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RESEARCH ARTICLE

Techno-Economic Assessment of Co-Located Battery Energy Storage Systems in Hybrid Wind-PV Power Plants: A Case Study in Brazilian Regulatory Landscape

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ABSTRACT The accelerated expansion of variable renewable energy in Brazil has intensified operational challenges related to grid congestion, generation curtailment, and the need for greater system flexibility. In this context, co-located Battery Energy Storage Systems (BESS) may support hybrid wind–photovoltaic power plants by shifting surplus generation, mitigating curtailment impacts, and improving the economic use of renewable resources. However, the financial attractiveness of BESS remains uncertain due to high capital costs, exposure to short-term market prices, limited remuneration for flexibility services, and the evolving Brazilian regulatory framework. This paper develops a stochastic techno-economic assessment of a hybrid wind–PV power plant with co-located BESS under Brazilian electricity-sector conditions. The proposed methodology combines Monte Carlo simulation with a discounted cash-flow model over a 20-year investment horizon with monthly time steps, incorporating renewable generation uncertainty, photovoltaic degradation, renewable generation seasonality, curtailment scenarios, spot-market settlement, BESS operation, transmission-related charges, taxation, operating costs, and financing. The Modified Internal Rate of Return is adopted as the main profitability indicator, while Value-at-Risk at the 95% confidence level is used to assess downside financial risk. The results show that curtailment significantly reduces profitability, while BESS can partially recover economic value under specific cost and market conditions. The findings indicate that optimal BESS sizing is influenced by curtailment intensity, battery CAPEX, price assumptions, future revenue-stacking opportunities, and the evolution of the regulatory framework, which may significantly affect the economic value and allowable applications of storage assets.

INDEX TERMS Hybrid wind-PV power plants, curtailment, battery energy storage systems, stochastic discounted cash flow, modified internal rate of return.

I. INTRODUCTION

Brazil has a highly renewable electricity matrix, however, the addition of more than 62 GW of solar photovoltaic capacity between 2020 and 2025 has intensified grid constraints. This rapid expansion has created substantial generation surpluses during peak solar hours, leading to significant renewable energy curtailment. In August 2025 alone, average curtailment rates for wind and solar generation reached 26%, while total curtailed renewable energy over the year was estimated at approximately 37 TWh [1]. The severity of this issue was highlighted during a low net-load event on August 10, 2025, when grid operators were forced to curtail approximately 98% of scheduled utility-scale wind and solar generation to maintain system stability. To mitigate these massive curtailments and provide firm capacity to the grid, co-locating

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Battery Energy Storage Systems (BESS) with hybrid wind-photovoltaic (PV) power plants has emerged as a compelling technical solution [1].

A primary advantage of these wind-PV power plants is the strong natural complementarity between wind and solar resources, which is particularly pronounced in Brazil's Northeast region [2]. However, evaluating the economic viability of combining these resources with battery storage requires advanced analytical methodologies. Traditional metrics such as the Levelized Cost of Energy (LCOE), although incorporating the time value of money through discounting, are often insufficient for assessing hybrid renewable plants with co-located storage because they do not adequately capture the temporal value of electricity, market-price spreads, flexibility-related revenues, curtailment mitigation, or the distribution of investment risk under uncertainty.

Instead, advanced models utilizing stochastic discounted cash flow analysis are recommended to accurately incorporate market dynamics, capital expenditures, and operational costs. Furthermore, from a techno-economic design perspective, solar PV technology is penalized by a greater need for storage capacity to shift its daily generation profile [3].

In terms of economic analysis for a Hybrid Power Plant, curtailments severely restrict grid injection, which directly undermines the project's profitability and investment viability. When power output is forcibly reduced, the plant loses expected revenue. Integrating BESS provides a direct solution by acting as a buffer that stores surplus renewable energy during curtailment periods [4], [5]. Rather than wasting this overproduction, the BESS charges when grid congestion is high or electricity prices are low. It then discharges the stored energy back to the grid when the curtailment period ends or when demand and market prices are higher. This strategy, known as energy arbitrage, creates an additional revenue stream [5], [6]. Ultimately, the BESS mitigates the economic impact of system-level curtailments, allowing for much higher utilization of peak renewable production and protecting the power plant's financial returns [7].

Recent studies have investigated the deployment of BESS in renewable energy plants from a variety of perspectives. Some studies focus on the use of storage to convert curtailed renewable energy into economic value, showing that the profitability of BESS depends strongly on technology cost, degradation, and the amount of recoverable curtailed energy [4], [5]. Other works assess the techno-economic performance of storage in wind or hybrid renewable plants, highlighting that the economic value of BESS is highly sensitive to battery CAPEX, operational strategy, and the market conditions under which charging and discharging occur [6], [8]. In parallel, studies on hybridization of renewable plants indicate that co-locating wind, solar, and storage can improve the use of existing grid infrastructure and expand the economically attractive range of hybrid configurations, particularly when curtailment becomes relevant [7]. However, most of these studies rely on deterministic assumptions or focus on operational optimization, without explicitly quantifying the joint effect of renewable uncertainty, curtailment scenarios, and regulatory constraints on risk-adjusted returns.

Despite these advances, there is still limited evidence on how curtailment intensity, stochastic renewable generation, storage size, battery cost, market settlement assumptions, and network-use charges jointly affect the risk-adjusted profitability of co-located BESS in hybrid wind–PV plants under Brazilian electricity-sector conditions. This gap is particularly relevant because Brazil combines three features that materially affect storage economics: (i) rapid renewable expansion with growing curtailment exposure [1], (ii) strong wind–solar complementarity in key renewable regions [2], and (iii) an evolving regulatory framework for storage and hybrid-plant operation, in which the monetization of flexibility remains only partially defined [3].

Moreover, most existing studies rely on deterministic approaches that do not capture the downside risk associated with renewable variability and market exposure, highlighting the need for a framework that combines stochastic generation modeling with risk-adjusted financial metrics. As a result, the investment case for BESS in Brazil cannot be inferred directly from studies conducted in other jurisdictions or from deterministic project-evaluation models that do not explicitly capture uncertainty in renewable generation, curtailment, and market settlements.

This paper addresses that gap by developing a stochastic techno-economic assessment framework for a hybrid wind–PV power plant with co-located BESS under Brazilian regulatory and market assumptions. The framework is particularly suited to the Brazilian context, where recent regulatory changes—including ANEEL Normative Resolutions 1,161/2026 and 1,162/2026 and the upcoming Capacity Reserve Auction for storage—are reshaping the treatment of storage assets in network-use charges and market participation.

The proposed approach combines Monte Carlo simulation with discounted cash-flow modeling over a 20-year horizon, explicitly representing uncertainty in renewable generation, photovoltaic degradation, monthly seasonality, curtailment scenarios, BESS operation, transmission-related charges, taxation, and financing assumptions. The financial attractiveness of each case is evaluated through the Modified Internal Rate of Return (MIRR), while downside risk is measured using Value-at-Risk at the 95% confidence level ($VaR_{95\%}$). The framework is then applied to assess how curtailment and BESS sizing interact to change project profitability and risk in a context where storage may simultaneously mitigate curtailed energy, enable time-shifting, and support a more efficient use of shared grid infrastructure [4], [5], [6], [7], [8].

The main contributions of this work are fourfold. First, the paper proposes a stochastic valuation framework for hybrid wind–PV plants with co-located BESS that is tailored to investment analysis rather than purely operational dispatch. Second, it quantifies the risk-adjusted impact of curtailment on project profitability, using MIRR and $VaR_{95\%}$ as complementary performance and risk metrics in a Brazilian hybrid

renewable project. Third, it evaluates how BESS size and battery CAPEX alter the economic value of storage under different curtailment levels, highlighting the existence of scenario-dependent optimal storage capacities rather than a monotonic "more storage is better" relationship. Fourth, it discusses the implications of these results for the emerging Brazilian regulatory landscape, showing under which conditions co-located storage can improve the bankability of hybrid renewable projects.

The remainder of this paper is organized as follows. Section II briefly reviews hybrid renewable plants and the economic role of co-located BESS. Section III presents the techno-economic rationale and the financial metrics adopted. Section IV describes the stochastic discounted cash-flow methodology. Section V presents case studies and sensitivity analyses. Section VI discusses the main findings and their regulatory implications. Section VII concludes the paper.

II. HYBRID POWER PLANTS

Hybrid power plants that integrate renewable energy sources, such as solar photovoltaic and wind energy with BESS have emerged as a highly effective solution to overcome the inherent intermittency of renewable generation [9], [10]. By co-locating these different technologies at a single point of grid interconnection, developers can share essential infrastructure—such as inverters, transformers, and cabling—which optimizes land use and significantly reduces overall capital costs [7], [11].

The strong natural complementarity between wind and solar resources helps balance out daily and seasonal energy fluctuations, creating a much more consistent energy production profile [12]. When a BESS is added to this combination, it acts as a vital buffer that can absorb surplus electricity and release it exactly when it is needed. This integration effectively transforms unpredictable renewable energy into a controllable, firm, and stable power supply that behaves similarly to conventional fossil-fueled power plants, thereby enhancing overall economic performance and bankability [13], [14].

In the Brazilian context, the complementarity between wind and solar resources is especially relevant in the Northeast region, where wind generation often peaks during evening and nighttime hours while photovoltaic generation is concentrated around midday [2], [12]. This temporal diversification can reduce the variability of aggregate renewable output and improve the utilization factor of the shared interconnection point. However, complementarity alone does not eliminate the economic consequences of transmission constraints and curtailment. When generation exceeds the effective export capability of the connection point or when system-level restrictions limit renewable dispatch, part of the available energy may still be spilled, directly reducing project revenues.

From an infrastructure perspective, hybridization with storage may also improve the economics of renewable projects because multiple technologies can share transformers, substation assets, internal electrical systems, and the point of common couplings [7], [11]. This feature is particularly relevant in projects facing connection bottlenecks, since the possibility of storing part of the otherwise curtailed generation may increase the economic productivity of the existing interconnection capacity. For this reason, the value of a co-located BESS should not be interpreted only as the value of energy arbitrage, but rather as the combined value of curtailed-energy recovery and improved use of constrained grid infrastructure.

In some jurisdictions BESS can enable investors to monetize curtailed renewable energy through time shifting and to access additional revenues from ancillary services [15]. BESS sub-second power response makes it particularly valuable for frequency regulation and short-term grid balancing, which can be more profitable than conventional energy sales [16]. Combined with capacity payments, firm PPAs, and energy arbitrage, these revenue streams support value stacking and improve the profitability and bankability of hybrid power plants.

Nevertheless, the economic value of BESS in hybrid plants is not intrinsic and depends strongly on the interaction among technical, market, and regulatory conditions. Previous studies have shown that the profitability of storage is highly sensitive to battery capital cost, operational strategy, market-price spreads, degradation, and the amount of recoverable curtailed energy [4], [5], [6], [7], [8]. In addition, the ability of a hybrid plant to monetize the flexibility provided by BESS depends on how electricity market settlements, network-use charges, and storage regulation are structured in the jurisdiction under analysis [3].

