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Smart Curtailment Management In Power Grids With High Renewable Penetration: The Role Of Batteries, Data Centers, And Flexibility Compensation Policies

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Abstract:
Background: *The rapid expansion of intermittent renewable energy sources has led to significant reconfigurations in power systems, particularly in regions with high levels of solar and wind energy generation. Among the challenges that have emerged, curtailment stands out as a critical issue, as it prevents the full utilization of the energy produced. In this context, the present study examines effective mitigation strategies involving the use of batteries, data centers, and flexibility remuneration mechanisms, based on both national and international research.*
Materials and Methods: *This investigation adopted a qualitative approach, selected due to the interpretive nature of the subject and the aim of thoroughly understanding the technical, regulatory, and strategic aspects surrounding curtailment management in systems with high penetration of renewable sources. The research procedures included bibliographic and documentary analysis, both essential for supporting the study's analytical foundation.*
Results: *The general objective of this study was to analyze intelligent curtailment management strategies in power systems with a high share of renewable sources. Emphasis was placed on the role of batteries and data centers as mitigating elements and on the comparative evaluation of flexibility remuneration policies implemented in Brazil and other countries. The results highlight the importance of integrated planning as a fundamental measure to prevent structural bottlenecks. Scenario forecasting for renewable generation was frequently mentioned in the reviewed literature as a key practice. The synergy between batteries and data centers demonstrated substantial operational advantages, especially when supported by public policies that promote system-wide flexibility.*
Conclusion: *Mitigating curtailment in renewable-intensive power systems requires a multifaceted approach that integrates technological, regulatory, and strategic measures. The coordinated deployment of batteries and data centers, combined with well-designed flexibility remuneration policies, offers promising pathways to enhance the efficient use of renewable energy. Integrated planning and predictive modeling emerge as critical elements for ensuring system adaptability and sustainability.*

Keywords: *Curtailment; Mitigation; Remuneration Systems; Strategic Aspects.*

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I. Introduction

The growth of intermittent renewable energy sources, notably solar and wind, has brought significant transformations to the structure of power systems, demanding new approaches to planning, operation, and regulation. As the contribution of these sources to energy matrices increases, challenges related to generation variability and transmission infrastructure constraints become more pronounced. These challenges frequently result in curtailment episodes, that is, the forced reduction of electricity production due to inadequate conditions for its full integration into the grid. This phenomenon, increasingly observed in regions such as Northeastern Brazil, underscores the need for integrated responses that combine technology, public policy, and remuneration models tailored to the evolving conditions of the energy sector.

In this context, it becomes progressively more important to investigate flexibility alternatives that integrate technological innovation and regulatory mechanisms capable of absorbing generation surpluses while enhancing system operation. The strategic deployment of batteries and data centers, when integrated in a coordinated manner with the power system, can play a substantial role in reducing losses, promoting stability, and preventing energy waste. Moreover, compensation mechanisms for non-injected energy and payment schemes for flexibility services, already tested in international markets, provide valuable guidelines for improving Brazil's regulatory framework. The integration of technological solutions and incentive policies presents a promising alternative for the effective management of curtailment in networks with a high share of renewable energy sources.

This investigation was conducted through a qualitative approach, selected based on the interpretive nature of the subject and the aim of developing an in-depth understanding of the technical, regulatory, and strategic aspects involved in curtailment management in systems with high renewable energy penetration. Bibliographic and documentary research procedures were adopted, both of which were essential in supporting the analysis.

The overall objective of this research was to analyze intelligent strategies for curtailment management in electric power systems with a high share of renewable sources, with a focus on the role of batteries and data centers as mitigating elements and on the comparative evaluation of flexibility remuneration policies implemented in Brazil and other countries. The specific objectives were as follows: (1) to investigate the causes, impacts, and evolution of the curtailment phenomenon in systems with high penetration of intermittent renewable energy in Brazil, particularly in the most affected regions, such as the Northeast; (2) to analyze, based on national and international bibliographic research, the technical-operational potential of batteries and data centers as flexibility solutions for curtailment mitigation in renewable-intensive systems; and (3) to assess and compare international compensation and flexibility remuneration policies (e.g., in the United Kingdom, Germany, and the United States) with mechanisms under development or implementation in Brazil, proposing guidelines to promote contractual fairness and systemic efficiency.

The structure of the present article was organized into four main sections to ensure clarity, coherence in argumentation, and compliance with the formal standards of scientific writing. The first section, the introduction, presents the scope of the topic, the research objectives, and the rationale for its importance. The subsequent section, materials and methods, describes the methodological strategy, the research procedures adopted, and the sources consulted. The third section addresses the theoretical framework, which is divided into three subsections that systematically organize the discussion on integrated infrastructure planning aimed at minimizing curtailment, technological solutions that provide flexibility through the use of batteries and data centers, and compensation and remuneration policies related to system flexibility. Finally, the concluding section summarizes the results, addresses the limitations of the research, and suggests directions for future studies. This structure not only aligns with established academic standards but also facilitates clear and fluid reading, promoting critical understanding of the content by readers.

