PSR InSight

ACCELERATING THE BRAZILIAN ENERGY TRANSITION

Comprehensive Energy Storage Meta-Analysis for Brazil

OCTOBER, 2025

PSR

TABLE OF CONTENTS

1. INTRODUCTION

Brazil's energy generation matrix is already recognized worldwide for its high share of renewables. However, the rapid expansion of solar and wind generation introduces new operational and planning challenges, particularly regarding system flexibility and supply security in the face of increasingly variable generation. In this context, Energy Storage Systems (ESS) emerge as strategic candidates to ensure system reliability and enable a deeper penetration of renewables without increasing dependence on fossil fuels.

This report seeks to answer a central question: what role can energy storage systems play in the Brazilian power sector, and what technical, economic, and regulatory conditions are necessary for their effective deployment?

To address this, the analysis focuses on five key dimensions:

- **Flexibility**: an assessment of the growing operational needs of the system due to wind and solar variability, increasing load and the limitations of the resources currently available.
- **Technologies**: identification of the most promising storage solutions for Brazil, with emphasis on lithium-ion batteries and pumped-storage hydropower, considering their maturity, costs, and suitability to system needs.
- **Benefits to the system**: evaluation of comparative operation scenarios showing how ESS can reduce system costs and contribute to supply security.
- **Economic viability:** an evaluation of the market conditions (including taxation) and how they (combined with the lack of regulation) affect negatively the economic viability of ESS in Brazil.
- **Regulation**: an examination of the regulatory advances underway at ANEEL and MME, as well as the remaining gaps that must be closed to create appropriate remuneration mechanisms, reduce uncertainties, and enable storage technologies to compete on equal footing.

By articulating these five aspects, the report provides technical and strategic insights for policymakers, regulators, investors, and other stakeholders. More than a diagnosis, it offers a roadmap of opportunities and recommendations to accelerate the integration of storage technologies, strengthening reliability, reducing costs, and enabling large-scale decarbonization.

2. FLEXIBILITY: AN OPERATIONAL CHALLENGE FOR THE BRAZILIAN POWER SECTOR

WHO CAN PROVIDE FLEXIBILITY TOMORROW?

Brazil's power system is evolving rapidly, and the growing need for flexibility and firm capacity cannot be met solely by the resources traditionally relied upon in the past. To address this challenge, the Brazilian Ministry of Mines and Energy (MME) has relied on electricity auctions. The two main types of auctions that have been carried out in the country are the so-called energy auctions – where the motivation for their execution comes from the need for distribution companies to acquire energy contracts to meet the consumption of their regulated consumers – and the so-called Capacity Reserve Auctions (LRCAP, Leilão de Reserva de Capacidade in Portuguese). The latter are designed to ensure the long-term adequacy of the power system by contracting resources capable of delivering reliable capacity, particularly during periods of high demand and low renewable output. In both auctions it is up to the MME, based on the planning studies, to choose which power sources are eligible to participate in the auction.

In the guidelines proposed for the two Capacity Reserve Auctions planned for 2026[1], the MME has chosen as technologies to provide capacity and flexibility Thermal Power Plants (TPP)[2] and Hydroelectric Power Plants (HPP), given their ability to offer dispatchable and controllable generation. However, these are not the only technologies that can provide such services. Energy storage technologies – referred to here as Energy Storage Systems (ESS) – also represent strong candidates.

Energy Storage Systems encompass a wide range of technologies that differ in construction, capacity and discharge duration, response time, efficiency, maturity level, and application. Their ability to supply flexibility, firm capacity, and ancillary services makes them key to the future of the Brazilian Power Sector. Understanding how different ESS can be integrated, and what their advantages and limitations are, will be the focus of the following chapter.

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1 By the end of August 2025, these guidelines are under discussion in a Public Consultation on MME's website (#195/2025).

2 Gas-fired, oil-fired and coal-fired power plants.

WHY BRAZIL NEEDS FLEXIBILITY?

Historically, the dominance of hydropower in Brazil's electricity matrix has shaped the sector's regulatory framework. This hydro-centric model fostered a strong synergy between generation and system operation, due to the dispatchability, vast storage capabilities, and ancillary services naturally provided by hydroelectric plants. However, this paradigm has gradually shifted in recent years due to structural changes in the energy mix, leading to operational challenges. As a result, significant regulatory adjustments are now necessary to maintain the reliability and efficiency of the power system.

A key driver of this transformation is the growing share of non-hydro renewable energy sources, primarily wind and solar photovoltaics, which are inherently variable and non-dispatchable. The integration of these intermittent sources into the grid, combined with operational restrictions in hydropower plants that prevent the dispatch of these resources according to the needs of the electrical system, has introduced new challenges in real-time supply-demand balancing and in maintaining voltage and frequency stability. This shift has significantly altered the traditional operational dynamics of the Brazilian Interconnected Power System, raising concerns about the system's ability to provide services - such as capacity, flexibility, reserves, and ancillary services - that were primarily supplied by hydroelectric plants with reservoirs.

Over the last decade Brazil has implemented and/or increased incentives for non-hydro renewable sources, especially for distributed solar generation. Solar generation directly reduces the net electricity demand during the day when solar output is high, thus lowering the need to dispatch other generation sources. However, after sunset, there is a concern about meeting peak demand, often leading to the use of more expensive generation sources, such as thermal power plants, including those fueled by diesel. Additionally, as solar capacity increases, significant load ramps can occur, marked by a sharp decrease in net demand at sunrise and a rapid increase at sunset, when solar generation quickly declines.

In this context, system flexibility refers to the power system’s ability to respond efficiently to rapid changes in net load caused by the variability of non-dispatchable renewable generation, especially the solar generation. As solar output fluctuates throughout the day - particularly during steep ramps at sunrise and sunset - the system must be able to quickly increase or decrease other sources of generation to maintain reliability and balance supply and demand. Ensuring adequate flexibility is therefore essential to accommodate the growing share of solar energy while avoiding the excessive use of costly or carbon-intensive generation during peak periods.

To analyze the system's flexibility needs, several assessments were conducted using official data from the Monthly Electric Operation Program[3] (PMO, *Programa Mensal da Operação* in Portuguese) prepared by the Brazilian National System Operator (ONS, *Operador Nacional do Sistema* in Portuguese) for February 2025, with a simulation horizon extending through December 2029. In this analysis, power plants were decommissioned after the end of their current power purchase agreements.

Figure 1 shows the projection of the net load for the most critical month in 2029, considering 400 scenarios of renewable resources, including both centralized and distributed generation. Normally, solar generation is more seasonally stable, with greater hourly variation. Wind generation has both hourly and seasonal uncertainties. Finally, the variability of the inflows is typically weekly with different seasonal characteristics for each river basin.

The net load was calculated based on the projected load, subtracting the minimum thermal generation and the expected solar (both centralized and distributed) and wind generation for each scenario, resulting in 400 net load scenarios. After the simulation, daily averages were computed for each of the 400 scenarios: the average for hour one from day 1 to the last day of the month, the average for hour two from day 1 to the last day of the month, and so on. The results are presented as the median values along with the 10th and 90th percentiles of the probability distribution. So, Figure 1 illustrates the most critical net load curve on a day in September/2029, the most critical month. This is because it is a month of transition between the dry and wet periods for many important basins and a month with large wind production (and variability).

[3] *The PMO is a plan that outlines how electricity will be generated and distributed across the country each month. It ensures that energy supply meets demand in the most reliable and cost-effective way possible, taking into account factors like weather forecasts, water levels in hydroelectric reservoirs, and fuel availability. The PMO helps coordinate the operation of power plants and transmission lines, aiming to maintain the balance and stability of the national electric system.*

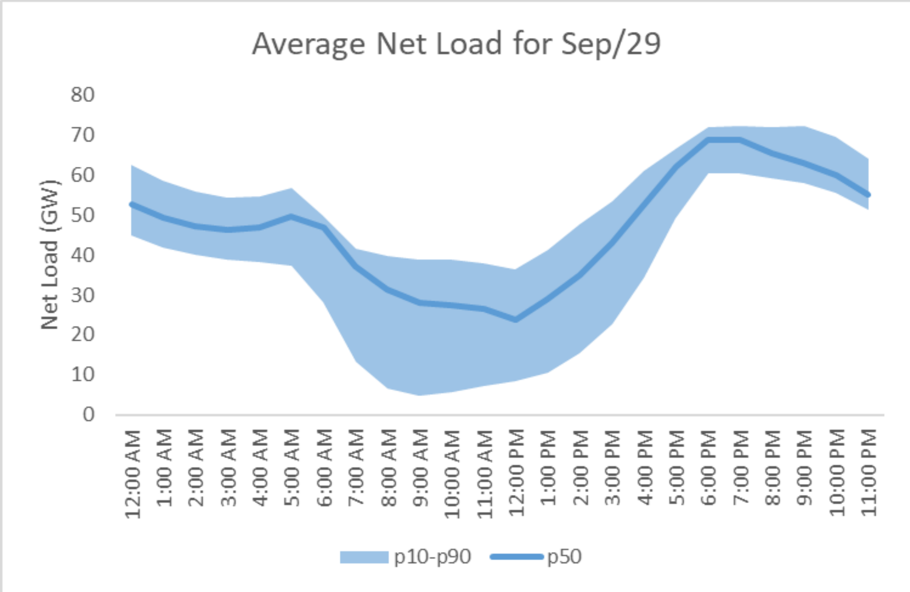

Figure 1 - Average Net Load for September/2029.

It is noteworthy that the peak net load in September 2029 reaches almost 70 GW for the median of the series. Rapid load ramps prior to this period may pose significant challenges to system operation. If not properly managed, these ramps can lead to capacity shortages and jeopardize grid reliability.

Due to operational constraints inherent to many generation technologies, fast-ramping resources are required to meet peak demand within short timeframes. In the future, additional fast-response resources will be essential to maintain system stability.

To assess the system's flexibility requirements across different time steps, we analyze the system's ramp-up needs for various months in 2029. For example, considering the 1-hour ramp-up, the system requires an average of 6 GW annually (Figure 2). However, in a more critical scenario, represented by the 99th percentile, this requirement can nearly triple, reaching 18 GW. Notably, the ramp-up requirement exhibits clear seasonality, which is negatively correlated with the wind season.

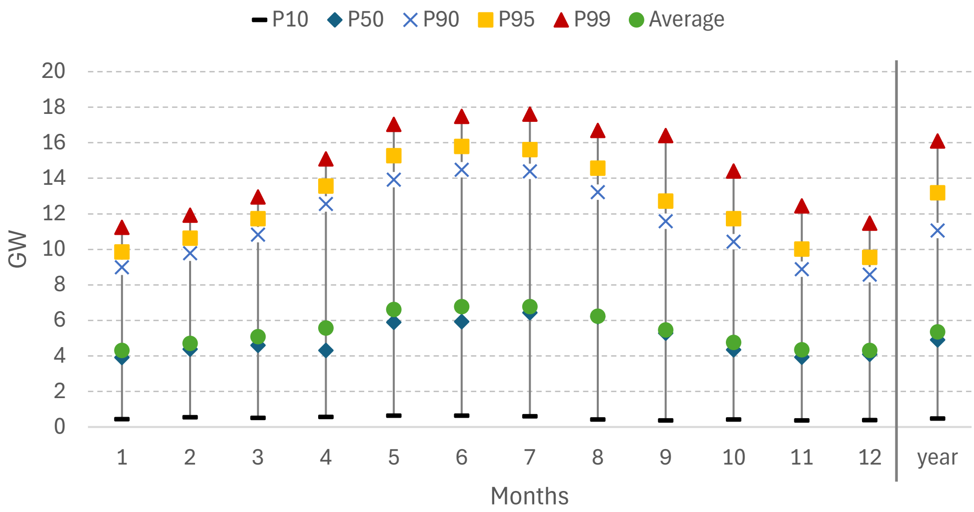

Figure 2 – System flexibility required for 1-hour (in GW)

The same assessment can be applied to upward ramps of 4-hour and 7-hour durations (Figure 3 and Figure 4). In these cases, the system requires an average of 20 GW and 30 GW annually, respectively. However, in critical scenarios, these numbers can exceed 50 GW and 60 GW, respectively.