Therefore, although hybrid wind–PV–BESS plants provide a promising technical solution for enhancing renewable energy integration, their investment attractiveness can only be adequately assessed through a techno-economic framework that explicitly captures the interdependencies among renewable generation uncertainty, curtailment exposure, and storage operation. Accordingly, this study evaluates a hybrid wind–PV power plant with a co-located BESS not merely as a technical configuration, but as an investment asset whose economic value is jointly determined by renewable energy production, curtailment scenarios, battery sizing, market settlement mechanisms, and the evolving Brazilian regulatory framework. This investment-oriented perspective provides the rationale for the techno-economic methodology presented in the following section.

III. TECHNO-ECONOMIC ANALYSIS

The economic assessment of hybrid renewable plants with co-located BESS requires a framework that integrates technical system behavior with long-term project finance. In this type of asset, financial performance is not determined solely by installed capacity or average annual generation. Instead, project value depends on the interaction among renewable resource uncertainty, curtailment exposure, battery operation, contractual energy positions, market settlement conditions,

capital expenditure, operating costs, taxation, and financing structure. For this reason, a purely technical analysis or a deterministic cash-flow evaluation is not sufficient to assess the investment attractiveness of storage-enabled hybrid plants under real market conditions.

In the specific case of hybrid wind–PV plants with BESS, the economic role of storage goes beyond simply increasing the amount of energy delivered. Storage may recover part of the energy that would otherwise be curtailed, shift renewable production to periods of higher economic value, and improve the management of deviations between simulated generation and contracted energy. At the same time, BESS increases capital expenditure and introduces an additional layer of uncertainty related to storage cost, utilization, and monetization. As a result, the economic value of BESS must be evaluated through a framework capable of capturing both the upside created by flexibility and the downside associated with investment risk and uncertain market conditions.

In this study, the techno-economic assessment is formulated as a stochastic discounted cash-flow model with monthly time steps over a 20-year investment horizon. The model combines simulated renewable generation, curtailment scenarios, BESS contribution, contractual settlements, transmission-related charges, taxes, operating costs, and financing assumptions to estimate the distribution of project returns rather than a single deterministic outcome. This probabilistic perspective is particularly relevant in the Brazilian power sector, where renewable generation variability, increasing curtailment, and evolving storage regulation can materially alter project cash flows and bankability.

To evaluate profitability, the Modified Internal Rate of Return (MIRR) is adopted as the main investment metric. MIRR is preferred to the traditional Internal Rate of Return (IRR) because it allows the analyst to separate the project financing rate from the reinvestment rate of intermediate positive cash flows, thereby avoiding the unrealistic assumption that all cash inflows can be reinvested at the project's own internal rate of return. This distinction is especially important in infrastructure projects with high upfront capital expenditure, long operational lifetimes, and uneven cash-flow profiles, such as hybrid renewable plants with co-located storage. In this context, MIRR provides a more economically consistent indicator of long-term project attractiveness than the conventional IRR.

In addition to expected profitability, the assessment must also account for financial downside risk. For this reason, the study uses $VaR_{95\%}$ to quantify adverse outcomes in the simulated return distribution. While MIRR provides a central measure of investment attractiveness, $VaR_{95\%}$ complements it by indicating how unfavorable project performance may become under low-generation, high-curtailment, or weak-market scenarios. The joint use of MIRR and $VaR_{95\%}$ therefore allows the analysis to capture both expected return and risk exposure, which is particularly relevant for capital-intensive assets subject to regulatory and market uncertainty.

Another important component of the techno-economic assessment is the Brazilian financing and regulatory environment. The economic value of BESS in Brazil depends not only on battery capital expenditure and renewable generation profiles, but also on the characteristics of the market-oriented Free Contracting Environment (ACL—Ambiente de Contratação Livre), including private long-term contracting arrangements, spot-market settlement, transmission-use charges, and the still-evolving remuneration mechanisms for energy storage and flexibility services. Within the ACL, private investments in merchant utility-scale solar and wind projects, self-production arrangements, and emerging technologies such as BESS and green hydrogen (H_2V) generally require higher risk premiums than investments in regulated assets.

Current corporate financial models reflect these ACL's dynamics through specific capital cost benchmarks. The Real Cost of Equity (Ke) is typically modeled between 10.5% and 12.5% p.a. to account for country risk, grid curtailment, and price volatility. Meanwhile, private debt raised via tax-exempt infrastructure bonds (''*Debêntures Incentivadas*'') settles around IPCA + 7.0% to 8.0% p.a., priced against the local NTN-B treasury curve plus an indexation spread. Ultimately, these factors yield a blended corporate market WACC between 8.5% and 10.0% real p.a., which serves as the standard hurdle rate for capital budgeting in the Brazil's private sector [17]. The regulatory WACC parameters adopted in the analysis were based on ANEEL (Brazilian Electricity Regulatory Agency) Despacho n° 1.174/2026, which updated the regulatory capital remuneration rates applicable from March 1, 2026 [18].

For the financial valuation, a representative hurdle rate of 9.67% p.a. is adopted within the 8.5%–10.0% real p.a. range considered representative of private-sector renewable-energy investments in Brazil. This annual rate is converted into an equivalent monthly rate and used as the reinvestment rate for positive intermediate cash flows in the MIRR calculation, reflecting the assumed opportunity cost for reinvesting intermediate positive cash flows. The MIRR financing rate is specified separately. The MIRR formulation explicitly distinguishes between the financing and reinvestment rates. The financing rate is set equal to the project debt cost of 7.49% p.a., whereas the reinvestment rate is assumed to be 9.67% p.a., consistent with the project hurdle rate adopted in the analysis.

Due to the capital-intensive nature of the power sector, a significant portion of third-party debt relies on these structures, with modern financing tied to the Long-Term Interest Rate (TLP). The TLP base curve is composed of a fixed inflation-adjusted real rate combined with the structural variation of the IPCA index, establishing a baseline long-term real rate that currently sits around IPCA +7.80% p.a. However, calculating the true all-in debt cost within a financial investment model requires analysts to incorporate additional layers beyond this baseline.

Consequently, the economic attractiveness of co-located BESS cannot be inferred solely from technical performance or from international benchmarks. It must be evaluated under assumptions that reflect the financial and regulatory conditions faced by project developers in the Brazilian electricity sector. Based on this rationale, the next section presents the stochastic methodology adopted to model renewable generation, curtailment, BESS contribution, cash flows, and risk-adjusted project returns for the hybrid wind–PV plant considered in this study

IV. METHODOLOGY

This section presents the stochastic techno-economic framework developed to assess the financial attractiveness of a hybrid wind–photovoltaic power plant with a co-located BESS under Brazilian electricity-sector conditions. The model is implemented into a stochastic discounted cash-flow model with monthly time steps over a 20-year investment horizon.

The uncertainty in renewable generation is represented through Monte Carlo simulation, allowing the analysis to capture the variability of wind and solar resources and its impact on project profitability. The final output of the model is a probabilistic distribution of MIRR, together with a downside-risk indicator based on $VaR_{95\%}$.

The proposed framework is explicitly investment-oriented rather than dispatch-oriented. Its purpose is not to reproduce the detailed chronological operation of the Brazilian power system or to optimize battery dispatch on an hourly basis. Instead, it is designed to evaluate how uncertainty in renewable generation, curtailment exposure, storage size, market settlement assumptions, and financing conditions jointly affect the long-term economic performance of the project. For this reason, renewable generation is represented stochastically at the annual level and then distributed across months using seasonal profiles, while the BESS is modeled through an equivalent energy-shifting capability consistent with the objective of long-term project valuation.

Accordingly, the methodology should be interpreted as a risk-adjusted project valuation model rather than as an operational dispatch model. The simplifications adopted in the representation of renewable generation, curtailment, and battery operation are deliberate and consistent with the scope of the paper, which is to identify how the joint interaction among curtailment intensity, battery size, market-price assumptions, and financing conditions affects project bankability and profitability.

Throughout the methodology, stochastic renewable generation and the contracted physical guarantee are represented in average power units (MWavg). Whenever monthly energy values are required for revenue and cash-flow calculations, these average power quantities are converted into energy by multiplying them by the corresponding number of hours in the month.

A. MODELING SCOPE AND MAIN ASSUMPTIONS

The hybrid plant is defined as an installed capacity of 100 MW, equally divided between wind and photovoltaic sources. Annual wind and solar generation are modeled as normally distributed random variables, based on expected generation levels and standard deviations. For each Monte Carlo scenario, annual values are randomly sampled for the entire project lifetime. The photovoltaic generation is adjusted by an annual degradation factor, representing the gradual reduction in panel performance over time. These annual generation values are then converted into monthly generation profiles using predefined seasonal curves for wind and solar resources. This procedure allows the model to reflect both interannual uncertainty and intra-annual seasonality in renewable energy production.

The total monthly generation of the hybrid plant is compared with the contracted physical guarantee, defined as the sum of the wind P90 generation and the solar P50 generation. The revenue model assumes that the contracted energy is remunerated through a Power Purchase Agreement (PPA), while deviations from the contracted amount are settled according to market price assumptions. When generation exceeds the contracted level, surplus energy may be sold at market prices, with part of the surplus potentially benefiting from the BESS through a premium selling price. When generation is below the contracted level, the model accounts for the financial effect of energy deficits, including the possibility of purchasing energy at a reduced price due to the operational contribution of the BESS.

The methodology also incorporates curtailment, which is treated as an annual reduction factor applied to the simulated monthly generation. In the curtailment scenario, part of the energy that would otherwise be unavailable for direct sale is assumed to be partially recoverable through the BESS, limited by its energy capacity and operational assumptions. The BESS is modeled with a rated power of 30 MW and an energy duration of four hours. A round-trip efficiency of 90% is assumed at the medium-voltage BESS terminals, representing the efficiency of the complete storage system over its useful life. To preserve battery lifetime, the model assumes the equivalent of one full daily cycle, converted into average energy in MWavg. This storage contribution is used to improve revenues by shifting curtailed or surplus energy to higher-value market opportunities.

Battery degradation and mid-life replacement are not explicitly modeled in the present framework. The assumed 90% round-trip efficiency should therefore be interpreted as a lifetime-average performance parameter rather than as a constant year-by-year representation of electrochemical performance. This simplification was deliberately adopted to preserve the investment-oriented and parsimonious nature of the stochastic valuation framework and to avoid introducing an additional layer of uncertainty associated with chemistry-specific degradation trajectories, operating conditions and augmentation strategies. Accordingly, the BESS

CAPEX adopted in this study should not be interpreted as explicitly incorporating a guaranteed 20-year constant-capacity performance. Instead, the model evaluates the economic role of storage under a representative lifetime efficiency assumption, while degradation and replacement are left for future extensions of the framework.