II. Material And Methods

The investigation was conducted using a qualitative approach, selected based on the interpretive nature of the subject under analysis and the intent to develop an in-depth understanding of the technical, regulatory, and strategic aspects involved in curtailment management within power systems with high penetration of renewable energy sources. According to Silva et al. (2022), the qualitative approach enables the analysis of complex phenomena in their multiple dimensions, allowing for the articulation of data and interpretations that go beyond numerical quantification and instead favor contextual and structural analysis. By addressing emerging technologies, regulatory frameworks, and public policy proposals, this approach offers appropriate tools to identify trends, recognize convergences, and challenge propositions grounded in the technical literature.

Bibliographic and documentary research procedures were adopted, both of which were essential to support the analysis. As described by Rodrigues and Neubert (2023), the literature review involved a systematic analysis of 37 academic articles—both national and international—selected due to their scholarly relevance, contemporaneity, and direct connection to topics such as power system flexibility, curtailment, and energy regulation. The substantial volume of sources provides a robust and representative foundation for the arguments developed throughout the study. The selection of bibliographic sources considered both indexed academic journals and technical publications from research institutions linked to the electricity sector, allowing for the construction of a broad and well-grounded perspective on the analyzed topics.

The documentary research enriched the investigation by incorporating data from institutional sources, including technical reports, regulatory guidelines, and statements issued by energy sector organizations. Among the documents examined, notable examples include recent publications from entities such as Fitch Ratings (2025), the Brazilian Electricity Regulatory Agency (ANEEL, 2022), the Climate Investment Partnership (CIP, 2021), and the Brazilian Association of Infrastructure and Basic Industries (ABDIB, 2025). As Gil (2022) points out, documentary research is essential for the investigation of current phenomena that are directly linked to regulatory decisions and sectoral policies. The combination of these two methodological approaches resulted in a solid theoretical foundation, capable of integrating empirical insights with critical analyses concerning regulatory guidelines and technological solutions implemented in the Brazilian energy context.

III. Literature Review

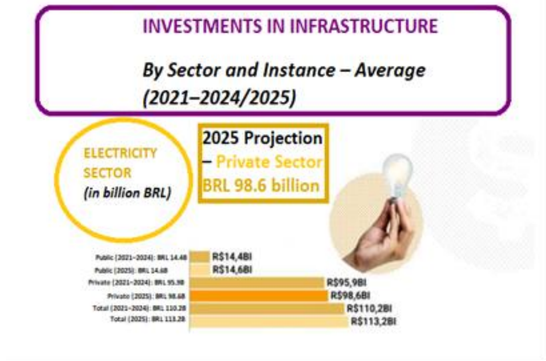
The theoretical framework was organized into three subsections, with the aim of highlighting the complexity and interdependence of technical, regulatory, and strategic aspects related to curtailment mitigation in power systems with high penetration of renewable energy sources. The first subsection (3.1) discusses integrated infrastructure planning and subsidy policies aimed at promoting renewable energy in Brazil, emphasizing the reduction of curtailment rates through more effective technical and financial criteria. Subsequently, the second subsection (3.2) explores technological solutions that enhance system flexibility, with a focus on the use of batteries and data centers in both standalone and integrated configurations. Emphasis is placed on load modulation and surplus energy storage. Finally, the third subsection (3.3) addresses compensation policies for curtailed generation and payment mechanisms for flexibility services, examining international experiences and their relevance to the Brazilian regulatory context. This structure enabled an integrated analysis of infrastructure, technology, and public policy, thereby fostering a comprehensive understanding of the topic.

Integrated Infrastructure Planning and Subsidy Policies for Renewable Expansion with Low Curtailment Rates in Brazil

The expansion of intermittent renewable energy sources in Brazil, particularly solar and wind, has revealed the growing incidence of curtailment—a phenomenon characterized by the forced reduction of generation due to structural constraints in the power grid. This issue becomes more pronounced in regions where the deployment of renewable sources advances at a faster pace than the adaptation of electrical infrastructure, as is the case in Northeastern Brazil (Gomes et al., 2025). The absence of cohesive planning between generation expansion and grid development has contributed to the underutilization of renewable resources, while also intensifying operational challenges in the national power system. Research conducted by Chiappini (2025) demonstrates that the accelerated growth of data centers exacerbates these pressures by increasing the specific demand for highly reliable energy, thus requiring organized responses in terms of planning and coordination.