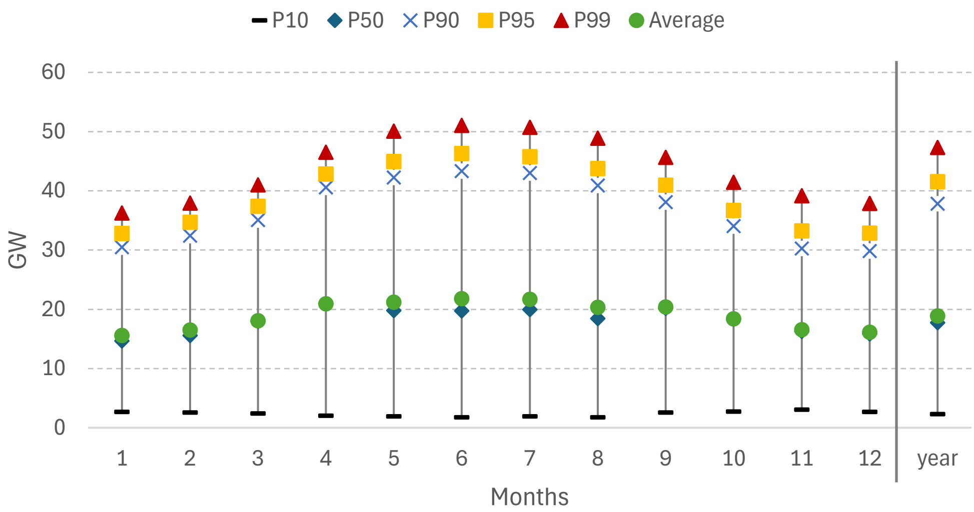

Figure 3 - System flexibility required for 4 hours (in GW)

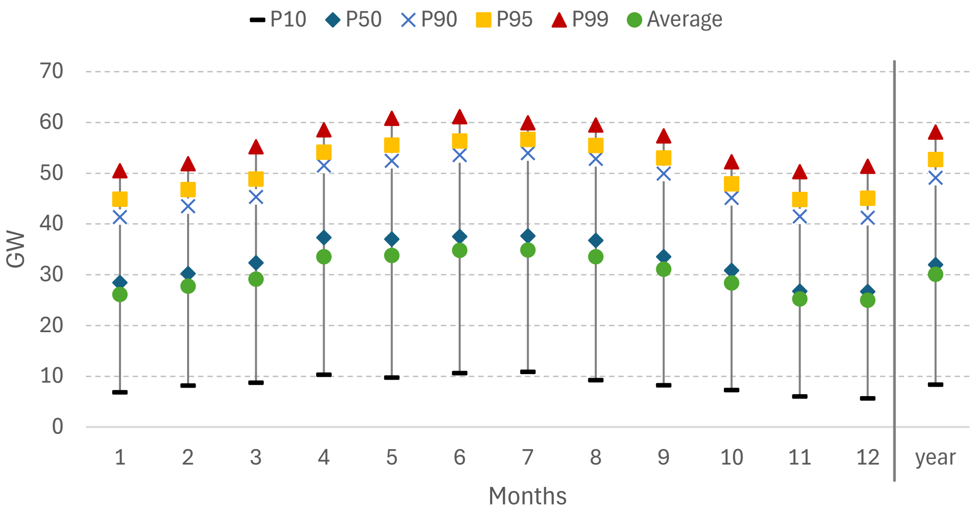

Figure 4 - System flexibility required for 7 hours (in GW)

The next graph (Figure 19) summarizes the system's requirements for different time steps in 2029. This overview is crucial for understanding which services the system will need and which technologies are best suited to provide them.

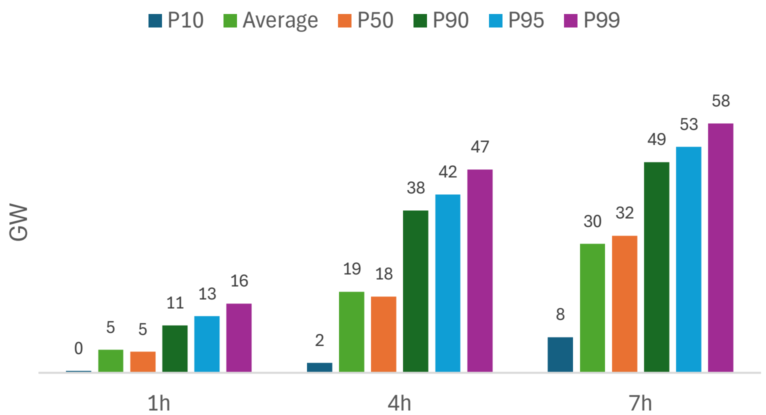

Figure 5 – System's flexibility requirements for different time steps (GW).

WHO PROVIDES FLEXIBILITY TODAY?

The available sources to fit the current needs of flexibility in Brazilian matrix are the dispatchable ones, e.g., hydro and thermal power plants. The thermal source is stable, provided it has the necessary fuel for generation and productivity is the same throughout the year. Some power plants are must-run while the other ones are dispatched combined with hydro power plants to match the necessary flexibility. The installed capacity for thermals in 2025 is 18.9 GW and its flexibility in 7h achieves 6.7 GW. The graph below shows the thermal flexibility according to the time requirements.

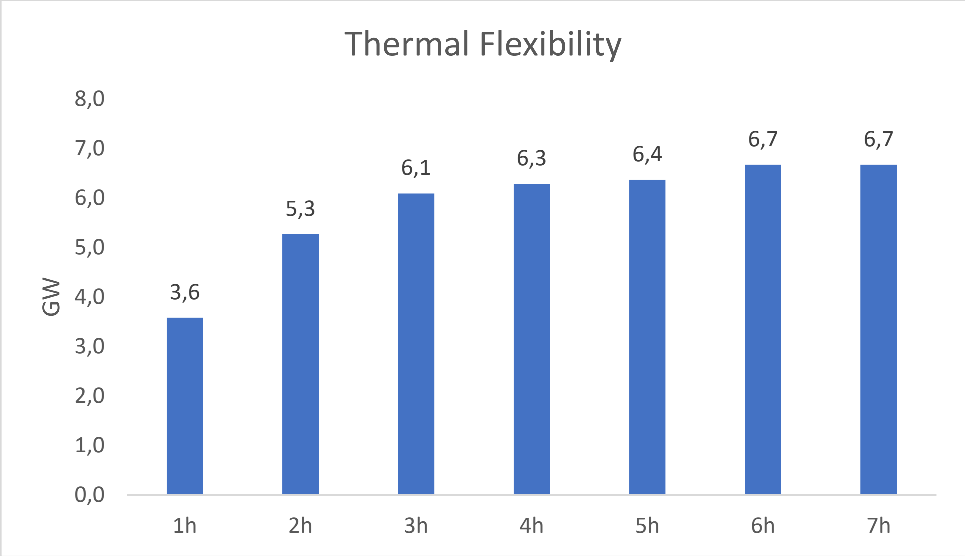

Figure 6 – Thermal flexibility capacity for different time steps (GW).

For hydro sources the situation is a little different. Their fuel is water, and productivity depends also on the reservoir levels. Some of the hydro power plants are run-of-river, while others are reservoir-based. For run-of-river plants, generation depends directly on the inflows, as they lack the ability to store water. Reservoir-based plants, on the other hand, can store water and operate more flexibly, but their productibility varies in accordance with the reservoir level. In Brazil, the dry and wet seasons significantly impacts the reservoirs levels, causing variations on the flexibility of hydropower plants throughout the year. As of 2025, the installed hydropower capacity is 108.1 GW, and its flexibility according to the time requirements is illustrated in the next graph[4] (Figure 7).

4 Values based on the maximum flexibility capacity registered in historical data.

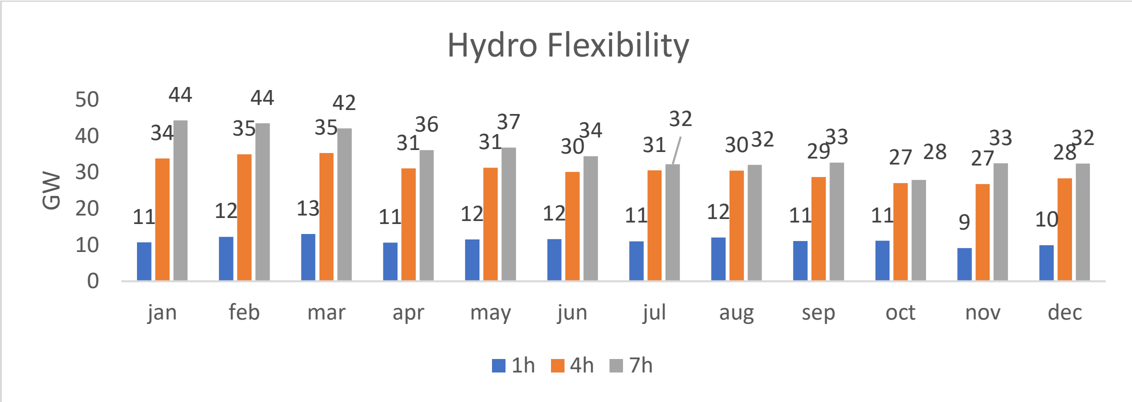

Figure 7 – Hydro flexibility capacity for different time steps and months (GW).

In summary, while hydropower and thermal plants continue to play a central role in meeting today's flexibility requirements, the structural transformation of Brazil's electricity matrix will increasingly demand complementary solutions. Future system reliability will depend not only on traditional resources but also on emerging technologies capable of delivering fast response and longer-duration services. Among these, energy storage systems (ESS) stand out as promising candidates.

The next chapter will therefore examine which storage technologies are best suited to address Brazil's evolving operational needs.

3. WHICH ESS TECHNOLOGIES ARE BEST SUITED FOR THE BRAZILIAN POWER SECTOR?

As seen, Brazil's power system is undergoing a significant transformation driven by the rapid growth of variable renewable energy sources such as solar and wind. To support this transition, ESS will play a fundamental role in ensuring system flexibility, reliability, and resilience. Among the broad range of storage technologies available globally and analyzed in detail in Annex 1, two stand out as the most promising for the Brazilian context: lithium-ion batteries and Pumped-Storage Hydropower (PSH).

These two technologies combine technological maturity, deployment experience, and cost competitiveness - key factors for short- to medium-term integration into the Brazilian grid. Lithium-ion batteries are particularly suitable for short-duration storage applications, offering fast response, modularity, and declining costs. PSH, on the other hand, is well suited for long-duration and large-scale storage, taking advantage of Brazil’s extensive hydropower expertise and topographic potential.

The comparative advantages of each technology are analyzed further in Annex 1, which provides a technical overview of the main storage technologies, including electrochemical, mechanical, chemical, thermal, and electromagnetic systems, along with their key parameters such as efficiency, discharge duration, response time, and investment costs.

From a system planning perspective, both lithium-ion and PSH are aligned with Brazil’s evolving operational needs, particularly for managing ramping events, but not only this: these technologies are also interesting, since they can help reducing curtailment of renewable energy (a matter that is at the core of several regulatory and market discussions nowadays), and providing ancillary services. The adoption of these two technologies is already being considered in regulatory discussions and even in the design of specific auctions for the technology[5], and they are expected to be the first to scale up in the country, even if on different time horizons, due, for example, to the difference between their implementation times.

However, the big question remains on what are the real benefits that these new technologies can provide to the system when compared with technologies already established in the Brazilian generation matrix.

HOW ESS CAN SUPPORT THE SYSTEM?

Short-term flexibility refers to the generator's ability to modulate its output - i.e., to perform controlled intra-day and intra-hour variations in power generation - to maintain the balance between supply and demand. This capability is essential for responding to rapid fluctuations in net load, especially in systems with high shares of variable renewable energy. Short-term flexibility ensures that the system can adapt to changes in generation and consumption patterns in real time, preserving reliability and operational stability.

Based on the figures shown in the previous section of generation and demand patterns, it is possible to compare the operation of the different solutions that can add flexibility, in terms of costs for the system. These costs, that do not include investment costs, are composed of the operating costs, the cost of energy deficits and the costs related to violation of some operative restrictions, mainly use of water restrictions.

The comparison of the system costs for meeting demand, will take into account four distinct scenarios: (i) a scenario called the Reference Scenario,

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[5] *Further details will be given in Chapter 4.*

which will consider the current configuration of electricity generation resources available to meet demand; (ii) a second scenario, called Scenario B, which will consider, in addition to the resources available in the Reference Scenario, an expansion of supply through a reference technology, that is already in operation in the Brazilian Power Sector and that should be eligible to participate in the next Capacity Reserve Auction[6] – gas-fired open-cycle thermal powerplants; (iii) the third scenario, called Scenario C, is similar to Scenario B, but the supply expansion will occur through a short-duration storage technology (batteries) rather than the reference technology; and (iv) the fourth scenario, called Scenario D, is similar to Scenario B, but the supply expansion will occur through a long-duration storage technology (pumped-storage hydro) rather than the reference technology.