The financial module estimates the project's cash flows on monthly steps. Initial capital expenditure includes wind, solar, and BESS investments, calculated from unit capital costs and installed capacities. Operating and maintenance costs (O&M) are estimated as monthly costs and calculated by multiplying technology-specific unit costs (BRL/kW/year) by installed capacity and dividing by 12 to obtain monthly values.

Additional deductions include sectorial charges, transmission-related costs based on the contracted network usage, taxes on gross revenue, and, when applicable, debt service payments. The model uses a monthly discount rate derived from the annual cost of equity to discount future cash flows.

In this study, the investment structure considered includes project financing. Under this approach, a predefined percentage of the initial capital expenditure is financed through debt, while the remaining portion is assumed to be covered by equity. The debt service is modeled using the Constant Amortization System (CAS), in which the principal repayment remains constant over the amortization period and the interest payments decrease progressively as the outstanding debt balance is reduced.

Finally, the model produces a distribution of MIRR values across all Monte Carlo scenarios. This distribution provides a probabilistic assessment of the project's financial performance rather than a single deterministic result. By analyzing the resulting MIR histogram, it is possible to evaluate not only the expected economic attractiveness of the hybrid wind-solar-BESS project, but also the downside risk associated with renewable resource variability, curtailment, market price exposure, storage performance, operating costs, and financing conditions.

The proposed methodology evaluates the economic viability of a hybrid renewable power plant composed of wind and photovoltaic generation with a co-located BESS. The computational model was implemented in Python. The final output is a probabilistic distribution of the MIRR (% p.a.) obtained through Monte Carlo simulation over a 20-year investment horizon, with cash flows evaluated monthly.

B. STOCHASTIC RENEWABLE GENERATION

For each Monte Carlo scenario, the annual generation of wind and photovoltaic components is represented by normally distributed random variables. In the model, the expected wind generation is defined by the wind P50 estimate, while the expected photovoltaic generation is defined by the solar P50 estimate. The standard deviations represent the uncertainty associated with the annual energy production of each generation plant. Therefore, for each Monte Carlo scenario s and year y, the annual wind and photovoltaic generation values are sampled from normal probability distributions, as follows:

$$G_{s,y}^{WND} \sim N\left(P50^{WND}, \left(\sigma^{WND}\right)^2\right) \tag{1}$$

$$G_{s,y}^{PV} \sim N\left(P50^{PV}, \left(\sigma^{PV}\right)^2\right) \tag{2}$$

where, $G_{s,y}^{WND}$ and $G_{s,y}^{PV}$ denote the annual average wind and photovoltaic generation values, respectively, for scenario s and year y, expressed in average megawatts (MWavg). The parameters $P50^{WND}$ and $P50^{PV}$ represent the expected annual generation levels of the wind and photovoltaic plants, while σ^{WND} and σ^{PV} denote the corresponding standard deviations associated with annual resource uncertainty.

The use of normal distributions at the annual level is intended to provide a parsimonious representation of renewable uncertainty within a long-term project valuation framework. In other words, the model seeks to capture the variability of annual energy production relevant to investment performance rather than to reconstruct the full chronology of hourly wind and solar output.

Although this representation does not explicitly model hourly correlations between renewable generation and market prices, it is adequate for the objective of comparing alternative BESS sizes and curtailment scenarios in a 20-year discounted cash-flow analysis with monthly steps.

The photovoltaic generation is then adjusted to represent the gradual degradation of the solar panels over time. If d is the annual degradation rate, the degraded photovoltaic generation is calculated by:

$$G_{s,y}^{PV,deg} = G_{s,y}^{PV}\,(1-d)^{y-1} \tag{3}$$

The transition from annual stochastic generation to monthly stochastic generation is performed using monthly seasonality factors (α_m^{WND} *and* α_m^{PV}), one value for each month m. The monthly generation used in the Monte Carlo simulation is then constructed by multiplying the annual stochastic generations for year y, ($G_{s,y}^{WND}$ and $G_{s,y}^{PV,deg}$) by the corresponding monthly seasonality factor.

For each scenario s, year y, and month m, the monthly generation of each technology and the total hybrid generation are calculated as:

$$G_{s,m}^{TOT} = (G_{s,y}^{PV,deg}\alpha_m^{PV}) + (G_{s,y}^{WND}\alpha_m^{WND}) \tag{4}$$

where, $G_{s,m}^{TOT}$ is the total hybrid generation, for scenario s and month m (MWavg).

Equation (4) shows how the annual random variables are converted into a Monte Carlo scenario with 12 monthly values. This procedure preserves the interannual uncertainty of renewable resources while also representing the intra-annual seasonality of wind and solar production. In the final implementation, the monthly seasonality factors should remain normalized so that the annual stochastic generation is preserved after monthly disaggregation.

C. CONTRACTED PHYSICAL GUARANTEE

The contracted physical guarantee of the hybrid plant is defined as the sum of the certified wind P90 generation and the photovoltaic P50 generation, as assumed in the Brazilian regulatory and contractual framework adopted for the case study. This value is used as the contracted monthly energy reference against which the simulated total generation is compared:

$$GF = P90^{WND} + P50^{PV} \tag{5}$$

where, GF is contracted monthly energy (MWavg), $P90^{WND}$ is the 90th percentile of the normal probability distribution of the wind annual certified energy and $P50^{PV}$ is the 50th percentile of the normal probability distribution of photovoltaic annual certified energy.

In the model, GF acts as the contractual benchmark for monthly revenue settlement and therefore plays a central role in determining surplus and deficit exposure under the PPA-plus-spot settlement structure

D. BESS CONTRIBUTION

The BESS contribution is represented by an equivalent energy-shifting capability, expressed in MWavg. Since the operational assumption, in this work, is one full daily cycle, the BESS energy contribution on a month basis is calculated as:

$$E^{BESS} = \frac{P^{BESS} h^{BESS} (\eta^{RTE}/100)}{24} \tag{6}$$

where, E^{BESS} is the average-power equivalent that BESS can manage in a daily basis (MWavg), P^{BESS} is the BESS rated power (MW), h^{BESS} is storage duration (hours), η^{RTE} is the round-trip efficiency (%) and 24 are the total number of hours in a day. So, the total energy a BESS can delivery in a monthly basis is $720 * E^{BESS}$(MWh).

It is important to emphasize that Eq. (6) does not represent an hourly state-of-charge dispatch model. Rather, it provides an aggregate estimate of the amount of energy that the BESS can shift, recover, or reallocate within the month, subject to its power rating, duration, round-trip efficiency, and daily cycling assumption. This representation is intentional and consistent with the investment-oriented scope of the paper. The objective is not to maximize arbitrage revenues through chronological dispatch, but to estimate the long-term economic value of storage under alternative curtailment and market conditions.

E. REVENUE MODEL WITHOUT CURTAILMENT

The revenue model combines: 1) a fixed PPA revenue associated with the contracted physical guarantee; 2) spot market settlements for deviations between simulated generation and the contracted amount; and 3) the BESS contribution.

The monthly PPA revenue is calculated by multiplying the contracted energy reference (GF) by the PPA price and by the assumed number of hours in a month:

$$R^{PPA} = GF \cdot p^{PPA} \cdot 720 \tag{7}$$

where, R^{PPA} is the fixed monthly PPA revenue ($), p^{PPA} is PPA contracted price ($/MWh) and 720 is the total number of hours in a month.

When curtailment is not considered, the monthly generation deviation from the contracted reference is defined as:

$$\Delta E_{s,m} = G^{TOT}_{s,m} - GF \tag{8}$$

where, $\Delta E_{s,m}$ is the monthly generation deviation from the contracted reference (MWavg), $G^{TOT}_{s,m}$ comes from Eq. (4) and GF comes from Eq. (5).

If $G^{TOT}_{s,m}$ is above the GF, this surplus of energy is sold at spot market and if total generation is below, the deficit is bought at spot market. $\Delta E_{s,m}$ is the spot market exposure in a monthly basis.

To introduce the use of BESS in an investment analysis, how is the objective of this work, it's necessary to consider three situations: a) when $\Delta E_{s,m} > 0$; b) when $\Delta E_{s,m} = 0$; and c) when $\Delta E_{s,m} < 0$.

If $\Delta E_{s,m} > 0$, the revenue brought by BESS in this situation happens when wind and PV farms produce a surplus of clean energy during some hours, BESS can capture a unique advantage by arbitrage with wind and photovoltaic surplus energy. Instead of selling that excess generation into the spot market in hours when prices are depressed, due to the supply glut, the plant operator can divert that free surplus straight into co-located commercial batteries. By storing its own oversupply at zero cost and holding it until the evening peak—when demand spikes and spot prices are at their highest—the investors transform a low-value generation surplus into a high-priced sale energy, maximizing the financial returns of its positive spot market exposure.

So, in this situation, when $\Delta E_{s,m} > 0$, the total revenue of the plant becomes:

$$R^{TOT}_{s,m} = R^{PPA} + R^{SPOT}_{s,m} + R^{BESS}_{s,m} \tag{9}$$

where, $R^{TOT}_{s,m}$ is the total revenue of month m ($), R^{PPA} comes from Eq. (7), $R^{SPOT}_{s,m}$ is the total spot market revenue of month m ($) and $R^{BESS}_{s,m}$ is the total revenue of month m from BESS energy management operation ($).

For the calculation of $R^{BESS}_{s,m}$, the volume of energy that the BESS can discharge during periods of higher spot market prices must be considered.

$$R^{BESS}_{s,m} = min\left(\Delta E_{s,m}, E^{BESS}\right) p^{sell}_{m} \cdot 720 \tag{10}$$

where, $\Delta E_{s,m}$ comes from Eq. (8), E^{BESS} comes from Eq. (6), and p^{sell}_{m} is the premium price that resembles the spot prices at its highest values for month m ($/MWh).

For the calculation of revenue brought by selling the remainder of the energy excess at spot market price its calculation is:

$$R^{SPOT}_{s,m} = \left[\Delta E_{s,m} - min\left(\Delta E_{s,m}, E^{BESS}\right)\right] p^{spot}_{m} \cdot 720 \tag{11}$$

where, p^{spot}_{m} is the spot market price of month m ($/MWh). In this work $p^{sell}_{m} > p^{spot}_{m}$ for every month m.

If $\Delta E_{s,m} = 0$, the revenue generated by the BESS does not depend on the existence of surplus clean energy from wind and photovoltaic plants. In this case, the BESS can still capture value through energy arbitrage, even in the absence of curtailment or generation surplus. Therefore, the storage system may provide economic benefits both when excess renewable generation is available and when arbitrage opportunities arise under normal operating conditions.

