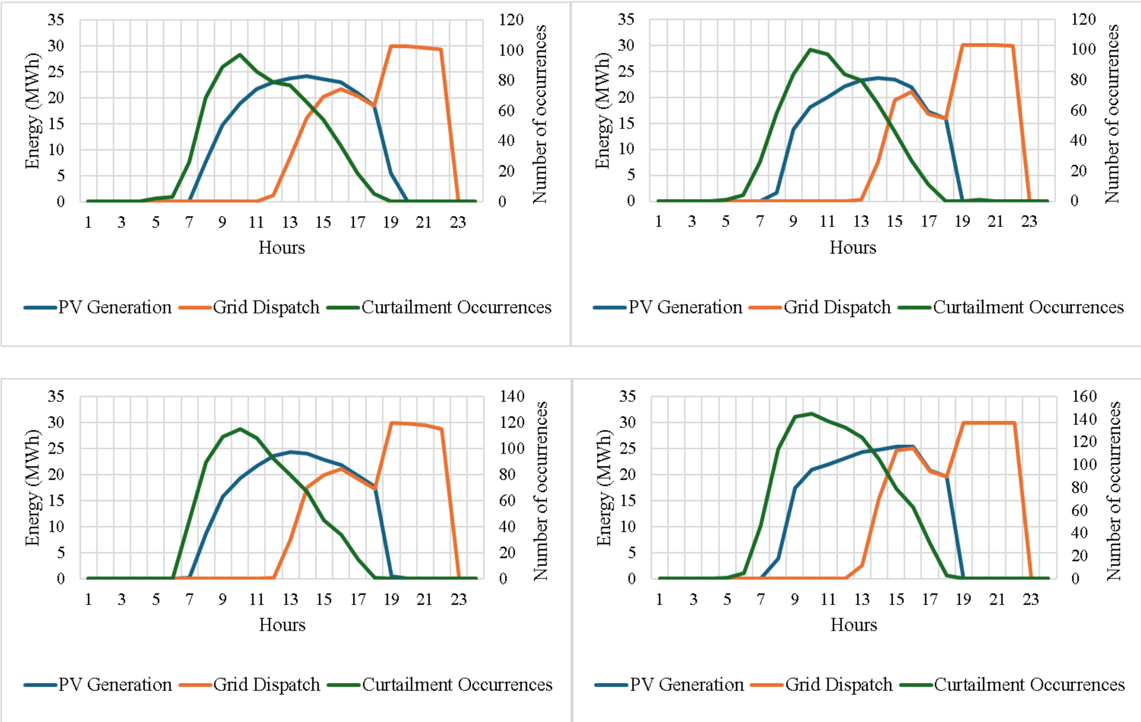

Figure 8: Hourly analysis of PV generation, BESS dispatch, and curtailment events under tracker conditions during the seasons: (a) Summer, (b) Fall, (c) Spring, and (d) Winter

5. Conclusion

This study evaluated the integration of BESS into PV plants in Northeast Brazil, focusing on three key aspects: identifying periods of greatest dispatch restriction, modeling and optimizing dispatch with BESS, and determining the appropriate battery capacity relative to plant rating.

The first objective was addressed through the analysis of monthly constrained-off reports published by the Brazilian National System Operator (NSO). Results revealed that curtailment occurs most frequently during the morning hours in the Northeast submarket, when solar production is high but demand growth remains limited. It can be observed that approximately 50% of all curtailment events occur between 7:30 and 11:00 a.m.; during this period, the simulated system integrated with BESS does not dispatch energy to the grid. Between 9 a.m. and 3 p.m., the average PV energy production accounts for about 80% of the daily output, while curtailment occurrences during this same period represented 68% of all events at autumn 2024. This mismatch underscores the importance of storage solutions capable of reallocating surplus energy to more valuable periods.

The second objective involved modeling and optimizing dispatch under scenarios with and without storage. The simulations demonstrated that BESS integration allows PV plants to capture morning overgeneration and shift delivery to the evening peak, between 6 p.m. and 10 p.m., when demand and market prices are higher and when most PV plants are already reducing output. With the growing integration of variable energy resources into the grid, daily hourly price variability is expected to increase over time, as observed in the 2024 Northeast submarket, where the price at 9 a.m. was 50% lower than at 7 p.m., resulting in twice the revenue for the project developer. This time-shifting strategy reduces curtailed energy, increases system efficiency, and improves alignment between PV generation and market signals.

The third objective focused on determining an adequate battery size. The results showed that a configuration of 150 MWh, with a daily obligation of 120 MWh and four hours of 30 MW discharge capacity, provides a balanced solution. This capacity ensures the system can absorb morning curtailment while reliably meeting evening demand, enhancing both technical performance and economic viability. During the 2027 simulation period (365 days), the battery did not achieve the daily target of 30 MW / 120 MWh on merely 8 days, and on 6 of those occasions, the energy shortfall was less than 1 hour (<30 MWh deficit).When operated in daily cycles with a depth of discharge (DOD) limited to 80%, the battery ensures a lifetime compatible with project requirements, maintaining performance and delivering 120 MWh per day for over 6,000 cycles, according to most lithium battery manufacturers. Considering that battery operation is typically restricted to business days, the expected lifetime exceeds 20 years, which is consistent with the PPAs currently offered to photovoltaic plants in Brazil.

In conclusion, the integration of BESS into PV plants in Brazil is technically effective and financially viable. The NPV analysis justifies storage integration as a strategic investment for financial/operational optimization, especially in scenarios with curtailment risk. By mitigating curtailment and strategically reallocating energy to periods of higher value, storage enhances plant profitability, supports grid adequacy, and creates new opportunities under mechanisms such as the capacity reserve auctions.

6. Acknowledgments

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