The Reference Scenario is also based on the dataset from the February 2025 Monthly Operation Program, PMO, with the following enhancements incorporated:

- Hourly representation of demand.
- Considering that there is variability (both hourly and seasonal) in the availability of hydro, wind, and solar resources, an effort was made to capture this variability by simulating not just one, but 400 renewable generation scenarios.
- Reservoir operation guidelines established by the government's energy oversight committee (CMSE, *Comitê de Monitoramento do Setor Elétrico*), which define how water should be managed in key hydroelectric plants under different conditions.
- Operational restrictions on generation imposed by multiple water-use requirements.
- Historical generation ramp rates for each hydro plant.
- All power plants that do not have contracts in 2029 were removed from the dataset, emulating the need for new contracts or the need of expanding the electricity offer.

From this Reference Scenario, a simulation was carried out so that the generation resources should meet the hourly net demand (i.e., demand net of renewable generation), resulting in the dispatch profile and associated system costs for 2029, the last year of the dataset. The following chart

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[6] In accordance with the proposed guidelines for the two auctions planned for 2026. It is important to highlight that, as previously mentioned, the expansion of hydroelectric power plants was also considered an eligible technology for participation in the auction. However, it is observed that, out of the total of 11 products planned to be traded in both auctions, 8 are intended for gas-fired thermal plants, which reveals the prominent role the government reserved for thermal power, hence its selection as the reference technology in the analyses presented here.

presents the average generation of the 400 renewable generation scenarios, for each month and for each generation source for the Reference Scenario.

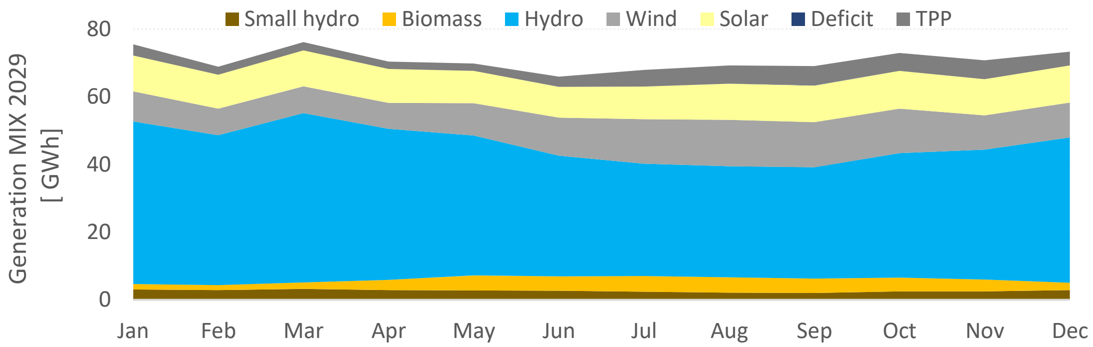

Figure 8 – Monthly generation mix: Reference Scenario.

An initial analysis of the graph above does not appear to reveal the existence of deficits — that is, a lack of resources to meet energy demand. However, as we examine more granular data (on a smaller temporal scale and moving away from average values to observe worst-case scenarios), we find that this is not the case. The following chart provides the deficits registered in the worst generation scenario of each month of 2029, in each submarket.

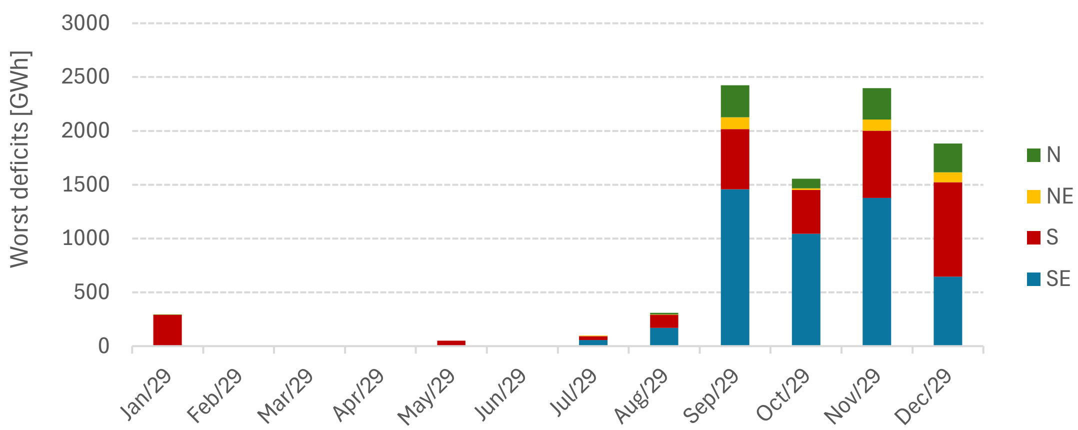

Figure 9 – Worst deficits per month and submarket.

Although the amount of non-supplied demand still seems small on monthly terms, the value is significant for some scenarios when analyzed on an hourly basis. Especially at the end of the dry season in the main basins of the system, starting in August. Figure 10 shows the maximum deficit for each hour of each month, considering the 400 renewable generation scenarios. This chart shows clearly that the worst deficits occur at night; however, deficits can also be observed during the day.

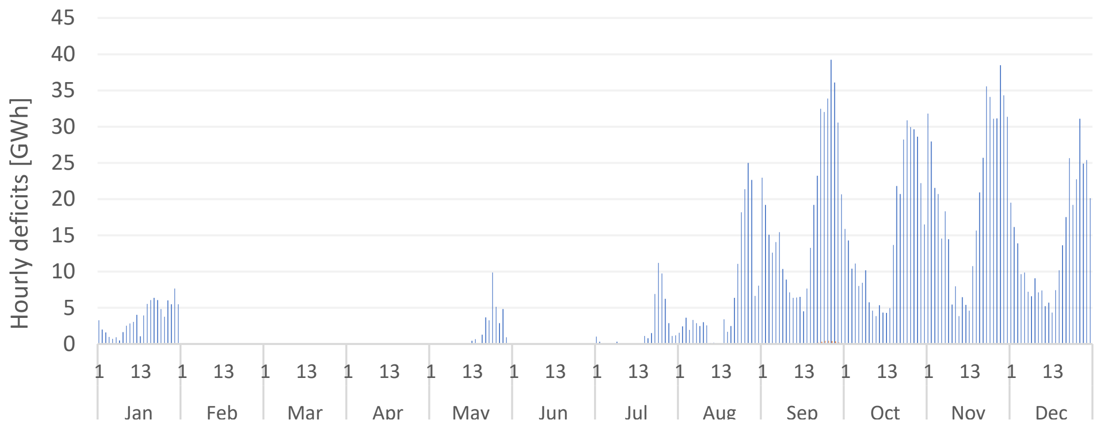

Figure 10 – Worst hourly deficits for each hour of each month of 2029.

In the case of energy deficits, the main generation source (hydro) is affected by severe inflows in such way that, even with the entire generation resources dispatched, it is not possible to entirely supply the load. In this case, there is a need for new plants with firm generation.

In the case of flexibility/capacity deficits, there are not enough generating units to meet the energy demand at some hours of the day, even when there would be primary resources available; or, even when there are generating units, there are operational restrictions that prevent the dispatch of these plants according to the needs of the electrical system. In this case, short and medium duration storage solutions could be candidates, as well as flexible thermal power plants.

In the first alternative simulation scenario ("Scenario B"), 32 GW of flexible TPPs were added to the system, distributed across the four submarkets[7], with a variable unit cost of R$ 1,000/MWh[8]. It is important to highlight that even TPPs with a high variable cost can operate continuously, helping the system with different services: capacity, flexibility, operative reserve and, of course, energy production. Figure 11 shows the average mix of generation for the first sensitivity case.

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[7] This capacity was estimated considering the deficits in a continuous 10-hour period of the Reference Scenario.

[8] This variable cost is more expensive due to the fully flexible characteristic of the TPP – flexibility increases the uncertain in the dispatch, reflecting in more expensive fuel cost.

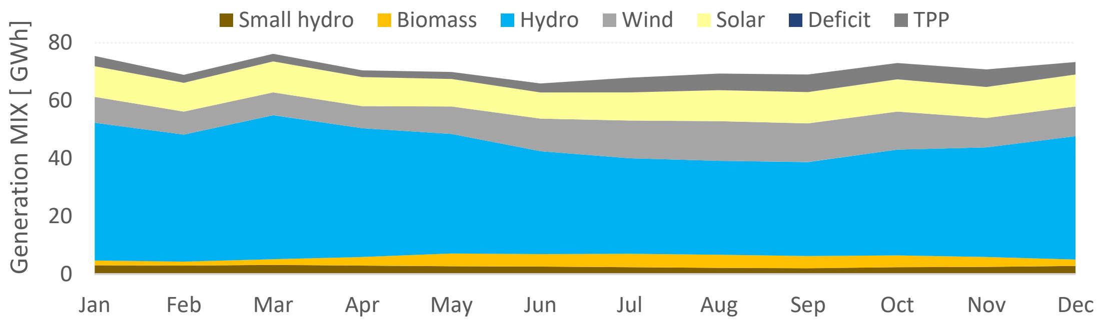

Figure 11 – Monthly mix generation: Scenario B.

The profile of the production remains almost the same as the Reference Scenario. However, there is an increase in the thermal dispatch and a reduction in both hydro production and deficits, reflected in the system costs presented below.

Table 1 – Comparison of average system costs for 2029 between Reference Scenario and Scenario B.

million R$	System Costs	Operative Cost	Deficit[9]	Others[10]
A – Reference Scenario	14,619	9,233	1,302	4,083
B – Scenario B	14,019	11,405	0	2,613
(B-A)	(600)	2,172	(1,302)	(1,470)

Table 1 shows the average system costs in 2029 composed of the operative cost (thermal dispatch cost), the cost of deficits and other costs for both simulations, and the difference between them.

It is possible to observe that there is no significant difference in system costs between Scenarios. However, in Scenario B the simulation considering the additional flexible TPP shows an increase in the cost of thermal dispatch followed by a reduction in the cost of deficits.

Aiming to analyze the energetic benefits provided by ESS and the impacts of its adoption into system costs, two additional scenarios were built replacing the flexible TPP by: 4-hour batteries ("Scenario C"); and 100-hours PSH ("Scenario D").

[9] *The cost of energy deficit is estimated by penalizing the deficits in the simulation by a high cost, which is updated annually by the Brazilian Energy Regulator (ANEEL) and that currently is R$ 8,327.76/MWh.*

[10] *Others, represent the costs of the violations of some operative restrictions, mainly use of water restrictions.*

The installed capacity of ESS was the same, 32 GW, divided into four submarkets. The costs resulting from all simulations are summarized below:

Table 2 - Comparison of average system costs for 2029 among all Scenarios.

million R$	System Costs	Operative Cost	Deficit[11]	Others
A – Reference Scenario	14,619	9,233	1,302	4,083
B – Scenario B	14,019	11,405	0	2,613
(B-A)	(600)	2,172	(1,302)	(1,470)
C – Scenario C	12,661	8,845	958	2,858
(C-A)	(1,958)	(388)	(345)	(1,225)
D – Scenario D	12,321	8,764	881	2,676
(D-A)	(2,298)	(469)	(422)	(1,407)

Compared to the Reference Scenario, the introduction of the 4-hour batteries reduced the system costs, on average, by R$ 1,958 million (a 13% reduction) in 2029. The 100-hour PSH reduced even more the average system costs (R$ 2,298 million, almost 16% lower than the initial value) in 2029.

However, despite the cost reductions, when compared to the Reference Scenario with TPP, all simulations with ESS presented deficits. This occurs because energy storage systems do not have the capacity, on their own, to generate energy continuously, as is the case with flexible thermal plants that have fuel availability. This indicates that those deficits are due to a lack of energy and not flexibility or capacity. So, to avoid all kinds of deficits, additional resources should be included in the system whether it is firm energy generation and/or seasonal energy storage systems.

In summary, the analyses conducted so far show that ESS are a technology that should be considered as a candidate resource for the system's expansion as they can, combined with firm energy generation, contribute to meeting demand at lower system costs.