If $\Delta E_{s,m} < 0$, this is exactly the opposite of what happens when wind and PV farms produce a surplus of clean energy during some hours. When wind and PV farms produce a deficit of clean energy during some hours, BESS still can capture an advantage by managing the energy deficit. Instead of buying the deficit generation into the real-time spot market in hours when prices are increased due to the excess demand of electricity, the BESS can shift the plant energy when spot prices are at their lowest—the investors transform a worst generation deficit into a low-priced buy energy, minimizing the financial deficits of its negative spot market exposure. So, in this work $p_m^{buy} < p_m^{spot}$, and p_m^{buy} is the premium price that resembles the spot prices at its lowest values for month m ($/MWh).

$$R_{s,m}^{SPOT} = \left[\Delta E_{s,m} - max\left(\Delta E_{s,m}, -E^{BESS}\right)\right] p_m^{spot} \cdot 720 \tag{12}$$

where, $\Delta E_{s,m}$, in this case, is always a negative number and so, $R_{s,m}^{SPOT}$ will be always a negative number too.

To $R_{s,m}^{BESS}$ calculation, at the same kind, we must consider the volume of energy that BESS can deliver, so.

$$R_{s,m}^{BESS} = max\left(\Delta E_{s,m}, -E^{BESS}\right) p_m^{buy}.720 \tag{13}$$

In the Equations (1) to (13), superscripts *WND*, *PV*, *BESS*, *SPOT*, *PPA*, *sell*, and *buy* denote wind, photovoltaic, battery storage, spot market price (p_m^{spot}), contracted price (p^{PPA}), premium selling price (p_m^{sell}), and reduced purchase price (p_m^{buy}), respectively. The scenario index is s, the year index is y and the month index is m.

F. REVENUE MODEL WITH CURTAILMENT

In the case of curtailment adopted, an annual curtailment factor is expanded into monthly values. The simulated generation is reduced by the curtailment factor, and part of the curtailed energy is assumed to be recoverable by the BESS through premium market opportunities. \

In this work we are only considering the BESS working with the amount of energy that was curtailed. Curtailment is treated as an exogenous scenario parameter rather than as the output of a physical dispatch model. Accordingly, the purpose is not to reproduce the operational logic of the system operator, but to quantify the economic effect of different curtailment levels on the project's revenue stream and to evaluate how much of that lost value may be mitigated by a co-located BESS.

For month m, the amount of energy that was curtailed is:

$$\Delta C_{s,m} = G_{s,m}^{TOT}(c_m/100) \tag{14}$$

where, $\Delta C_{s,m}$ is the curtailed energy (MWavg), $G_{s,m}^{TOT}$ comes from Eq. (4), and c_m is curtailment factor of month m (%).

So the remaining energy after curtailment is:

$$G_{s,m}^{curt} = G_{s,m}^{TOT} - \Delta C_{s,m} \tag{15}$$

where, $G_{s,m}^{curt}$ is net generation after curtailment (MWavg), for scenario s and month m (MWavg).

To calculate the total revenue considering curtailment and BESS operation, the proposed approach accounts for the portion of curtailed energy that can be recovered or economically utilized through the battery. This amount is limited by the technical energy capacity of the BESS, expressed in MWavg, as defined in Eq. (6). Therefore, the recoverable energy is determined as the minimum value between the curtailed energy and the available BESS energy capacity. The recovered energy is then valued using a premium selling price, which represents the potential benefit of shifting curtailed energy to periods with higher spot market prices.

Thus, the total revenue of the hybrid plant can be expressed as:

$$\begin{aligned} R_{s,m}^{TOT_curtail} &= R^{PPA} + \left[\left(G_{s,m}^{curt} - GF\right) p_m^{spot} \cdot 720\right] \\ &+ \left[min\left(\Delta C_{s,m}, E^{BESS}\right) p_m^{sell} \cdot 720\right] \end{aligned} \tag{16}$$

where, $R_{s,m}^{TOT_curtail}$ is the total revenue considering curtailment for a month m ($), R^{PPA} comes from Eq. (7), $G_{s,m}^{curt}$ comes from Eq. (15), GF comes from Eq. (5), $\Delta C_{s,m}$ comes from Eq. (14), E^{BESS} comes from Eq. (6) and both premium selling price (p_m^{sell}) and spot market price (p_m^{spot}) are explained above.

It is important to note that the revenue components in Eq. (16) are mutually consistent and do not imply double counting of curtailed energy. The post-curtailment generation term is based on G^{curt}, which already excludes the energy removed by curtailment. Therefore, the curtailed energy subsequently recovered through the BESS does not simultaneously generate spot-market revenue through the post-curtailment generation term. Instead, the BESS revenue component represents an additional revenue stream associated exclusively with the portion of curtailed energy that can be recovered, stored, and later sold under the assumed premium selling price. Accordingly, total revenue under curtailment is obtained by combining the PPA-related revenue, the net spot-market revenue from the remaining non-curtailed generation, and the incremental revenue generated by the BESS from recoverable curtailed energy.

This representation should be interpreted as a valuation layer built on top of the stochastic renewable production model. In other words, the BESS does not create additional energy; it changes the timing and commercial destination of part of the renewable energy that would otherwise be curtailed or sold under less attractive market conditions. The resulting cash-flow impact therefore depends on the combined effect of curtailment intensity, BESS size, and the assumed premium prices used to monetize shifted energy.

G. FINANCE CALCULATION

The CAPEX (Capital Expenditure) is the sum of wind, photovoltaic, and BESS investments. The wind and photovoltaic investments depend on the total installed capacity, while the BESS investment depends on its rated power and duration.

Monthly operating cash flows are obtained from total revenue considering curtailment ($R_{s,m}^{TOT_curtail}$) or not ($R_{s,m}^{TOT}$), by subtracting taxes, operation and maintenance costs, sectorial charges, and transmission-related cost (*TUC*).

The transmission-related cost (*TUC*) paid by users of the transmission grid for the use of high-voltage transmission assets, remunerates the transmission infrastructure that transports electricity from generators to load centers and distribution systems, and *MUST* is the *"Montante de Uso do Sistema de Transmissão"* meaning the contracted amount of transmission system use.

So, the transmission-related cost (*TUC*) is:

$$TUC = \left(MUST - P^{BESS}\right) \cdot 1000 \cdot TSUT \tag{17}$$

where, *TUC* is transmission use charge ($ per month), *MUST* is ''Montante de Uso do Sistema de Transmissão'' (MW), P^{BESS} is the BESS rated power (MW), and *TSUT* is Transmission System Use Tariff ($/kW per month).

The reduction in MUST represented in Eq. (17) is introduced as a scenario assumption for the economic analysis. The current Brazilian regulatory framework allows the presence of a co-located BESS to affect the contracted network-use amount under specific technical and contractual conditions, including limits applicable to the permissible reduction. Accordingly, the formulation $MUST - P^{BESS}$ is used here as a simplified representation of the potential transmission-cost benefit associated with storage.

Annual O&M expenses are calculated using technology-specific unit costs expressed in BRL/kW/year, multiplied by the installed capacity of each technology. These annual amounts are subsequently divided by 12 to obtain the monthly O&M expenses incorporated into the free cash flow calculation.

So, the Free Cash Flow is:

$$\begin{aligned} FCF_{s,m} = &\left(R_{s,m}^{TOT} \ or \ R_{s,m}^{TOT_curtail}\right) \\ &- \tau_{gr}\left(R_{s,m}^{TOT} or R_{s,m}^{TOT_curtail}\right) \\ &- T_{s,m}^{PROFIT} - O\&M - SC - TUC - DS_m \end{aligned} \tag{18}$$

where, $FCF_{s,m}$ is free cash flow for each scenario s and month m, $R_{s,m}^{TOT}$ comes from Eq. (9), $R_{s,m}^{TOT_curtail}$ comes from Eq. (16), τ_{gr} is the gross-revenue taxation accordingly Brazil's fiscal system, $T_{s,m}^{PROFIT}$ is a profit-based taxation component for each scenario s and month m ($), *O&M* is operation and maintenance cost ($ per month), *SC* is sectorial charges ($ per month), *TUC* comes from Eq. (17) and DS_m is the complete debt-service payment, including both interest and principal amortization in month m ($).

The fiscal treatment adopted in the model separates gross-revenue taxation and profit-based taxation. The 3.65% gross-revenue taxation adopted in the model is not intended to represent corporate income taxation. Rather, it corresponds to the combined cumulative PIS/Pasep and Cofins contributions, at rates of 0.65% and 3.0%, respectively. Whereas a separate 25% effective tax rate is used as a simplified representation of profit-based taxation under the Brazilian Presumed Profit (*Lucro Presumido*) framework. Accordingly, the 3.65% component is applied directly to gross revenue, while the 25% component is associated with the project's profit-related tax base.

This treatment represents a simplified profit-based taxation assumption adopted for the stochastic investment assessment. Although the Brazilian Presumed Profit framework provides the regulatory context for the taxation discussion, the adopted formulation does not reproduce its statutory presumed-revenue tax-base calculation. Instead, it provides an approximation of income-tax effects within the monthly discounted cash-flow framework. The profit-based taxation component is accounted for separately from the gross-revenue taxation, avoiding overlap between the two taxation terms.

The corresponding $T_{s.m}^{PROFIT}$ is calculated according to Eq. (19).

$$T_{s,m}^{\text{profit}} = \tau_{profit} \cdot \max\left(0, TP_{s,m}\right) \tag{19}$$

where, $T_{s,m}^{PROFIT}$ is a profit-based taxation component for each scenario s and month m ($), τ_{profit} is the profit-based taxation under Presumed Profit regime and $TP_{s,m}$ is taxable-profit base component for each scenario s and month m ($).

In Brazil, the Presumed Profit tax regime can be an attractive option for renewable electricity generation companies, particularly wind and solar power producers with relatively high operating margins. Under this regime, taxable-profit base ($TP_{s,m}$) is calculated using predetermined percentages of revenue rather than actual accounting profits. For electricity generation and sales activities, the standard presumed profit margins are generally 20%, subject to applicable rules and adjustments. This regime can offer tax efficiency and administrative simplicity, especially for projects with stable revenues and low operating costs.

So, the calculation of the assumed taxable-profit base $TP_{s,m}$ is:

$$TP_{s,m} = 0.2(R_{s,m}^{TOT} or R_{s,m}^{TOT_curtail}) \tag{20}$$

The tax calculations adopted in this study are based on a simplified representation of the Brazilian regulatory and taxation framework. Given the complexity of Brazil's tax system, a profit-based tax rate (τ_{profit}) of 25% is assumed to approximate profit-based taxation under the Presumed Profit regime. This assumption is intended to provide a consistent basis for the economic and financial assessment of renewable electricity generation projects, rather than to reproduce the detailed tax obligations applicable to individual companies. Consequently, potential variations arising from specific tax classifications, fiscal incentives, revenue structures, and regulatory provisions are not explicitly considered.