As already seen, Brazil needs resources capable of providing flexibility to the system, and energy storage systems — due to their ability to provide this and other necessary services — should also be considered as candidate technologies in the expansion of supply. Therefore, the next questions that

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11 As the occurrence of energy deficits is undesirable, a penalty function can be incorporated into the mathematical model of hydrothermal dispatch in the objective function of the problem whenever there is a deficit. With this, the problem of hydrothermal dispatch becomes that of minimizing the operating cost plus the cost of penalizing the energy deficit over the entire planning horizon. Currently, this value is unique, regardless of the depth of the deficit, and is updated annually by Aneel.

should be addressed are: do these technologies already face economic and regulatory conditions to enter the system?

4. ARE ESS ECONOMICALLY VIABLE IN BRAZIL?

Despite the potential for ESS to play a relevant role in all segments of the sector, from generation to transmission, distribution, and consumption, in Brazil these technologies are still in their early stages, with limited applications. Below we provide some specific examples of battery deployment in the Brazilian Electric System:

1. **Forte de São Joaquim Hybrid Thermal Power Plant – Generation asset:** Contracted through an auction to supply energy to isolated systems[12] as part of a hybrid solution consisting of a biofuel thermal plant, a photovoltaic power plant, and a battery storage system. The plant was expected to begin operations in August 2025.
2. **ISA Cteep Energia Brasil – Transmission Asset:** A 30 MW battery storage system with a discharge duration of 2 hours (60 MWh) installed at the Registro substation in São Paulo state, as part of the transmission infrastructure. The investment is remunerated through a fixed annual revenue defined by the regulator, amounting to US$ 4.680.000 per year, which includes an O&M revenue of 2% of the investment.
3. **COPEL – Distribution Asset in a R&D context:** A 1 MW storage system with a capacity exceeding 1 MWh, composed of lithium batteries, a power converter, a transformer to increase voltage levels, and connection and protection devices. The system is connected to the grid to strengthen the network during peak demand periods and ensure power supply in case of outages. This initiative is part of a Research and Development program coordinated by the National Electric Energy Agency (ANEEL).

In addition, some specific applications are also emerging as viable. As an example, it is worth highlighting the auction to supply certain isolated systems in the Northern region of the country, that took place last

12 The term "Isolated System" refers to an electrical system that, in its normal configuration, is not connected to the National Interconnected System (SIN). Currently, there are about 200 isolated locations in Brazil, mostly in the Northern region.

September, in which the winning projects consist of hybrid power plants (thermoelectric + photovoltaic) with battery systems[13].

Also, there are also studies that indicate the economic feasibility of applying batteries in certain specific cases. For example, one of the Study Notebooks of the Ten-Year Expansion Plan 2035, published by the Energy Research Company (EPE, in Portuguese), points to the feasibility, under specific circumstances, of using behind-the-meter batteries as a substitute for diesel generation used by regulated consumers during peak hours to reduce costs.

This limited development of ESS in Brazil, as will be seen, can be explained by two factors: (i) market conditions and taxation still do not make storage systems economically viable in the country in a broader sense; and (ii) the lack of adequate regulatory treatment for these technologies creates barriers for their integration into the system. The latter topic will be discussed in the next chapter.

When it comes to a broader use of ESS, price arbitrage is one of the primary applications in the power sector, enabling energy optimization by storing electricity when prices are low and dispatching it when prices are higher. The effectiveness of arbitrage depends on the magnitude of price variations throughout the day.

The table below uses the cost estimates for ESS presented in Annex 1 as a reference to estimate the daily average energy price differences required for the asset – whether a battery or a pumped storage plant — to become economically viable, considering only revenues from price arbitrage.

Table 3 – Average Energy Price Differences required for remunerating an ESS, according to its CAPEX.

Technology	Scenario	CAPEX Range (US$/kW)	Average Energy Price Differences (US$/MWh)[14]
Utility-scale lithium-ion battery (4-hour)	NREL (2024)	1,250 – 2,000	152
	Thundersaid (2023)	876	72
	Brazilian Price quotation[15]	1,020 – 1,380	112

13 According to the 'Auction Report', released in September 2025: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-856/Informe%20Vencedores%20SISOL%20v2%201.pdf

[14] *Considering a 100 MW battery and a 1000 MW pumped storage plant.*

[15] *This quotation was obtained based on interactions with market agents.*

Pumped Storage Plants	NREL (2024)	2,970 – 4,500	161
	Thundersaid (2023)	2,250	100
	EPE (2025)	1,200 – 1,600	65

Using batteries as an example, it is estimated that for a battery storage system to be economically viable in Brazil – considering investment, operation, and maintenance costs – in average, it would be necessary a price daily average difference between US$ 72 and US$ 152 per MWh sustained for four hours per day, considering a lifespan of 15 years.

For pumped storage plants, performing a similar exercise while accounting for the specific characteristics of this technology shows that, in average, it is required a daily average difference between US$ 65 and US$ 161 per MWh sustained for eight hours per day, assuming a 40-year lifespan. It is important to highlight the significant uncertainty regarding installation costs in Brazil, given the numerous factors that influence the costs of power plants, including: installed capacity (MW) and duration (hours); the construction of longer or shorter tunnels and the head height; the use of an existing reservoir and the size of new reservoirs to be built; and the type of rotation (fixed or variable).

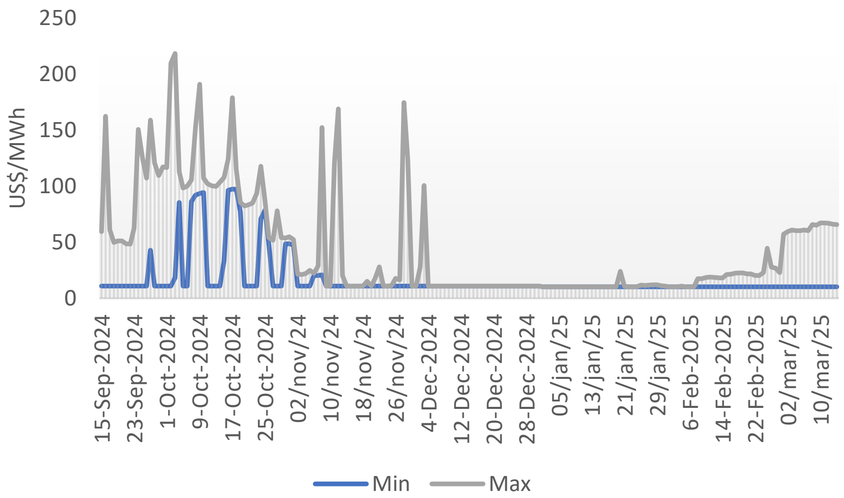

Figure 12 - Price Variation in the Spot Market (15/march/2024 - 14/march/2025) Source: CCEE

However, based on the current price formation model in Brazil, which is calculated on an hourly basis, there is low price granularity throughout the days. Additionally, the remuneration through price arbitrage is limited by the difference between the minimum spot price (referred to as PLD_{min}) and the maximum spot price (referred to as PLD_{max}), whose values in 2025 were set at US$ 10,24/MWh and US$ 269.50/MWh, respectively. The chart below illustrates the maximum and minimum price variations over a six-month period (from September 15, 2024, to March 14, 2025). During this period, the average spread was US$ 29.

Therefore, it is crucial to explore other potential revenue sources to make these technologies economically viable given their ability to provide different services (revenue stacking). In this regard, capacity remuneration and ancillary services are mentioned as potential revenue streams for these technologies in Brazil, as well as revenues related to other applications such as services for end-users.

The following figure shows, for an example of illustrative nature, the importance of revenue stacking. It is only through the sum of revenues arising from the provision of different services that the ESS in the example is able to cover its costs (capital costs, operation and maintenance, and taxes).

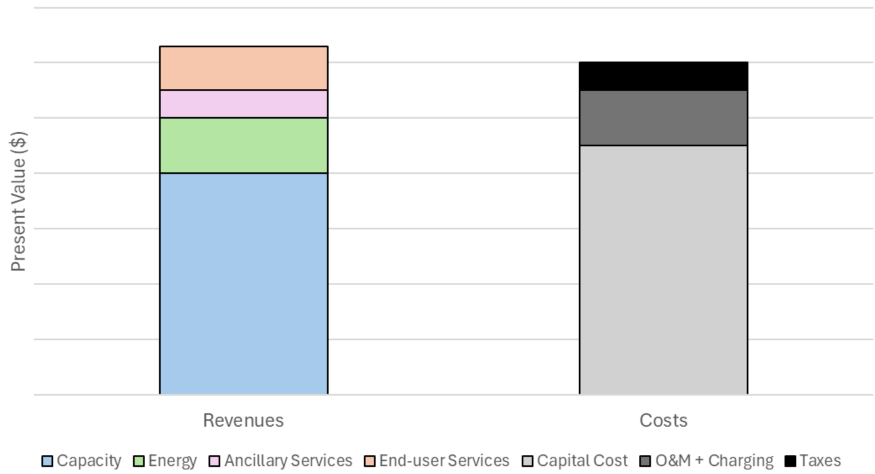

Figure 13 – Comparison between revenue streams related to the range of services an ESS can deliver and its costs.

Regarding capacity remuneration in Brazil, the Ministry of Mines and Energy has proposed holding a dedicated auction for the procurement of battery storage systems to ensure capacity availability. The auction was originally expected to take place in 2025; however, its definition was delayed, and it is now anticipated that the auction should take place in 2026. Nevertheless, some preliminary guidelines have already been presented:

- Supply period of 10 years, starting in 2029;
- Delivery of maximum power for 4 hours daily, as requested by the National Electric System Operator (ONS);
- Systems must have a minimum power availability of 30 MW;
- Developers will receive a fixed annual revenue, paid in 12 monthly installments, which may be reduced by 1% to 30%, based on the project's performance and compliance with dispatch commitments;

- Dispatch and charging will not be managed by the agent, but by the System Operator, so there will be no revenues from price arbitrage.

So far, there has been only one specific auction for capacity contracting, in which only thermal power plants were eligible to participate. In this context, the average Fixed Revenue was US$ 144/kW per year, with a 15-year contract and the supply start scheduled for 2026.

As seen, a storage asset cannot be made viable today in Brazil solely through price arbitrage revenues — it is necessary to enable these assets to capture other sources of revenue. In this regard, regulation plays a fundamental role. We will explore this topic, as well as other recommendations, in the following chapter.

5. HOW CAN REGULATION SUPPORT ESS INSERTION IN THE COUNTRY?

THE CURRENT STATE OF AFFAIRS

Since October 2023, the National Agency of Electric Energy (ANEEL), the Brazilian Regulator, has been discussing the implementation of an energy storage regulatory roadmap aiming at creating the regulatory foundation for a broader implementation of ESS in the country. The process has been structured into three discussion cycles, with completion expected by 2027:

- **1st Cycle:** Focus on foundational issues, including conceptual definitions, concession rules, grid access and usage, and remuneration models, covering both battery storage and closed-loop pumped storage.
- **2nd Cycle:** Emphasis on open-loop pumped storage hydropower plants and the development of regulatory sandboxes to enable value stacking, which is crucial for the economic feasibility of storage in the generation system.
- **3rd Cycle:** Exploration of aggregators for various services and the development of new business models, such as storage applications to mitigate curtailment and constrained-off situations.

The first cycle was initially expected to be concluded in the first half of 2025; however, due to delays, it was not completed yet. When concluded, this cycle will allow progress in energy storage technologies through the definition of concession processes, connection costs, and revenue sources. Revenue sources remain one of the key discussion points in this phase, and even with the proposed developments, this issue still presents numerous uncertainties.

Although stacking revenue streams is supported, the Agency has not provided detailed explanations on how this capability to accumulate multiple revenue sources will be enabled.

In the context of allowing ESS to provide other services to the system such as ancillary services, a regulatory "sandbox" is planned for the procurement of reactive power support services for voltage control, with no technological restrictions, although no specific date has been set for its implementation. Currently, this service is predominantly provided by thermal and hydropower plants. The goal of this approach is to enable the inclusion of various technological solutions, fostering greater competitiveness and innovation, as well as facilitating the integration of storage systems with existing infrastructure. At present, this service is compensated through a regulated tariff, with the applicable rate for 2025 set at US$ 1.72 /Mvar-h. However, within the scope of this sandbox, both the value and the method of remuneration will be reviewed.

In addition to reactive power support services, there are expectations for regulatory sandboxes to be created for other ancillary services, such as secondary frequency control and black start. Under the current regulation, the agents providing these services, primarily hydroelectric plants, receive a fixed remuneration of US$ 11,735 and US$ 8,801 per year.

These advances in the regulatory front are important for allowing the revenue stacking to become a reality for ESS. However, in order to establish a regulatory framework that enables the integration of ESS in a sustainable and beneficial way for the system, PSR believes that additional steps must be taken. We will present these in the following section.

Finally, aside from the regulatory discussions, another point relevant for the economic viability of storage technologies is the taxation. There is a high tax burden on storage assets compared to traditional generation sources. While solar and wind assets received tax incentives in the past, current tax rates, as shown in Figure 13, may act as a disincentive to investments in batteries in Brazil. On average, it is estimated that costs increase by 76% after taxes are applied. This discrepancy in comparison to solar and wind sources is due to the lack of tax incentives for storage.

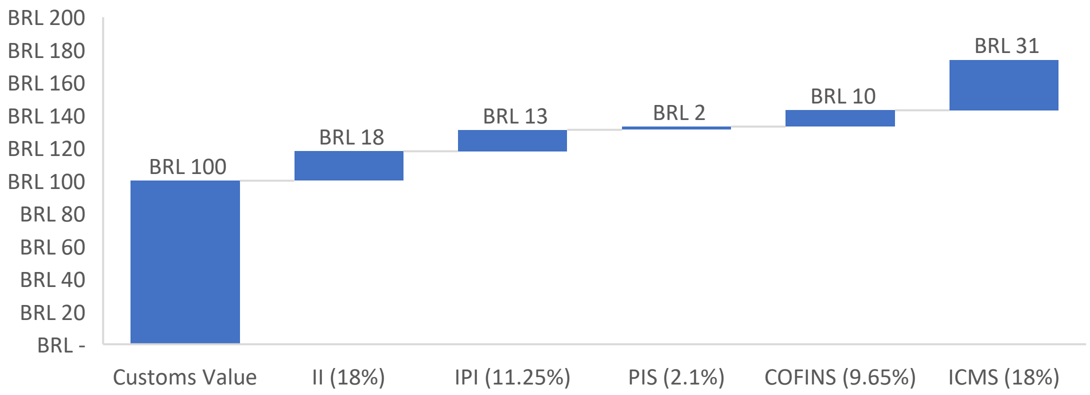

Figure 14 - Tax effect on the price of an imported lithium battery system (example based on BRL 100).

Brazil has the Special Regime for Incentives for Infrastructure Development ("REIDI"), aimed at reducing the tax burden on infrastructure projects. Participation in this regime suspends the requirements for PIS and COFINS contributions on the acquisition, leasing, and importation of goods and services – however, an update to Law No. 11,488/2007, which established this mechanism, may be necessary to include energy storage. Additionally, for a storage project to be eligible under this regime, it must undergo an approval process with ANEEL, which may present an additional obstacle to implementation.

In terms of environmental license, pumped storage plants are the most sensitive, as there is currently no specific regulation for them, despite expectations that the licensing process for a PHS plant will be similar to that of conventional hydroelectric plants. Consequently, the environmental licensing of hydraulic works for hydropower generation exceeding 10 MW requires the preparation of an Environmental Impact Study (EIA) and an Environmental Impact Report (RIMA), in accordance with Conama Resolution 01/86.

ACTIONABLE INSIGHTS

Based on the considerations presented so far, it is possible to draw some important conclusions regarding the integration of storage technologies into the Brazilian electricity sector.

- Brazil currently has limited participation of storage technologies: this, however, is not due to a lack of system need for the attributes they can provide. As an example, this study demonstrated with simulations how ESS can contribute to support the flexibility needs of the system.

- Among the various available storage technologies, those that show the highest maturity and most competitive costs for the power sector are lithium-ion batteries and PSH:
    - Lithium-ion batteries are ideal for short-duration applications of up to four hours, offering fast response, modular deployment, and falling costs[16].
    - PSH, in contrast, is best suited for long-duration and large-scale storage, leveraging Brazil's geographic potential and extensive experience in hydropower development.
- From a system perspective, both lithium-ion and PSH are fully aligned with Brazil's evolving operational needs - particularly for managing ramping events. However, their value extends beyond this: these technologies can also help reduce renewable curtailment (a growing concern in current regulatory and market discussions) and provide ancillary services, contributing to greater overall system efficiency.

Despite this potential, these solutions still face significant structural barriers to their large-scale development in Brazil. Based on the economic and regulatory analyses conducted, three main areas of concern were identified:

1. **<u>Unfavorable Tax Regime:</u>**

The Brazilian tax structure disproportionately penalizes storage technologies, especially batteries. Unlike other technologies, storage systems do not fit neatly into existing categories of generation, transmission, or distribution - which limits access to fiscal incentives and infrastructure support programs.

- **REIDI:** The REIDI - Brazil's main incentive program for infrastructure projects — currently does not include storage technologies, as they are classified neither as generation nor as transmission asset. An explicit inclusion in this framework is needed so that ESS can benefit from this regime.
- **Import Duty:** Technologies such as solar photovoltaics benefited from import duty exemptions to support early market development, but this incentive ended in 2023. Since then, import tariffs have increased — initially to 9.6%, then to 10.8 % in 2024, with import quotas established. In November 2024, Gecex Resolution No. 666 raised the rate further to 25%, significantly increasing the cost of imported equipment. Specifically in relation to BESS, stakeholders have raised concerns about its classification under the *Nomenclatura Comum do*

[16] The expected cost reduction is discussed on several technical references. In this report we mention two references: BloombergNEF (2023) and PNNL (2022).

Mercosul (NCM), a standardized tariff code system used across Mercosur countries to determine customs duties and import tax rates. Depending on the assigned NCM code, the applicable *alíquota* (import tax rate) may vary, directly affecting the project's cost structure and competitiveness.

- **ICMS (State Value-Added Tax):** This is the most significant state-level tax affecting project costs in the electricity sector. Exemptions or incentives for storage technologies depend on agreements approved by CONFAZ (National Council for Fiscal Policy), which brings together the federal government and the finance secretaries of all states and the Federal District. CONFAZ's main role is to coordinate tax policy across states, particularly with respect to ICMS, by approving agreements on exemptions, incentives, and harmonized rules.

These tax distortions directly affect the upfront cost and competitiveness of storage projects and underscore the need for targeted fiscal reforms to level the playing field.

2. **Inadequate Remuneration and Absence of Revenue Stacking Mechanisms**

Historically, energy sources in Brazil have been remunerated solely for the energy supplied to the system. However, storage technologies have a distinct operational profile, they consume energy during low-demand periods and deliver it back when the system needs it most. Their economic value therefore lies in time-shifting energy and providing flexibility, capacity, and grid support services. The current regulatory framework must evolve to properly recognize and remunerate these attributes:

- Capacity: Law No. 14,182/2021 established the possibility of capacity auctions with fixed remuneration. However, to date, only thermal plants have been contracted. Including storage technologies will require discussion on grid connection procedures, licensing requirements, and authorization models — issues that are directly linked to the regulatory roadmap currently under development by ANEEL.

- Ancillary Services: Existing regulations were designed for a predominantly hydro-based and dispatchable system. With the growing share of variable renewables, there is a pressing need to update the rules and contracting mechanisms for ancillary services, where storage can play a key role.

- Flexibility: Flexibility remains an unrecognized attribute in Brazil's current regulation. Explicitly defining and valuing this attribute will be essential for enabling fair market participation and for incentivizing investment in storage assets.

The absence of clear mechanisms for capacity, ancillary services, and flexibility remuneration limits the economic viability of storage projects. Developing a comprehensive revenue framework is critical to unlock private investment and enable large-scale deployment.

3. **Environmental Licensing**

Environmental licensing poses a specific challenge, particularly for PSH projects, whose hybrid nature resembles conventional hydropower plants. In Brazil, new hydropower projects have faced increasing social and regulatory resistance, making it essential to develop differentiated licensing criteria for PSH.

- Open or Semi-Open Loop PSH, which use existing reservoirs or natural water courses, tend to cause greater interference in water bodies and may therefore require more extensive environmental impact assessments and longer licensing processes.
- Closed-Loop PSH, which operates with two artificially isolated reservoirs, have significantly lower environmental impacts because they do not alter river flow regimes or affect aquatic ecosystems. As such, it is recommended that these projects benefit from streamlined and differentiated licensing procedures, recognizing their limited environmental footprint and high systemic value.

Establishing tailored environmental licensing procedures for PSH — particularly for closed-loop systems — is essential to reduce project risks, shorten approval timelines, and enable Brazil to leverage its hydropower expertise for a new generation of low-impact storage assets.

Given these points, it is essential to define a strategy for the coming years. In this regard, key steps have been outlined for the period from 2025 to 2028, focusing on short-term actions and on the entities responsible for implementing them. These items are classified as high, medium, or low priority for unlocking the integration of storage technologies in Brazil.

1. September/2025 - June/2026

Who and What?	Why?	Priority Level	Status
ANEEL: Completion of the 1st cycle of the roadmap, defining concession rules, grid access and usage, and remuneration models,	Relevant to the upcoming capacity reserve auction announced by the government and for other initiatives	High	**Completed** – Approved on August 14, 2025

covering both battery storage and closed-loop pumped storage	related to storage solutions.		
MME: approval of guidelines for the capacity reserve auction, including not only batteries but also PSH.	Including PSH would enhance competitiveness in delivering the services the system needs. This is possible due to the maturity of both technologies.	High	**On Hold** – Awaiting MME's final decision after the analyses of contributions presented in the Public Consultation.
ANEEL: Start of public participation in the auction bidding process	Considering the estimated date for the auction in 2026, it is important that the discussion process is completed ahead of time to ensure everything stays on track.	High	**On Hold** – Awaiting the auction guidelines

2. July/2026 – December/2026

Who and What?	Why?	Priority Level	Status
MME and Ministry of Finance: Inclusion of storage technologies in Ordinance No. 318/2018, which defines the technologies considered in the REIDI	This would help reduce the cost of these technologies, given the high tax burden, particularly PIS/COFINS.	High	**Under Discussion –** On the agenda of the MME
CCEE/ANEEL/MME: Execution of a specific LRCAP (Capacity Reserve Auction Process) for storage.	This will ensure the realization of the planned auction agenda, even though demand for storage may not be very high in the first phase.	High	**Under Discussion –** Proposal submitted under MME Public Consultation No. 176/2024, but still

			without definitions
ONS: Initiating a sandbox for contracting reactive support ancillary services through a competitive mechanism.	A mechanism to test the participation of other technologies, such as storage, in the provision of ancillary services.	Medium	**Approved** – Waiting for ONS to proceed with the matter
IBAMA/ANEEL/ANA: Discussion regarding environmental issues involving reservoirs in pumped storage hydropower plants (PSH).	Environmental concerns have been a recurring topic, and it is essential to address these issues to ensure the sustainable development of PSH plants.	High	**Not started** – ANEEL indicated the need for joint discussion, but no progress has been made.

3. January/2027 – June/2027

Who and What?	Why?	Priority Level	Status
ANEEL: completion of the second cycle of the roadmap with the publication of regulations for open-cycle and semi-open cycle PSH plants.	This step is crucial to enable the inclusion of PSH plants beyond those with a closed cycle, expanding the options for energy storage and grid balancing.	High	**Planned** – Proposed by ANEEL in its roadmap
ANEEL: promotion of discussion on the application of Storage as a transmission and distribution asset	This point is fundamental to enabling the maximization of battery applications.	High	**Planned** – Proposed by ANEEL in its roadmap
ANEEL: Adjustment of the ancillary services regulation (REN 1,030/2022).	Adopting a capacity-based approach to deliver what the system needs, without restriction by technology.	Medium	**Not formally included –** A next step following the results of the sandboxes already planned.

4. July/2027 – December/2028

What?	Why?	Priority Level	Status
ANEEL: completion of the third cycle and publication of the roadmap and resolution.	Important in the context of using batteries as a mechanism to reduce energy curtailment, a crucial topic with significant impact on the Brazilian electricity sector.	High	**Planned** – Proposed by ANEEL in its roadmap
MME and/or ANEEL: creation of incentives for battery installation in UCs with Micro and Mini Distributed Generation (MMDG)[17].	Focusing on the use of storage systems for end consumers as a way to better integrate MMDG into the grid.	Low	**Not planned – However, it has been a mechanism applied in international experiences.
ANEEL/CCEE: review of price formation	Greater granularity in price formation, not only on an hourly basis. Another key point is the review of the minimum and maximum spot prices.	Medium	**Preliminary Discussions** – CCEE has been conducting studies on the topic[18].
MME: creation of a mechanism to incentivize the conversion of existing hydropower plants (UHEs) into pumped hydro plants.	Similar to the mechanism implemented in Portugal, where compensation could be provided through the extension of the concession period.	Low	**Not planned** – However, it has been a mechanism applied in international experiences as a way to leverage existing hydroelectric resources.