This simplification allows the analysis to focus on the comparative economic performance of the evaluated scenarios while acknowledging that actual tax liabilities may differ from the modeled estimates.

When the project is evaluated without financing, DS_m is equal to zero. When financing is considered, a fraction of the initial investment is financed, and the debt is repaid using the Constant Amortization System (CAS).

At this stage, the methodology combines technical and financial assumptions into a single monthly cash-flow stream. The resulting free cash flow is therefore the key variable connecting renewable uncertainty, curtailment, storage contribution, market settlement, and project finance within the valuation framework.

H. FINANCIAL INDICATORS AND MONTE CARLO PROCEDURE

For each Monte Carlo scenario, the proposed stochastic discounted cash-flow model generates a sequence of monthly free cash flows over the 240-month investment horizon. The Modified Internal Rate of Return (MIRR) is adopted as the principal profitability indicator because it explicitly distinguishes between the financing cost associated with negative cash flows and the reinvestment return associated with positive cash flows.

The MIRR calculation employs two distinct annual effective rates: a financing rate of 7.49% p.a., corresponding to the assumed project debt cost, and a reinvestment rate of 9.67% p.a., corresponding to the representative hurdle rate adopted in the financial analysis. Since cash flows are calculated monthly, both annual rates are converted into equivalent effective monthly rates using compound-interest equivalence, as expressed in Eq. (21).

$$\begin{aligned} i_f &= (1+0.0749)^{1/12} - 1 \\ i_r &= (1+0.0967)^{1/12} - 1 \end{aligned} \tag{21}$$

where, i_f and i_r are the effective monthly financing and reinvestment rates, respectively.

The financing rate is used to discount all negative cash flows to the beginning of the investment horizon, while the reinvestment rate is used to compound all positive cash flows to the end of the investment horizon. This procedure yields the present value of negative cash flows and the future value of positive cash flows, respectively, as defined in Eq. (22).

$$\begin{aligned} PV_s^- &= \sum_{m=1}^{N} \frac{max(-FCF_{s,m}, 0)}{(1+i_f)^m} \\ FV_s^+ &= \sum_{m=1}^{N} max(FCF_{s,m}, 0)(1+i_r)^{N-m} \end{aligned} \tag{22}$$

where, PV_s^- is the absolute present value of negative cash flows (\$), FV_s^+ is the future value of positive cash flows at the end of the investment horizon (\$), $FCF_{s,m}$ comes from Eq. (18) and $N = 240$ months.

For each Monte Carlo scenario, the monthly MIRR is derived from Equation (23).

$$MIRR_s = \left(\frac{FV_s^+}{PV_s^- + (CAPEX - Fin)} \right)^{1/N} - 1 \tag{23}$$

where, $MIRR_s$ is Modified Internal Rate of Return per month, PV_s^- and FV_s^+ comes from Eq. (22), CAPEX is the sum of wind, photovoltaic, and BESS investments (\$) and *Fin* is the portion of the project CAPEX that is financed through debt (\$).

In this work it was assumed that 80% of the project CAPEX is financed through debt, while the remaining portion is covered by equity. Therefore, the MIRR calculated in this study represents an equity MIRR.

Throughout the remainder of this work, all references to the MIRR correspond to the annual MIRR rather than the monthly MIRR. The monthly MIRR can be converted into its annual equivalent using the following equation $MIRR = (1 + MIRR_s)^{12} - 1$.

The methodology produces a MIRR value for each Monte Carlo scenario. Repeating this procedure across all simulated scenarios yields a probability distribution of MIRR values rather than a single deterministic estimate. This distribution provides a probabilistic view of project performance under uncertainty, allowing the analysis to capture the effect of renewable generation variability, curtailment, storage contribution, market-price exposure, operating costs, and financing conditions on the economic attractiveness of the hybrid wind–PV–BESS project.

In addition to the average MIRR, the study evaluates downside financial risk using $VaR_{95\%}$, which measures the lower tail of the simulated return distribution and indicates the magnitude of adverse outcomes under unfavorable scenarios.

The overall simulation procedure can therefore be summarized as follows: (i) annual wind and photovoltaic generation are sampled for each Monte Carlo scenario; (ii) photovoltaic degradation and monthly seasonality are applied; (iii) monthly generation is compared with the contracted physical guarantee; (iv) curtailment scenarios and BESS contribution are incorporated; (v) revenues, costs, taxes, transmission charges, and debt service are calculated on a monthly basis; and (vi) MIRR and $VaR_{95\%}$ are computed from the resulting project cash flows. This sequence produces a stochastic risk–return assessment of the hybrid plant under alternative BESS sizes, curtailment levels, and economic assumptions.

V. DATA AND VARIABLES MODELED

This section summarizes the technical, economic, financial, and regulatory inputs adopted in the stochastic valuation model, as well as the scenario variables used in case studies and sensitivity analyses. Its purpose is twofold. First, it provides transparency regarding the data and assumptions that feed the Monte Carlo discounted cash-flow framework presented in Section IV. Second, it clarifies which variables are treated as fixed project inputs, which are modeled as

stochastic uncertainties, and which are varied across scenarios to assess the economic sensitivity of co-located BESS in the hybrid wind–photovoltaic project.

The modeled project corresponds to a hybrid renewable power plant composed of 50 MW of wind generation and 50 MW of photovoltaic generation, totaling 100 MW of installed renewable capacity, with the possibility of adding a co-located BESS. The reference BESS configuration considered in the base curtailment-mitigation case has a rated power of 30 MW and a storage duration of 4 hours, although additional battery sizes are evaluated in the sensitivity analysis. The simulation horizon is 20 years, with monthly cash flows and Monte Carlo representation of renewable generation uncertainty.

Table 1 presents the input data for the analysis, where ''AA'' stands for authors' assumptions.

The percentage-based renewable-generation parameters reported in Table 1 are expressed as capacity factors relative to the installed capacity of each technology. Accordingly, the wind P50 capacity factor of 41.3% corresponds to 20.65 MWavg, while the photovoltaic P50 capacity factor of 21.0% corresponds to 10.50 MWavg. The wind and photovoltaic standard deviations, reported as 14% and 12%, respectively, are defined relative to their corresponding P50 values rather than as absolute percentage-point deviations. Thus, $\sigma^{WND} = 0.14P50^{WND} = 2.891$ MWavg and $\sigma^{PV} = 0.12P50^{PV} = 1.260$ MWavg. The wind and PV P90 values are calculated from the assumed normal distribution as $P90 = P50 - 1.2816\sigma$.

In this study, the wholesale electricity price reference was based on DCide's Pool Denergia dashboard [19], which provides market-based forward price benchmarks for Free Contracting Environment (ACL – Ambiente de Contratação Livre). These prices should be interpreted as forward contract price references for bilateral electricity transactions, rather than as the official short-term settlement price. In Brazil, the official short-term market price (spot price) is the Difference Settlement Price (Preço de Liquidação das Diferenças – PLD), calculated and disclosed by Brazilian Electricity Market Operator (CCEE) commonly referred as the Brazilian Electricity Commercialization Chamber. CCEE performs key market-operation functions, including contract registration, energy accounting, and the financial settlement of electricity transactions [20].

Within this framework, imbalances between contracted energy and measured generation or consumption are settled in the short-term market, known as the Mercado de Curto Prazo (MCP). These differences are valued using the *"Preço de Liquidação das Diferenças"* (PLD), often translated as the Differences Settlement Price and commonly interpreted as the Brazilian spot-market price for electricity. The PLD is expressed in BRL/MWh and calculated for each submarket and hourly settlement period, reflecting system operating conditions and the marginal cost of supplying electricity, subject to regulatory minimum and maximum limits.

TABLE 1. Assumptions adopted in the simulation.

Variable	Value	Unit of Measurement	Data Source
PPA Price	275	BRL/MWh	[19]
Average Spot Market Price	350	BRL/MWh	[20]
Premium Selling Price (p_m^{sell})	525	BRL/MWh	AA
Reduced Purchase Price (p_m^{buy})	175	BRL/MWh	AA
Wind CAPEX	5	M BRL/MW	[17]
Wind O&M Expenses	110	BRL/kW/year	[17]
PV CAPEX	3	M BRL/MW	[17]
PV O&M Expenses	60	BRL/kW/year	[17]
BESS CAPEX (4 hours)	5	M BRL/MW	[17]
BESS O&M Expenses	130	BRL/kW/year	[17]
BESS RTE (Round-trip efficiency)	90%	Percentage	AA
Project lifetime	240	Months	AA
Wind P50	41.3%	Percentage of wind installed capacity	AA
Wind P90	33.9%	Percentage	AA
Wind Relative Standard Deviation	14.0%	Percentage of wind P50	AA
PV P50	21.0%	Percentage of PV installed capacity	AA
PV Relative Standard Deviation	12.0%	Percentage of PV P50	AA
Solar Factor Degradation	0.4% p.a.	Percentage	AA
Sectorial Charges	15	BRL/kW/year	[17]
Profit-Based Taxation (Brazilian Presumed Profit Framework)	25%	Percentage	[17]
Gross-Revenue Tributes	3.65%	Percentage	[17]
TSUT (Transmission System Use Tariff)	7	BRL/kW/month	AA

TABLE 2. Financial assumptions adopted in the simulation.

Variable	Value	Unit of Measurement	Data Type
Financed shared	80%	Percentage of CAPEX	AA
MIRR financing rate	7.49%	Percentage per year	AA
MIRR reinvestment rate	9.67%	Percentage per year	AA
Amortization period	120 months	Month of the cash flow	AA
Amortization system	CAS	-	AA

The Premium Selling Price (p_m^{sell}) and Reduced Purchase Price (p_m^{buy}) are authors' assumptions representing, respectively, higher-price and lower-price market periods that may be exploited through BESS energy arbitrage. These values are intended to approximate typical price spreads observed between evening peak and off-peak periods in the Brazilian electricity market.

These price parameters are not intended to reproduce observed hourly PLD trajectories, but rather to provide simplified representations of the economic opportunities available to the BESS within the investment-oriented framework adopted in this study. Both p_m^{sell} and p_m^{buy} are treated as user-defined input parameters, allowing analysts to modify their values and perform customized sensitivity or scenario analyses according to alternative market-price assumptions.

The financial assumptions used in the simulations are summarized in Table 2, where "AA" stands for authors' assumptions. The model assumes that 80% of the project CAPEX is financed through debt, while the remaining portion is covered by equity. The cost of debt is represented by an annual interest rate of 7.49%. Debt repayment is considered over a 120-month period, ending in the 120th month of the projected cash flow. The amortization schedule follows the Constant Amortization System (CAS), under which the principal repayment remains constant throughout the financing period and the interest component decreases as the outstanding debt balance declines. These parameters define the project's debt service profile and are incorporated into the financial cash-flow analysis.