[17] *Broadly speaking, MMDG is the generation connected to the distribution network with an installed capacity of up to 5 MW.*

[18] *https://www.meta2formacaodepreco.com.br/*

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7. ANNEX 1: DETAILED REVIEW OF ESS TECHNOLOGIES

ESS can be classified according to the type of storage, divided into five main categories. The table below shows these types and some examples of these technologies.

Table 4 – Review of storage technologies.

Technology	Definition	Examples	
Electrochemical Energy Storage	Systems that store energy through chemical	Conventional batteries	**Lithium-ion batteries Lead-acid batteries, Nickel-cadmium batteries**

	reactions, converting electricity into chemical form and releasing it as electricity when needed	High temperature batteries (systems that operate at a high nominal temperature where, during discharge, sodium is oxidized, forming ions that later combine with the positive electrode)	**Sodium-Sulfur (NAS) Batteries** **Sodium-Nickel-Chloride Batteries**
		Flow batteries	**Redox Flow Batteries (RFB)**
Mechanical Energy Storage	Systems that use gravity, acceleration or compression to store kinetic energy.	**Compressed Air Energy Storage (CAES)** stores energy by using electricity to compress air at high pressure. When needed, the compressed air is released to drive a turbine and generate electricity.	
		Flywheel Energy Storage (FES) stores energy as kinetic energy in a high-speed rotating mass (flywheel). The flywheel is connected to an electric machine that acts as a motor to store energy and as a generator to release it into the system.	
		Pumped Storage Hydro (PSH) is a hydropower plant with two water reservoirs at different elevations. During low demand, water is pumped to the upper reservoir, storing energy. During peak demand, water is released back down through turbines, generating electricity for the grid.	
Chemical Energy Storage	Systems that use electricity for a chemical process to produce fuel, storing energy in chemical bonds, which is released during combustion.	Hydrogen, ammonia, synthetic fuels, drop-in fuels, and methane.	The simplest charging process is water electrolysis to produce **hydrogen**, which can be stored in compressed or liquid gas tanks to adhering to porous materials.
Thermal Energy Storage	Systems that use electricity to store thermal energy in a carrier, which can later be converted into electricity or	The most widespread thermal energy storage technology is the **molten salts-based solution**. These systems allow thermal energy to be stored in salts and later extracted through a stream cycle.	

	used as direct heat.	
Electrical and Magnetic Energy Storage	Systems that store energy directly in electric or magnetic fields, requiring an initial energy supply through a current flow, similarly to batteries.	**Capacitor:** consists of two electrodes separated by a dielectric material. In an external electric field, the dielectric forms electric dipoles, which are stationary charge pairs and do not generate a current.
		Supercapacitor: the metallic or carbon electrodes are immersed in an electrolyte liquid with ions that resist losing charge. The electrode releases or captures electrons, creating a potential difference. A thin charge layer of opposite sign forms on the electrode surface, resulting in much higher capacitance than a traditional capacitor.
		Superconducting storage system: consists of superconducting coils, a cryogenic cooling system, and an inverter. Energy is stored in the coil's magnetic field through current flow. When discharged, the magnetic field generates a current, supplying electricity into the grid.

Each of the technologies presented here, due to their structural characteristics, has different types of applications and advantages and limitations that are well documented in literature.

- Electrochemical storage: these systems are known for their high energy density, fast response times and high efficiency. Depending on the size of the system, the discharge duration can range from minutes to days. Particularly for the Lithium-ion batteries, they possess high energy and power density and high roundtrip efficiency, making them the most used system in short-duration applications (4 hours or less). One of the main advantages of this ESS is the modular design, that allows flexible deployment. However, the main limitations are related to the high costs due to critical materials like lithium, limited lifespan with capacity degradation over time and environmental concerns regarding battery disposal and recycling.
- Mechanical storage: these systems are the main reference when it comes to large-scale and long-duration storage applications. However, their energy density is much lower than the energy density of chemical or electrochemical technologies. Another advantage that is worth mentioning is the extremely long lifespan. The main limitations are

related to the topography dependency; the environmental impacts and the high cost for implementing the solution.

- Chemical storage: the main technical references consulted refer to hydrogen as the prominent energy carrier. The main advantages mentioned for this technology are the extremely high energy density, surpassing conventional batteries, the virtually unlimited storing time, with minimal energy losses and other applications beyond the electricity sector. However, the real role of hydrogen as energy storage for the power sector depends on its broader economic use, which is influenced by production, transportation and storage costs and innovation in end-use applications. Beyond the costs, other concerns regarding this type of chemical storage are related to low efficiency in energy conversion processes and the need for a specialized infrastructure for safe handling.
- Thermal storage: also suitable for long-duration storage, thermal storage can support concentrated power plants and cogeneration, or heating and cooling applications in buildings. The main advantages of this technology are the cost-effectiveness for large-scale storage, the long lifespan with minimal degradation and the compatibility with thermal power infrastructure. However, the main limitations are the low efficiency when converting heat back to electricity, the slow response times and the need of effective thermal insulation to minimize energy losses.
- Electrical and magnetic storage: this technology is suitable for short-term energy storage with ultra-fast response times. The literature mentions also as advantages the high efficiency and the long operational lifespan with minimal wear and tear. And as limitations worth mentioning are the limited storage capacity for long-duration applications, high costs associated with materials like superconductors and the need for extremely low temperatures for superconducting applications.

The table below summarizes the main technical features of the technologies mentioned. A detailed discussion regarding investment costs will be presented later.

Table 5 – Main technical features of storage technologies.

Technology	Capacity	Discharge duration[19]	Response time[20]	Conversion efficiency (approximately)	Lifetime (years)[21]
Lead-acid batteries	1kW-100MW	Minutes-Days	Milliseconds	85%	3-10
Lithium-ion batteries	1kW-100MW	Minutes-Days	Milliseconds	85%	5-15
Compressed Air	10MW-100MW	Hours-Weeks	Minutes	50%	20-40
Flywheel	10kW-5MW	Seconds-Hours	Minutes	85%	15+
Pumped Storage Hydro	500MW-5GW	Minutes-Weeks	Seconds to minutes	80%	40-60
Hydrogen	10MW-1GW	Hours-Months	Minutes	25%	5-30
Molten salts	1kW-300MW	Hours	Minutes to hours	40%	30
Supercapacitor	10kW-10MW	Seconds-Minutes	Milliseconds	90%	20+

The following image indicates the global composition of installed capacity by storage technologies in 2014, as estimated by IEA (2014). The data highlights the overwhelming dominance of PSH, which accounted for more than 90% of the total energy storage capacity, also due to its large proportions.

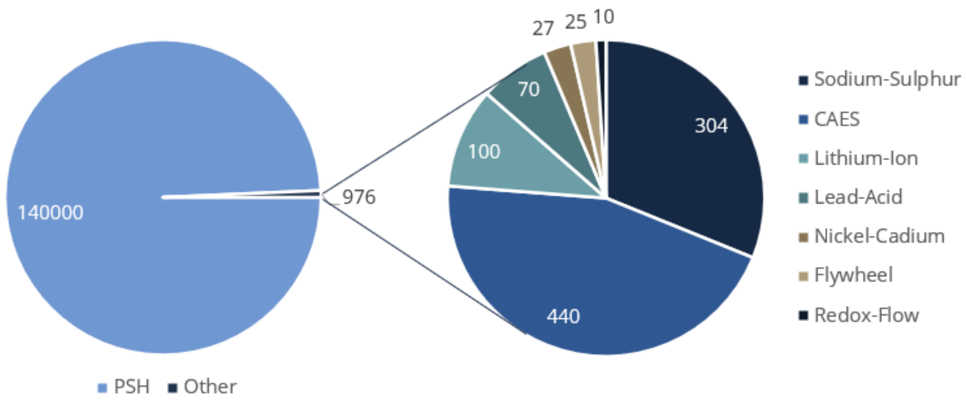

Figure 15 - Main energy storage technologies connected to the global power grid, in MW (Source: IEA, 2014)

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[19] *IEA (2015).*

[20] *European Commission (2020).*

[21] *World Energy Council (2020).*

In recent years, the installed capacity of PSH has grown to 180 GW. Additionally, there has been an exponential increase in lithium-ion battery capacity, which has become the dominant technology for utility-scale batteries and behind-the-meter batteries, which amount to an addition of 33 GW and 54 GW respectively[22]. This trend can be observed in the following figure.

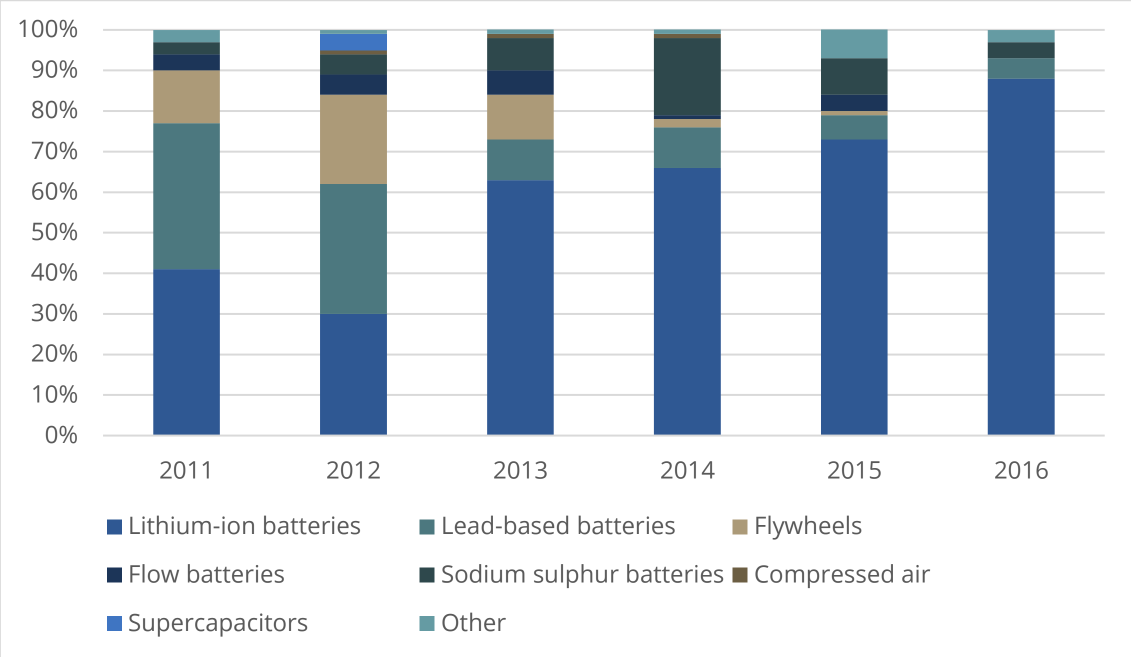


Figure 16 – Technology mix in storage installations excluding pumped hydro (Source: IEA, 2019).

This is due to both cost reductions and performance improvements[23]. Additionally, hydrogen is also mentioned by the International Energy Agency as an emerging technology that has potential for the seasonal storage of renewable energy.

The dominance of PSH and lithium-ion batteries can be explained by a combination of the level of maturity of both technologies and the investment costs.

MATURITY OF THE STORAGE TECHNOLOGIES

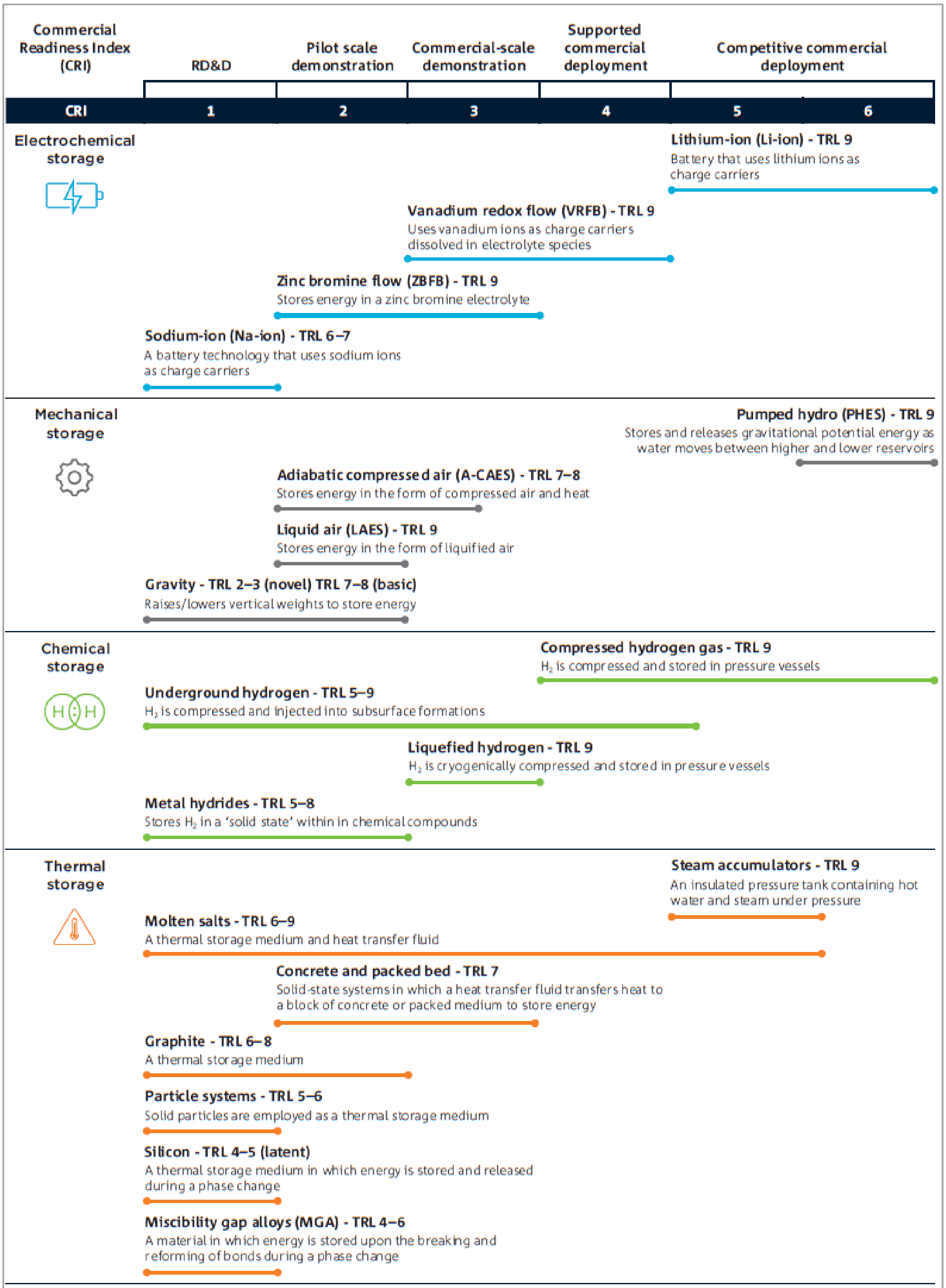
The next figure, taken from the Renewable Energy Storage Roadmap developed by CSIRO (2023), illustrates where different storage technologies fall within the Commercial Readiness Index (CRI) classification. This index determines a framework designed to assess the commercial maturity of emerging technologies. It is complementary to the Technology Readiness

[22] *IEA (2024a).*

[23] *IEA (2024b).*

Level (TRL) framework, which is also used to categorize the technologies in the figure and aims at assessing the maturity of a technology.

While the CRI considers commercial aspects of deployment, such as market demand, policy support, financing availability, supply chain maturity, and economic viability, the TRL focuses primarily on technical aspects. From the figure, it is worth highlighting the development stage of both lithium-ion batteries and pumped hydro storage, which stand out as the most advanced technologies among those evaluated within the CRI framework.



Notes: This diagram illustrates the technological readiness level (TRL)/commercial readiness index (CRI) reached for the end-use applications discussed in this roadmap and as of December 2022. For several technologies, TRL/CRI may differ based on the maturity of integration into emerging end uses. Terminology: RD&D, research, development and demonstration.

Figure 17 - Summary of Energy Storage Technology Maturity. Source: CSIRO (2023).

INVESTMENT COSTS

Total investment costs (CAPEX) in energy storage technologies can be measured in $/kW or $/kWh terms. The choice between $/kW and $/kWh depends on the storage technology and its intended application. Electrochemical storage systems, like batteries, are typically evaluated in $/kWh, as they are designed for energy storage over time. In contrast, mechanical storage technologies such as PSH, CAES and flywheels are often assessed in $/kW, as they prioritize power output. Ultracapacitors, despite being electrochemical, are also best compared in $/kW due to their short-duration, high-power discharge characteristics. In terms of cost-efficiency, technologies with higher energy-to-power (E/P) ratios (e.g., PSH and CAES) are more cost-effective when analyzed in $/kWh, whereas those with lower E/P ratios (e.g., ultracapacitors and flywheels) are better evaluated in $/kW.

Regardless of the unit of measurement considered, common sense in literature is that total CAPEX exhibits significant variability (EPE, 2025) (Mongird et al., 2019) (NREL, 2024) (PNNL, 2022). This dispersion stems from several factors, including differences in technology maturity, project scale, site-specific engineering and civil works requirements, and regional labor and material costs.

For example, PSH is a mature technology, with investment costs highly site-dependent, primarily due to the geological and topographical characteristics of each location, which heavily influence civil construction complexity and cost.

In the case of lithium-ion batteries, while costs have declined rapidly over the past decade and, as shown in Figure 22, are expected to decrease even further in the next decade due to economies of scale and advances in manufacturing, the literature still reports a broad range for utility-scale systems.

Figure 18 - Volume-weighted average lithium-ion battery pack and cell price split from 2013 to 2024 (real 2024 US$/kWh). Source: BloombergNEF (2023)

This variation is influenced by differences in battery chemistry, storage duration, depth of discharge, system integration requirements (such as power electronics and thermal management), and even the business model under which the technology is deployed.

Similarly, CAES systems, also a mature technology but less widespread, show also a wide cost range, depending on whether the storage is diabatic, adiabatic, or isothermal, and whether pre-existing geological formations can be used.

Therefore, when evaluating CAPEX across energy storage technologies, it is essential to account not only for this variability but most importantly for the contextual factors behind it. A simple comparison of unitary costs ($/kW or $/kWh) may be misleading without a clear understanding of the assumptions, scale, and use cases that underpin each estimate.

For example, when it comes to the specificities of the Brazilian Power Sector with a short to mid-term deployment perspective, the PSH and lithium-ion batteries stand out as the most suitable technologies to be developed[24]. The Brazilian potential for PSH development is huge and it can be leveraged on the large experience acquired with the construction of thousands of MW of hydro power plants. Lithium-ion batteries might have their debut in the Brazilian Power Sector earlier than PSH due to its maturity and rapid deployment, as well as expected (further) cost reduction in the near term.

Table 6 presents the CAPEX estimated by different sources for ion-lithium battery and pumped storage hydro plants, as these technologies have the most documented data available. PSH exhibits a wider range of investment costs, which is explained due to site-specific characteristics like topography and geology, project scale and design complexity, in addition to regulatory and environmental compliance requirements.

Table 6 - Capex variation of lithium-ion and pumped storage hydro

Technology	Scenario	CAPEX Range (US$/kW)
Utility-scale lithium-ion battery (4-hour)	NREL (2024)	1,250 – 2,000
	Thundersaid (2023)	876
	Brazilian Price quotation[25]	1,020 – 1,380

[24] Although CAES appears as one of the three most cost-effective technologies (CAPEX wise), it has some disadvantages as specific geological requirements, lower efficiency and design and operation complexity that place it as a "less interesting" alternative for Brazil, when compared to PSH and lithium-ion battery.

[25] This quotation was obtained based on interactions with market agents.

	PNLL (2023)	1,460 – 1,780
Pumped Storage Plants	NREL (2024)	2,970 – 4,500
	Thundersaid (2023)	2,250
	EPE (2025)	1,200 – 1,600
	PNLL (2023)	1,810-3,760

In order to compare the CAPEX of different storage technologies, we considered estimates derived from the *Grid Energy Storage Technology Cost and Performance Assessment* (PNNL, 2022), which were obtained from discussions with developers and industry stakeholders, literature, commercial datasets, and real-world storage costs of deployed systems across the United States.

The analysis was done for energy storage systems considering different combinations of power and energy duration, as shown in Figure 19. The power and duration were selected based on current and potential future applications for each technology. Additionally, some cases were included to enable comparisons between categories - for example, PSH and CAES are mainly used for long-duration storage, but a 4-hour duration is included to benchmark against other technologies.

Comprehensive cost estimates are presented for 2021, with projections extending through 2030 for each technology. The costs for 2021 and 2030 are presented in Figure 20 and Figure 21, respectively.

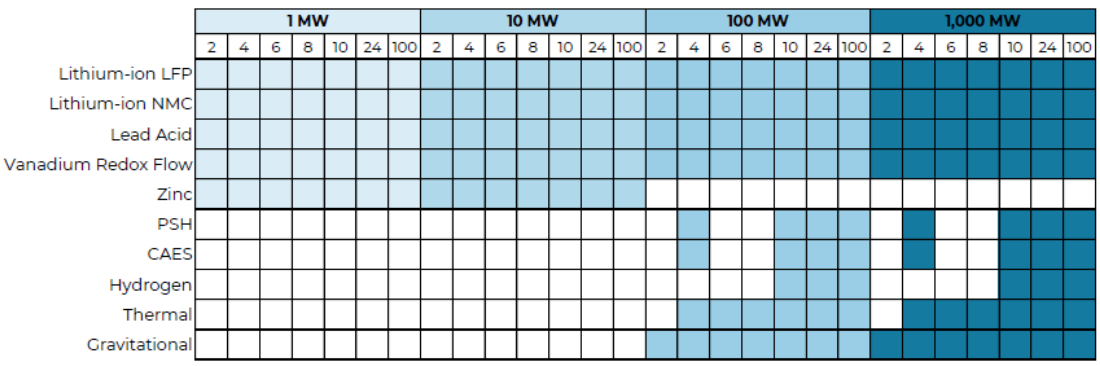


Figure 19: Power Capacity (MW) and Energy Duration (hour) considered for each storage technology. Source: PNNL (2022).

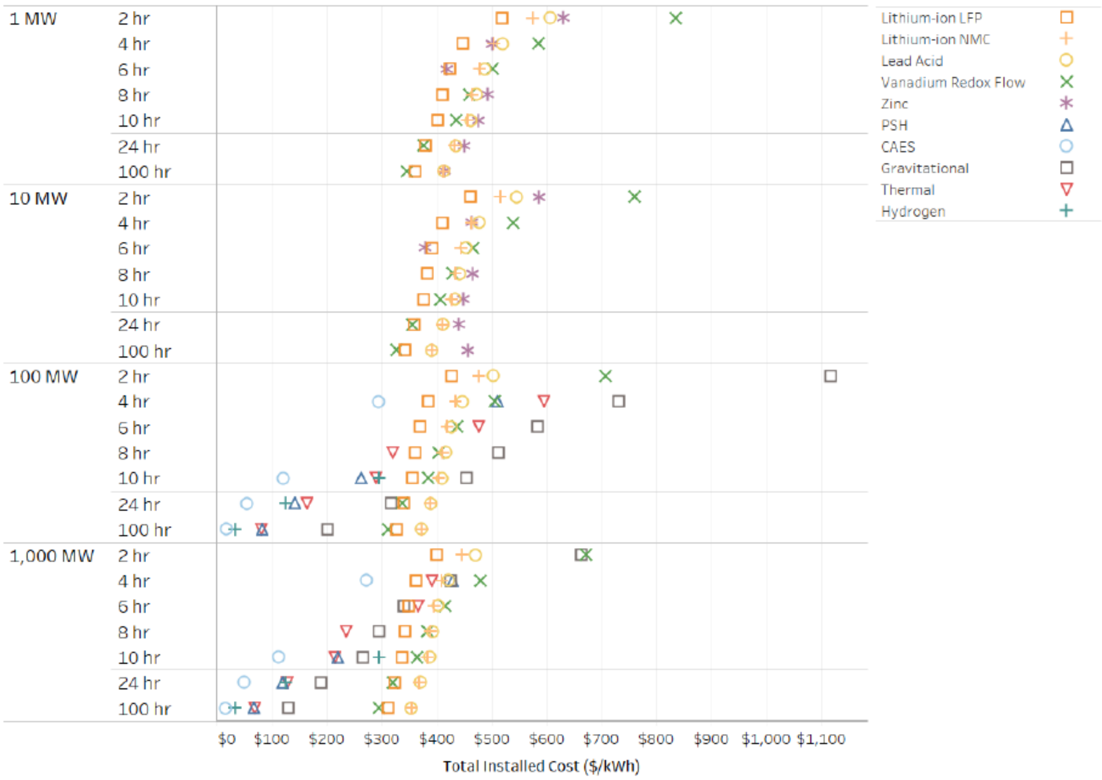


Figure 20: Capex of different storage technologies in 2021, in US$/kWh. Source: PNNL (2022).