VI. RESULTS

This section presents the techno-economic results obtained from the stochastic discounted cash-flow model with monthly steps developed for the hybrid wind–photovoltaic power plant with a co-located BESS. The simulations were performed using 2,000 Monte Carlo scenarios and considered the financing structure based on Constant Amortization System (CAS). The main financial indicator used to compare the scenarios was the MIRR reported in terms of its mean value and downside-risk indicator, expressed as $VaR_{95\%}$.

A. CASE 1 - REFERENCE CASE

The first simulation was defined as the reference case without curtailment and without BESS. In this case, the curtailment was set equal to zero over the entire investment horizon, meaning that no generation was restricted by system-level constraints..

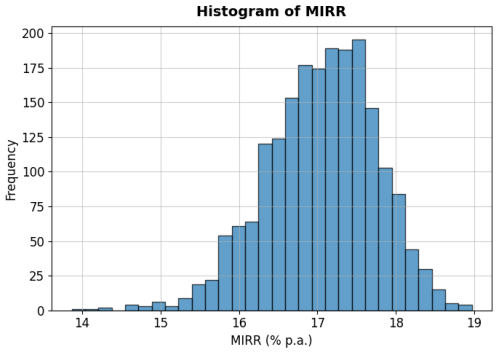

FIGURE 1. Case 1 - reference case without curtailment and without BESS.

Under these assumptions, the project achieved a mean MIRR of 17.03%, with a standard deviation of 0.70% and a $VaR_{95\%}$ of 15.85% (Fig. 1). This result represents the upper benchmark of the analysis, since all available renewable generation is assumed to be commercially available and the project does not incur additional investment or operating costs associated with the storage system.

B. CASE 2 - 20% CURTAILMENT LEVEL WITHOUT BESS

When a 20% curtailment level was introduced without BESS, the financial performance deteriorated significantly. The mean MIRR decreased from 17.03% to 9.65%, while the $VaR_{95\%}$ declined from 15.85% to 8.04% (Fig. 2). This result confirms the strong negative impact of curtailment on the economic viability of hybrid renewable power plants. In this scenario, part of the wind and photovoltaic generation that would otherwise be available for sale is lost, reducing the project's revenue base while fixed investment, operating costs, sectorial charges, transmission-related costs, and debt service remain in place. Therefore, the curtailment constraint directly reduces expected profitability and increases the relevance of technologies capable of recovering or repositioning part of the restricted energy.

C. CASE 3 - 20% CURTAILMENT LEVEL WITH BESS

The introduction of BESS under the 20% curtailment scenario improved the project's financial performance. The 30 MW / 4 h BESS was assumed to provide two main contributions. First, it reduces the contracted network-use requirement by lowering the Montante de Uso do Sistema de Transmissão (MUST) in accordance with the BESS power

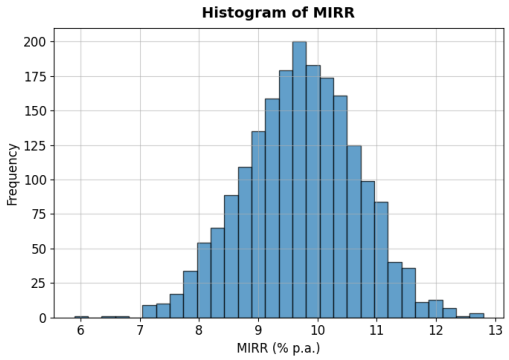

FIGURE 2. Case with curtailment and without BESS.

TABLE 3. Initial cases of analysis.

Cases	Curtailment	BESS	Mean MIRR	$VaR_{95\%}$
Case1	No	No	17.03%	15.85%
Case 2	20%	No	9.65%	8.04%
Case 3	20%	30 MW / 4 hours	12.54%	11.24%

rating, thereby decreasing the transmission-related cost calculated in Eq. (17) (aligned with the recent evolution of the Brazilian regulatory framework, particularly ANEEL Normative Resolutions No. 1,161/2026 and No. 1,162/2026); and second, it allows part of the curtailed energy to be stored and later sold under a premium price assumption.

For this case, the mean MIRR increased to 12.54%, with a standard deviation of 0.76% and a $VaR_{95\%}$ of 11.24%. Compared with the curtailed case without BESS, this represents an increase of 2.89 percentage points in the mean MIRR and 3.20 percentage points in the downside-risk indicator. Therefore, under the assumed cost and revenue parameters, the BESS partially offsets the financial loss caused by curtailment. Considering that the company adopts a minimum acceptable $VaR_{95\%}$ threshold of 10%, Case 2 would not satisfy the company's risk-return criterion, since its $VaR_{95\%}$ is equal to 8.04%. However, with the inclusion of the BESS in Case 3, $VaR_{95\%}$ increases to 11.24%, indicating an improvement in the lower-tail return threshold, with the 5th-percentile return increasing from 8.04% to 11.24%.

Therefore, from the perspective of the company's risk metric, investment in the BESS could be considered acceptable under the assumptions adopted in this analysis. Table 3 summarizes the mean MIRR and $VaR_{95\%}$ obtained for the three initial cases considered in the analysis.

D. SENSITIVITY ANALYSIS WITH DIFFERENT BESS SIZES FOR A 20% CURTAILMENT

The sensitivity analysis across different BESS sizes, using the same 20% curtailment level, demonstrates that the economic value of storage is not directly proportional to the installed capacity. As shown in Table 4 and Fig. 3, six configurations were evaluated, considering BESS power ratings of 15, 20, 30, 35, 45, and 60 MW, all with the same storage duration of 4 hours and MUST was assumed to decrease according to the BESS power rating, subject to the simplified scenario formulation adopted in Eq. (17). This assumption is used to quantify the potential economic impact of transmission-use optimization and does not represent an unrestricted regulatory entitlement.

TABLE 4. Sensitivity analysis for 20% curtailment.

BESS / 4 hour	Mean MIRR	$VaR_{95\%}$
15 MW	11.59%	10.17%
20 MW	12.10%	10.84%
30 MW	**12.54%**	**11.24%**
35 MW	12.26%	10.88%
45 MW	11.11%	9.67%
60 MW	9.00%	7.61%

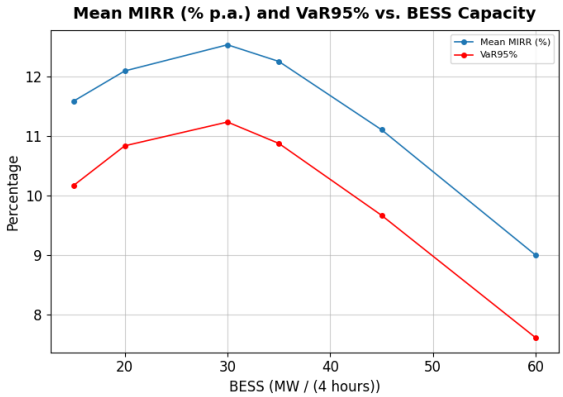

FIGURE 3. Sensitivity analysis for 20% curtailment with different BESS sizes (MW / 4 hours).

For the 20% curtailment case, the best result was obtained with a 30 MW / 4 h BESS, which produced the highest mean MIRR and the highest $VaR_{95\%}$ among the tested configurations. A smaller 15 MW / 4 h BESS produced a mean MIRR of 11.59% and a $VaR_{95\%}$ of 10.17%, indicating that the storage capacity was insufficient to capture the full economic opportunity created by the curtailed energy. Increasing the BESS to 20 MW / 4 h improved the mean MIRR to 12.10% and the $VaR_{95\%}$ to 10.84%. The 30 MW / 4 h configuration reached the best balance between additional revenue, reduction in network-use requirements, capital expenditure, and operating expenses.

Beyond this point, however, additional storage capacity reduced the project's profitability. A 35 MW / 4 h BESS resulted in a mean MIRR of 12.26% and a $VaR_{95\%}$ of 10.88%, slightly below the 30 MW case. Larger systems showed a more pronounced decline: the 45 MW / 4 h BESS reduced the mean MIRR to 11.11%, while the 60 MW / 4 h BESS reduced it further to 9.00%. This behavior indicates that oversizing

TABLE 5. Sensitivity analysis for 30% curtailment.

BESS / 4 hour	Mean MIRR	$VaR_{95\%}$
15 MW	6.98%	5.50%
20 MW	7.73%	6.32%
30 MW	9.20%	7.94%
35 MW	**9.66%**	**8.35%**
45 MW	9.58%	8.27%
60 MW	8.10%	6.68%

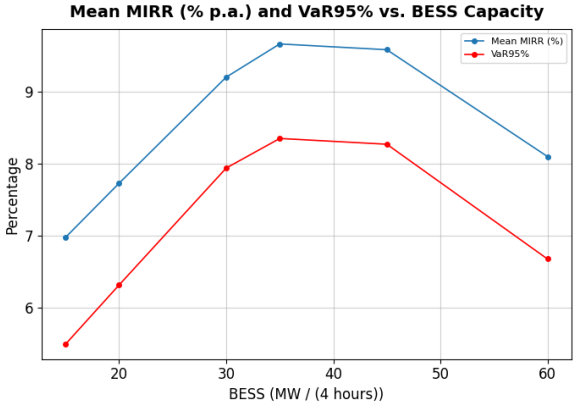

FIGURE 4. Sensitivity analysis for 30% curtailment with different BESS sizes (MW / 4 hours).

TABLE 6. Sensitivity analysis for 30% curtailment and with BESS CAPEX Reduced by 50%.

BESS / 4 hour	Mean MIRR	$VaR_{95\%}$
15 MW	8.80%	7.32%
20 MW	10.87%	8.79%
30 MW	12.47%	11.21%
35 MW	13.31%	12.13%
45 MW	**13.78%**	**12.53%**
60 MW	13.27%	11.93%

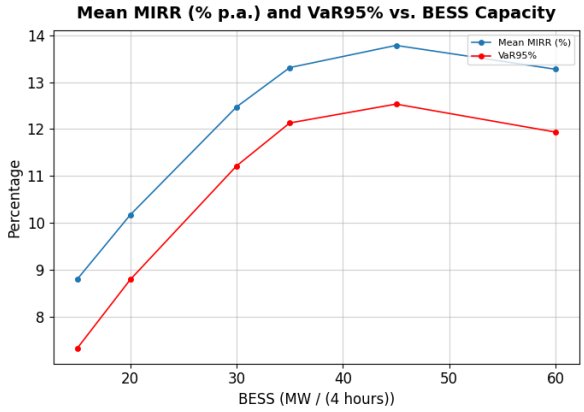

FIGURE 5. Sensitivity analysis for 30% curtailment with different BESS sizes (MW / 4 hours) and with BESS CAPEX reduced by 50%.

the BESS leads to diminishing marginal returns. Although a larger battery can theoretically recover more curtailed energy, the incremental revenue is not sufficient to compensate for the additional CAPEX and O&M expenses under the adopted assumptions. Thus, the results indicate the existence of an economically optimal BESS size rather than a simple rule in which larger storage systems always improve project value.