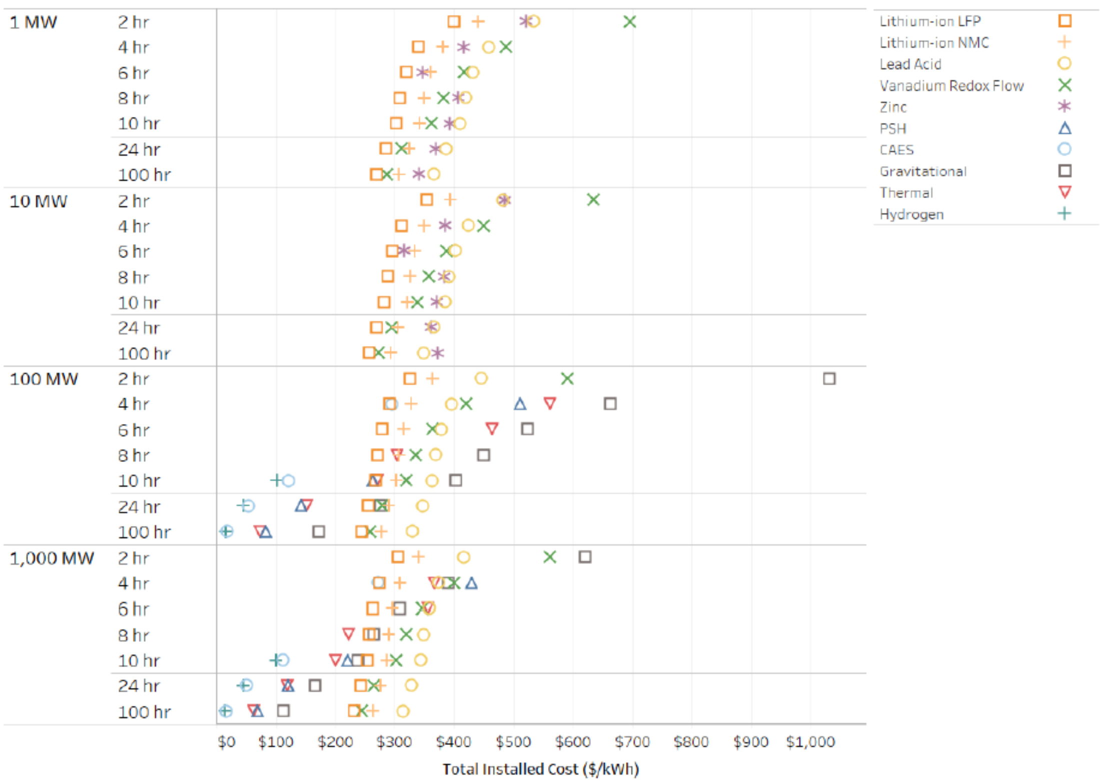


Figure 21: Capex of different storage technologies in 2030, in US$/kWh. Source: PNNL (2022).

As the charts indicate, lithium-ion batteries and pumped storage hydro, which are the most mature technologies, are also among the most competitive ones in terms of investment costs per kWh.

PSH, which is the current dominant grid storage technology, is among the second or third most competitive alternatives for storage durations of 10, 24, and 100 hours. In 2021, the estimated cost for a 100 MW, 10-hour system was $263/kWh, with the reservoir and powerhouse being the most significant cost components. For a 24-hour system, the total installed cost reduces to $143/kWh.

For durations of 4 hours or more, CAES is the lowest-cost storage technology, with a 100 MW, 10-hour system estimated at $122/kWh. However, its feasibility and economic competitiveness depends on access to naturally occurring caverns.

Battery storage solutions, which have grown rapidly in the past decade, are among the most competitive technologies for shorter-scale storage (up to 10 MW), especially lithium iron phosphate (LFP) batteries, which is currently the main type of lithium-ion batteries, alongside with nickel manganese cobalt (NMC). For larger scales (above 100 MW), LFP batteries remain among the most cost-effective for shorter-term storage, being the first or second most competitive technologies for storage duration up to 8-hour, with costs ranging from around $430/kWh (1-hour) to $360/kWh (8-hour).

For the estimated 2030 installed costs, LFP and CAES have nearly identical costs for 100 MW 4-hour configurations ($291/kWh and $295/kWh, respectively). CAES continues to be a low-cost option for longer durations due to minimal cavern expenses but is slightly outperformed by Hydrogen energy storage system (HESS) for durations exceeding 10 hours. For 100 MW, 100-hour systems, the estimated installed costs are $18/kWh for CAES and $15/kWh for HESS, making HESS the most cost-effective option at extended durations.

Specifically in the case of lithium-ion batteries, a considerable reduction in CAPEX is expected, making this alternative even more competitive. As Figure 22 indicates, NREL (2024) estimates a reduction from 50% to 70% by 2050, depending on the scenario[26]. In the case of PSH, the long-standing history of hydropower development in Brazil may help accelerate the learning curve and adoption of PSH. Finally, as will be seen later, these two technologies are also well suited to the system's needs.

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[26] NREL cost projections are categorized into three scenarios (Advanced, Moderate and Conservative), which differ related to the pace of cost reduction.

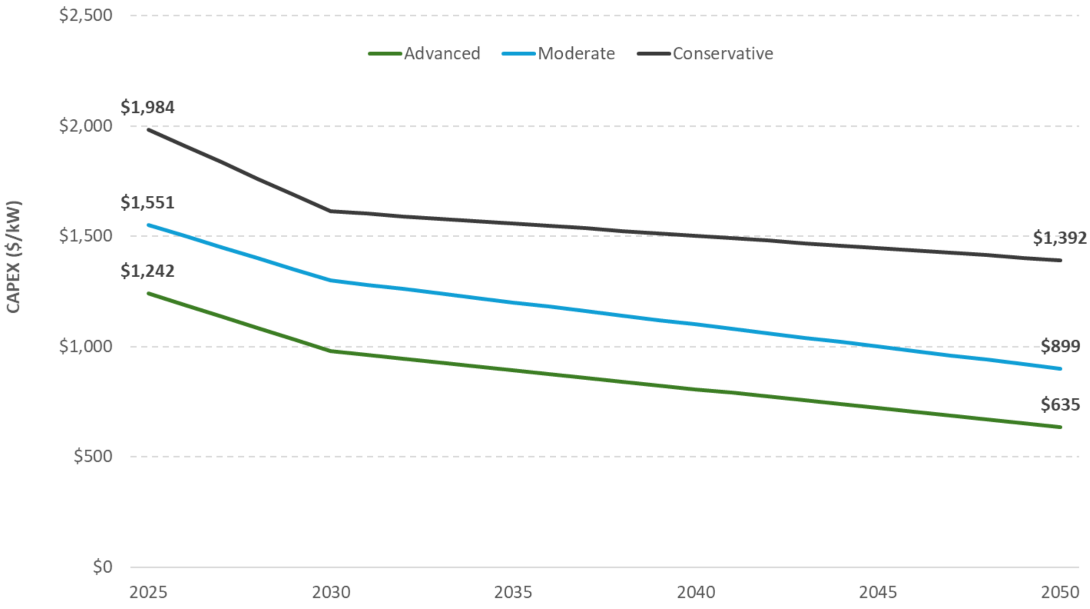

Figure 22: CAPEX reduction curve for a 4-hour lithium-ion battery. Source: NREL (2024).

APPLICATIONS OF STORAGE TECHNOLOGIES IN THE BRAZILIAN POWER SECTOR

The various energy storage technologies presented have played a crucial role across multiple sectors, including mobility, residential and commercial use, industry, and particularly the power sector — the focus of this study. Their ability to store energy from different sources (including the grid) and later supply it for various applications is increasingly being leveraged, driven by the wide range of services they can provide to electric power systems.

These technologies are applicable across various segments of the power sector, from generation and transmission, where they function as centralized resources, to distribution and consumption, where they are classified as decentralized resources.

As centralized resources within power grids (primarily in medium and high voltage networks), these systems have emerged as strong candidates for a wide range of power system services. Beyond addressing the need for flexibility, which helps maintain sustainability levels and prevents renewable energy curtailment, they also play a role in power or capacity supply and ancillary services. More recently, they have also been evaluated for reliability and resilience services.

In addition to centralized applications, storage technologies also operate as distributed resources, serving localized or specific needs by either connecting directly to distribution networks or remaining behind-the-meter at consumer facilities. As distributed resources, they offer a broad range of applications and services, including power quality, reliability, and continuity of electricity supply. Moreover, they can support consumer-specific technical and commercial strategies.

The following figure provides a summary of these applications, with a focus on batteries and pumped storage plants, given their technological maturity and the investment costs estimated and discussed in previous sections.

Applications			Batteries (Lithium)	Pumped Storage
Generation Balance		Spot Market		
		Future Markets		
System Services	Operational Management	Network-congestion management		
		Ramping		
	Frequency stability	Spinning Reserve		
		Primary Control power		
		Secondary control power		
		Tertiary control power		
		Long-term reserve		
	Voltage stability and quality	Supply of short-circuit power		
		Supply of active power		
	Security of supply and rebuilding	Ability to do a blackstart		
		Uninterruptible power supply		
		Contribution to securing the supply of power		
Subtitles: Very well-suited Well-suited Basically suited/research needs Not suited or application not possible				

Figure 23 - Batteries and Pumped storage applicability. Source: adapted from Sterner, M., Stadler, I. (2019).

Currently, few examples of energy storage applications exist in Brazil, mainly due to regulatory barriers, which will be analyzed in Section **Error! Reference source not found.**. However, as illustrated in Figure 23, there is significant potential for these technologies in the country. The most relevant applications in the Brazilian context are detailed below:

1. **Flexibility (Ramping):** Flexibility is a key concept related to energy balancing over time, and its importance is growing in discussions around storage applications. It expands the scope of grid balancing by considering both the response time of energy sources and their capacity to store and supply energy. This approach is critical for managing increasingly variable, uncertain, and non-coincident generation and consumption profiles.

2. **Ancillary Services (Frequency stability and Voltage stability and quality):** In addition to energy production itself, power systems require a range of services related to maintaining physical parameters for network security and stability, as well as ensuring power quality. Some of these services, known as Ancillary Services, are essential and are typically provided by generators and specialized equipment installed on the grid. As a result, storage technologies are well-positioned as prime candidates for delivering ancillary services, as they can simultaneously provide multiple functions, including frequency control, reactive power support, and power quality enhancement.
3. **Reliability and Resilience (Contribution to securing the supply of power):** A resilient power system is one that can continue operating and/or recover quickly from failures, unexpected events, or adverse conditions. Resilience is directly linked to the system's ability to absorb impacts, adapt to changes, and return to its normal state or a new functional state, ensuring the continuity of operations. Storage technologies contribute to power reliability by reducing or eliminating short-duration supply interruptions. As a means of mitigating power supply disruptions, storage systems are also a valuable solution for utilities serving groups of consumers with stricter service quality requirements.
4. **Renewable Energy Integration (Network-congestion management and Uninterruptible power supply):** Due to their ability to balance renewable energy generation, instantaneously injecting power into the grid when renewable output drops or absorbing excess energy when generation exceeds demand, storage technologies are increasingly being deployed to support the expansion of renewable energy sources in a sustainable manner. In this context, storage also plays a key role in generation curtailment reduction. When energy supply exceeds demand or when there are transmission constraints renewable generators can be forced to limit their production. This can lead to revenue losses from energy sales and have an impact on contract fulfillment. Therefore, one of the main objectives of storage deployment is to minimize generation curtailment, a growing challenge in many countries.