E. SENSITIVITY ANALYSIS WITH DIFFERENT BESS SIZES FOR A 30% CURTAILMENT

The simulations were also extended to a more severe curtailment case of 30%. Under this condition, the economic performance of all BESS configurations declined substantially in comparison with the 20% curtailment case, as shown in Table 5 and Fig. 4.

For the tested BESS capacities, the mean MIRR ranged from 6.98% to 9.66%, while the $VaR_{95\%}$ ranged from 5.50% to 8.35%. The best result was obtained with a 35 MW / 4 h BESS, which produced a mean MIRR of 9.66%, a standard deviation of 0.76%, and a $VaR_{95\%}$ of 8.35%. A 45 MW / 4 h BESS produced a very similar mean MIRR of 9.58%, but with a slightly lower $VaR_{95\%}$ of 8.27%. This indicates that, when curtailment becomes more severe, the optimal storage size shifts upward in comparison with the 20% curtailment case, because a larger volume of restricted energy becomes available for recovery and time shifting.

These results show that the optimal BESS capacity depends on the interaction between curtailment intensity, storage investment cost, operating expenses, network-use benefits, and the price premium obtained when curtailed energy is shifted to higher-value periods. For moderate curtailment levels, the 30 MW / 4 h BESS was the most attractive configuration. For higher curtailment levels, the optimal configuration moved toward 35 MW / 4 h, since the additional recoverable curtailed energy improved the economic justification for a larger battery. However, in both cases, very large BESS capacities were not economically optimal under the base CAPEX assumptions. This confirms that BESS sizing must be treated as an optimization problem rather than a purely technical decision.

F. SENSITIVITY ANALYSIS WITH DIFFERENT BESS SIZES FOR A 30% CURTAILMENT AND WITH BESS CAPEX REDUCED BY 50%

An additional sensitivity considered the case in which BESS CAPEX is reduced by 50% under the 30% curtailment scenario. In this case, the best-performing configuration shifted toward a larger battery, with the 45 MW / 4 h BESS identified as the most attractive option, as shown in Table 6 and Fig. 5. This result reinforces the importance of battery cost reduction as a key driver for the economic feasibility of storage in hybrid renewable power plants. As BESS CAPEX decreases, the penalty associated with oversizing becomes less severe, allowing larger systems to capture additional value from curtailed energy and from the reduction of grid-use requirements.

Overall, the results demonstrate three main findings. First, curtailment has a substantial negative effect on the financial

TABLE 7. Sensitivity analysis without curtailment and with BESS CAPEX reduced by 50%.

BESS / 4 hour	Mean MIRR	$VaR_{95\%}$
15 MW	15.99%	14.65%
20 MW	15.59%	14.30%
30 MW	14.89%	13.54%
35 MW	14.57%	13.22%
45 MW	13.84%	12.40%
60 MW	12.81%	11.40%

performance of hybrid wind–photovoltaic projects, reducing both expected profitability and downside-risk performance. Second, BESS can partially mitigate this effect by recovering curtailed energy and enabling its sales under more favorable price conditions, while also contributing to the reduction of network-use requirements. Third, the economic attractiveness of BESS is highly sensitive to sizing: undersized batteries fail to capture the full value of curtailed energy, whereas oversized batteries introduce additional CAPEX and O&M costs that are not fully compensated by incremental revenues. Therefore, the main contribution of the proposed stochastic investment-analysis framework is not to demonstrate that BESS is always economically attractive, but rather to support investors in identifying the conditions under which a given BESS capacity can maximize the risk-adjusted return of the hybrid project.

G. SENSITIVITY ANALYSIS WITH DIFFERENT BESS SIZES WITHOUT CURTAILMENT AND WITH BESS CAPEX REDUCED BY 50%

This subsection evaluates the economic performance of different BESS sizes under a scenario without curtailment, assuming a 50% reduction in BESS CAPEX. In this case, the BESS is not used to recover curtailed renewable generation, since all wind and photovoltaic production is assumed to be fully available for commercial settlement. Therefore, the economic value of storage is limited mainly to energy arbitrage and to the reduction of transmission-related costs associated with the contracted network-use requirement. The results are presented in Table 7 and Fig. 6.

The results indicate that, even under a significantly lower battery investment cost, increasing the BESS capacity does not improve the financial performance of the hybrid project when curtailment is absent. The best-performing configuration is the 15 MW / 4 h BESS, which achieves a mean MIRR of 15.99% and a $VaR_{95\%}$ of 14.65%. As the storage capacity increases, both profitability and downside-risk indicators decrease progressively. For example, the mean MIRR declines from 15.99% for the 15 MW / 4 h configuration to 12.81% for the 60 MW / 4 h configuration, while the $VaR_{95\%}$ decreases from 14.65% to 11.40%. This trend shows that, in the absence of curtailed energy, the additional revenues obtained through arbitrage are not sufficient to compensate for the incremental CAPEX and O&M costs associated with larger storage systems.

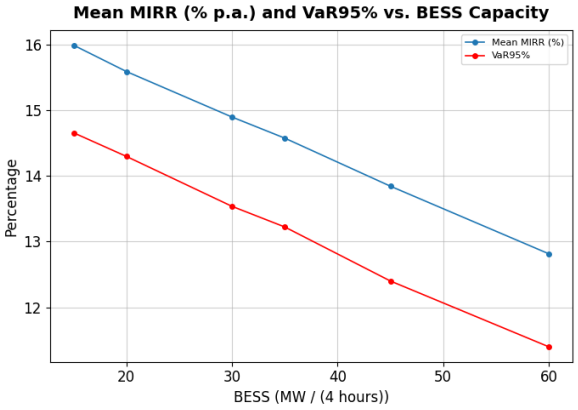

FIGURE 6. Sensitivity analysis without curtailment with different BESS sizes (MW / 4 hours) and with BESS CAPEX reduced by 50%.

These findings are particularly relevant when compared with the reference case without curtailment and without BESS, which presented a mean MIRR of 17.03% and a $VaR_{95\%}$ of 15.85%. Although the 50% CAPEX reduction substantially improves the competitiveness of storage, none of the evaluated BESS configurations outperforms the reference case without storage. This suggests that, under the assumptions adopted in this study, the economic justification for BESS deployment is strongly dependent on the existence of curtailment or additional revenue-stacking mechanisms. Without curtailment, the BESS does not create enough incremental value to offset its investment and operating costs, even when battery CAPEX is reduced by half.

Therefore, the results reinforce that BESS sizing should not be determined only by technical capability or by cost reduction expectations. Instead, the optimal storage capacity depends on the interaction between available energy-shifting opportunities, market price spreads, network-use benefits, investment cost, and regulatory remuneration mechanisms. In scenarios without curtailment, smaller BESS configurations are economically less penalizing, but the overall investment case remains weaker than the no-BESS reference case. This indicates that future business models for storage in Brazil should consider additional value streams, such as ancillary services, capacity adequacy, congestion management, and other flexibility products, in order to improve the bankability of BESS projects beyond energy arbitrage alone.

These findings also have others relevant implications for future regulatory and business-model development in Brazil. Under the current revenue assumptions, BESS value in Brazil, due to the current regulatory framework, is only associated with energy arbitrage, curtailment mitigation, and reduction of network-use requirements. However, several variables remain highly uncertain over the 20-year investment horizon, including future curtailment levels, PLD behavior, BESS CAPEX trajectories, and the emergence of additional revenue-stacking opportunities. For this reason, future research should extend the present stochastic discounted

cash-flow framework by incorporating Real Options Analysis, allowing the valuation of managerial flexibility under uncertainty, such as the option to defer storage investment, expand BESS capacity, or adapt the commercialization strategy as market and regulatory conditions evolve.

The results show that, depending on battery investment costs, curtailment levels, and market-price assumptions, the investor may identify an optimal BESS power capacity, expressed in MW, that maximizes both the expected financial return, measured by the mean MIRR, and the downside-risk performance, measured by $VaR_{95\%}$. Therefore, the main contribution of the analysis is not to prescribe a universal BESS size or investment decision, but to demonstrate how storage sizing can be evaluated probabilistically under uncertainty and how the economic attractiveness of BESS depends strongly on future cost reductions, curtailment exposure, and the emergence of additional revenue streams.

Several input variables considered in this analysis are subject to significant uncertainty over the medium and long term. Their future behavior is difficult to forecast over the next five years and becomes even more uncertain over a 20-year investment horizon. Among the most relevant uncertain variables are the curtailment level, the PLD price, which directly affects both the premium purchase price and the premium selling price, the BESS capital expenditure, and the potential development of BESS revenue-stacking opportunities. In principle, each of these variables could be explicitly modeled as a stochastic parameter within the proposed framework. However, as the number of uncertain variables increases, the analysis naturally moves beyond a conventional stochastic discounted cash-flow approach and toward a Real Options Analysis framework. ROA would allow the valuation of managerial flexibility under uncertainty, including the possibility of postponing investment, expanding storage capacity, adapting the operating strategy, or responding to future changes in market prices, curtailment levels, technology costs, and regulation.

VII. PROPOSALS FOR POLICY INCENTIVES IN BRAZIL AND NEW REGULATORY FRAMEWORK

The results obtained in this study indicate that the economic attractiveness of co-located BESS in hybrid wind–photovoltaic power plants depend strongly on curtailment levels, battery investment costs, market price signals, and the possibility of monetizing multiple services provided by storage. Although BESS can technically mitigate curtailment by storing surplus renewable generation and shifting it to periods of higher system value, the current business case remains limited when the storage system is remunerated only through energy arbitrage. Therefore, the large-scale deployment of BESS in Brazil requires not only technological cost reductions, but also a regulatory framework capable of explicitly recognizing and remunerating the flexibility, reliability, and system-support services provided by energy storage.

A first regulatory improvement would be the formal definition of energy storage as a distinct asset class within the Brazilian electricity sector. Under the current regulatory structure, storage may be interpreted differently depending on whether it behaves as load, generation, or grid-support infrastructure. This ambiguity creates uncertainty regarding market participation, tariff treatment, network charges, taxation, and operational responsibilities. A clear regulatory classification would reduce investment risk and provide a more stable basis for project development, financing, and long-term contracting. Such a framework should recognize the dual nature of BESS, since the same asset may consume electricity during charging periods and inject electricity during discharging periods, while also providing services that are neither purely generation nor consumption.

To address these challenges, ANEEL finalized a landmark regulatory framework following the conclusion of Public Consultation n° 39/2023. This updated framework establishes a clear taxonomy for Energy Storage Systems (Sistemas de Armazenamento de Energia – SAE) by introducing a bifurcated operational structure that mitigates previous tariff ambiguities. The first category comprises autonomous systems that operate under the centralized control and dispatch of the National Grid Operator (Operador Nacional do Sistema Elétrico – ONS). To incentivize large-scale utility deployment - particularly to alleviate transmission constraints and renewable curtailment - these centrally dispatched assets are granted specific exemptions from network usage charges during their charging cycle. Conversely, the second category encompasses free-operation systems that function independently within the free market (ACL) or behind-the-meter for price arbitrage. These assets remain subject to standard symmetrical grid-charging mechanisms, acting as conventional loads during consumption and as generation units during injection [21]. Although this hybrid framework successfully removes significant barriers for grid-support infrastructure ahead of national capacity auctions, the asymmetrical tariff treatment between autonomous and free-market storage systems underscores an ongoing debate regarding complete regulatory optimization for independent commercial stakeholders.

A second important measure would be the creation of specific mechanisms to remunerate flexibility services. Batteries can contribute to the power system by providing fast frequency response, voltage support, ramp-rate control, congestion relief, reserve capacity, black-start capability, and short-term balancing. However, if these services are not explicitly priced, the value created by storage remains only partially captured by investors [22]. In this context, Brazil could develop competitive ancillary-service markets or, as an intermediate regulatory step, adopt regulated procurement mechanisms through which BESS and other flexible resources are explicitly allowed to compete with conventional technologies for the provision of system-support services. This would support a more efficient allocation of system costs and benefits, while creating additional revenue streams that improve the bankability of storage projects.

Another relevant proposal is the development of regulatory mechanisms that allow BESS to participate in capacity adequacy and reliability products. As the share of variable renewable energy increases, the Brazilian power system will require resources capable of delivering firm capacity during periods of high demand, low renewable output, or network stress. Properly sized and operated storage systems can provide this contribution, especially when co-located with hybrid renewable plants. Therefore, capacity auctions or reliability contracts should include technical requirements that allow BESS participation, considering parameters such as discharge duration, availability, response time, state-of-charge management, and performance during critical system events. This would enable storage to be remunerated not only for the energy it delivers, but also for its contribution to system adequacy.

To mitigate the operational challenges imposed by high penetration of variable renewable energy (VRE) and to ensure systemic reliability, the Brazilian Ministry of Mines and Energy introduced on June 1st, 2026, a regulatory milestone via Normative Ordinance MME No. 136/2026, establishing the guidelines for the first Capacity Auction focused on utility-scale energy storage (Leilão de Reserva de Capacidade de 2026 – Armazenamento, LRCAP 2026) [23]. Scheduled for December 2026, this landmark procurement mechanism targets the contracting of power capacity from BESS across two distinct modalities: 1) a national content-restricted auction; and 2) an open technical competition. Engineered to enhance grid flexibility and continuous peak-load management, the regulatory framework stipulates rigorous performance requirements, including a minimum round-trip efficiency ($\eta_{\mathrm{RTE}} \geq 85\%$), the capability to sustain up to two full daily operational cycles, and a mandatory continuous power injection duration of 4 hours per cycle under centralized dispatch by the National Electric System Operator (ONS). Furthermore, the integration methodologies enforce advanced ancillary capabilities—specifically grid-forming inverter controls—while employing spatial location incentives to deploy these storage assets at weak or constrained transmission substations, effectively optimizing network expansion costs and systemic inertial response.

The treatment of curtailment should also be improved. In the absence of appropriate incentives, curtailed renewable energy represents a loss for investors and a loss of clean energy for the system. A regulatory framework could allow hybrid plants with co-located BESS to recover part of this value when storage demonstrably reduces curtailment or alleviates local grid constraints. This could be implemented through specific curtailment-mitigation products, congestion-management contracts, or locational incentives for storage deployment in areas with recurrent renewable generation restrictions. Such mechanisms would be particularly relevant in regions with high wind and solar complementarity, where the integration of BESS could improve the utilization of existing transmission infrastructure.

In addition, transmission-related costs should be reviewed to avoid double charging and to better reflect the effective contribution of BESS to the transmission system. Since storage can both withdraw and inject energy, inappropriate tariff design may penalize the asset twice, reducing its economic viability even when it provides net benefits to the grid. A more efficient tariff structure should distinguish between energy consumed for final demand and energy temporarily stored for later reinjection. Moreover, if the BESS reduces peak injection, mitigates congestion, or lowers the contracted network-use requirement, these benefits should be reflected in the calculation of transmission-related costs.

Policy incentives may also play an important transitional role while BESS costs remain high, and market mechanisms are still under development. These incentives could include tax reductions for storage equipment, accelerated depreciation, preferential financing lines, investment grants for pilot projects, or temporary revenue-support mechanisms for projects that demonstrate measurable system benefits. However, such incentives should be designed carefully to avoid long-term dependence on subsidies. Their main purpose should be to reduce early-stage investment barriers, support learning effects, stimulate domestic technical expertise, and accelerate the creation of a competitive storage market.

Regulatory sandboxes represent another important policy instrument for Brazil. Through sandbox arrangements, regulators, system operators, market agents, and investors could test new business models, metering rules, dispatch procedures, settlement mechanisms, and service remuneration schemes under controlled conditions. This would be especially useful for hybrid renewable plants with co-located BESS, since their operation involves interactions among generation, storage, transmission access, curtailment management, and market settlement. The lessons obtained from sandbox projects could support the gradual development of permanent regulation based on empirical evidence rather than purely theoretical assumptions.

Finally, the Brazilian regulatory framework should encourage revenue stacking as a central principle for BESS business models. The economic value of storage rarely depends on a single service. Instead, storage becomes more attractive when it can combine revenues from energy arbitrage, curtailment mitigation, ancillary services, capacity products, congestion management, and transmission-cost optimization. Therefore, regulation should avoid unnecessary restrictions that prevent the same asset from providing multiple services, provided that technical performance, metering, and settlement requirements are clearly defined. Enabling revenue stacking would improve project bankability and allow BESS to be valued according to its full contribution to the power system.

Overall, the results of this study suggest that BESS deployment in Brazil should not be evaluated only as a technology for private energy arbitrage. Its broader value lies in the ability to provide flexibility, improve renewable energy integration, reduce curtailment, support system reliability, and increase

the efficient use of transmission infrastructure. For this value to be captured, Brazil will need a regulatory framework that combines clear asset classification, appropriate tariff treatment, competitive remuneration for flexibility services, capacity-market participation, curtailment-mitigation incentives, and transitional policy support. Such measures would reduce investment uncertainty and create the conditions required for BESS to become a technically and economically relevant component of Brazil's renewable electricity future.

VIII. CONCLUSION

This paper investigated the economic value of a co-located battery energy storage system (BESS) in a hybrid wind–photovoltaic power plant under curtailment conditions, using a stochastic discounted cash-flow framework tailored to the Brazilian electricity-sector context. The proposed methodology combines renewable generation uncertainty, curtailment scenarios, storage-related revenue recovery, transmission-use effects, and financing assumptions into a probabilistic assessment of project profitability based on the Modified Internal Rate of Return (MIRR). In doing so, the study moves beyond purely operational analyses of hybrid renewable plants and focuses on a question of direct relevance to investors and developers: under which conditions can BESS improve the financial attractiveness and bankability of hybrid renewable projects exposed to constrained grid conditions?

The results indicate that curtailment is a first-order driver of project economics. By reducing the fraction of renewable generation that can be effectively monetized, curtailment shifts the MIRR distribution downward and can materially weaken the financial performance of the hybrid plant. Within this context, the BESS creates value primarily by mitigating revenue losses rather than by acting as a generic arbitrage asset. Under curtailment, storage recovers part of the lost economic value through energy shifting, curtailed-energy recovery, and, under the assumptions adopted in this work, transmission-related savings. However, the results also show that the economic contribution of BESS is not unconditional. Its value depends on the interaction among curtailment intensity, storage size, battery CAPEX, and the market assumptions used to monetize shifted energy.

A second important conclusion is that the economic benefit of storage is not monotonic with battery size. Although larger BESS configurations increase the technical ability of the plant to recover curtailed energy, the marginal financial gain tends to decrease beyond a certain range, indicating the existence of economically efficient storage sizes rather than a simple ''more is better'' relationship. In addition, the sensitivity analysis suggests that battery cost trajectories play a decisive role in shaping the long-term investment case for storage. Under current cost assumptions, the profitability of BESS may remain limited in scenarios with modest curtailment or narrow price-spread opportunities. By contrast, lower battery CAPEX substantially improves the viability of storage and expands the range of project configurations in which BESS can enhance risk-adjusted returns.

In practice, BESS in hybrid renewable plants should be evaluated not only as a flexibility resource, but also as a financial hedge against curtailment, with sizing based on curtailment exposure, price spreads, battery costs, and transmission charges. For regulators, the results show that the bankability of these projects depends on how curtailment risk is allocated and on whether market design allows storage to monetize its system value.

This study has some limitations that should be acknowledged. First, curtailment is treated as an exogenous scenario parameter rather than as the outcome of a chronological system-dispatch model. Second, the BESS is represented through an equivalent energy-shifting capability rather than through an hourly state-of-charge optimization model. Third, the premium buying and selling prices used to represent storage-related market opportunities are scenario-based assumptions and may influence the magnitude of the estimated storage value. Future work could extend the present framework by integrating endogenous curtailment modeling, higher-resolution battery dispatch optimization, and more detailed price formation mechanisms. Additional extensions may also include multi-service revenue stacking, ancillary services, and alternative regulatory arrangements for hybrid renewable plants with co-located storage.

It should be noted that the BESS benefits reported in this paper assume that the storage system shifts, every day, the energy corresponding to one equivalent full cycle. Since a lower realized utilization can only reduce the energy recovered by the BESS, these benefits should be regarded as an upper bound. In practical applications, the realized utilization of the BESS should therefore be treated as a project-specific input when sizing storage.

The results reinforce that the business case for storage is context-dependent and that its value emerges most clearly when renewable projects face structural revenue leakage and constrained monetization of clean energy. Under these conditions, BESS can play a meaningful role in improving the resilience, profitability, and long-term bankability of hybrid wind–photovoltaic investments.

Future research should extend the proposed framework by incorporating additional sources of uncertainty, including long-term PLD behavior, future curtailment trajectories, BESS cost reduction pathways, battery degradation, replacement strategies, and the emergence of new regulatory products for flexibility and capacity. Incorporating battery degradation—specifically capacity fade, augmentation, and replacement costs—may diminish projected economic returns and shift the optimal BESS sizing toward smaller capacities.

In addition, Real Options Analysis should be considered as a complementary methodology, since it would allow the valuation of managerial flexibility under uncertainty. This would make it possible to assess strategic decisions such as delaying the storage investment, expanding BESS

capacity over time, or adapting the commercialization strategy in response to future market and regulatory conditions. Such extensions would provide a more complete representation of the investment decision process and better reflect the strategic nature of BESS deployment in hybrid renewable power plants.

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