The formulation of public policies aimed at forecasting investments in transmission and storage infrastructure has been analyzed by institutions such as the Interministerial Infrastructure Planning Committee (CIP, 2021). These policies must consider technical criteria that ensure the approval of new renewable energy projects only when there are guarantees of grid dispatch capacity and secure connection. Moreover, international experience highlights the importance of strategic subsidies—not only to promote the implementation of renewable energy sources but also to support their integration with storage solutions and load management systems. Within this context, the concept of "integrated infrastructure planning" as proposed by Silva Filho and Pompermayer (2022) provides a foundation for understanding how forward-looking decisions, grounded in growth and adaptability scenarios, can significantly reduce curtailment levels. Figure 1 below presents an overview of Brazil's energy-related infrastructure investments:

Figure 1 – Overview of Energy Infrastructure Investment in Brazil



Source: Leão (2025)

It is precisely in this regard that the combination of battery storage systems and flexible loads—such as data centers—emerges as an effective alternative for curtailment reduction. According to Cintra (2025), data centers, which are significant energy consumers, have the capacity to act as flexible components of the power grid by adjusting part of their demand in response to price signals or the availability of renewable generation. The integration with battery systems, as proposed by Fagundes (2025), enhances this capability by allowing for the temporary retention of energy surpluses. This model, currently under evaluation in several international markets (Nycander et al., 2020), requires modifications to regulatory frameworks and remuneration policies for flexibility services. As emphasized by Guevara and Dib (2022), appropriate pricing mechanisms for ancillary services provided by flexible consumers are essential to the success of such arrangements.

The adoption of these strategies in Brazil demands alignment with the specific characteristics of the national electricity system, as well as articulation with sustainability and governance objectives, as discussed by Gomes et al. (2025).

Before proceeding further, it is essential to highlight the main dimensions of integrated planning for the expansion of renewable energy sources with reduced curtailment rates in Brazil. Table 1 summarizes the main structural challenges and proposed solutions identified in the current literature.

Table 1 – Key Elements for Integrated Infrastructure Planning with Low Curtailment Rates in Brazil

Strategic Dimension	Identified Challenges	Proposed Solutions
Transmission Expansion	Delays in auctions and grid construction	Anticipatory planning based on renewable penetration scenarios (CIP, 2021)
Generation-Grid Coordination	Project approvals without evacuation guarantees	Technical criteria for permitting and integration with long-term plans (Silva Filho & Pompermayer, 2022)
Storage and Load Flexibility	Lack of clear incentives for batteries and data centers	Compensation policies for flexibility services (Fagundes, 2025; Cintra, 2025)
Subsidies and Financing	Focus exclusively on generation, ignoring system integration	Integrated subsidies and cross-financing mechanisms (ABDIB, 2025)

Source: CIP (2021); Silva Filho & Pompermayer (2022); Fagundes (2025); Cintra (2025); ABDIB (2025)

The table presents a systematic summary of the primary strategic issues linked to integrated infrastructure planning for the deployment of renewable energy in Brazil, especially in scenarios marked by elevated curtailment rates. The framework emphasizes the importance of a multisectoral and proactive approach by addressing critical aspects such as transmission expansion, generation-grid coordination, load and storage flexibility, and subsidy policies. The suggested solutions highlight the necessity of stringent technological standards, specific incentives for flexibility services, and cohesive finance strategies. These aspects collectively emphasize that the mitigation of curtailment primarily depends on the synchronization of infrastructure development, technology innovation, and public policy.

Technological Flexibility Solutions for the Power System: Advanced Applications of Batteries and Data Centers in Curtailment Mitigation in High Renewable Penetration Environments

The adoption of energy flexibility strategies has emerged as a technically significant response to curtailment reduction in power grids with high penetration of renewable sources. Among the prominent technological solutions, battery storage systems provide multiple functionalities that go beyond mere energy accumulation. Studies conducted by Schmidt et al. (2019) and Santos et al. (2023) demonstrate that batteries can operate as dynamic assets, contributing to grid stability, load shifting, and the absorption of intermittent surpluses. According to Souza (2020) and Lima (2020), there is empirical evidence of practical applications in medium-voltage networks in Brazil, where temporal management of storage enhances supply continuity indexes. Furthermore, research by Morais Filho (2020) and Uliana (2023) indicates that the strategic spatial distribution of these systems is essential to optimize operational benefits and minimize the occurrence of uncontrolled curtailment.

Another important element is the use of data centers as flexible loads, whose considerable energy demand can be adjusted in accordance with renewable generation availability. This capability allows them to function as demand regulation mechanisms, particularly during periods of peak wind or solar generation. Studies by Liu et al. (2020), Ma (2022, 2023), and Brito and collaborators have addressed innovative methodologies for managing energy consumption, incorporating models based on machine learning and artificial intelligence, which promote optimized energy use without compromising the quality of computing services. At the international level, experiences such as the one reported in Shanghai by Bedeschi (2025) illustrate the feasibility of submerged data centers powered by marine renewable sources, which reduce thermal impact and enhance energy efficiency. This hybrid approach was analyzed by Choi et al. (2022) and Mahbod et al. (2022), showing favorable results in terms of emission reductions and sustainable computational performance.

The combination of batteries and data centers represents a strategically valuable synergy, as it enables the integration of temporary storage with active demand management. Correia et al. (2020) and Costa (2023) emphasize that such integration must be coordinated with regulatory adaptations and specific remuneration mechanisms for the services provided by this hybrid solution. Campos et al. (2022) point out that in networks characterized by high intermittency, this combination enhances operational predictability and reduces system marginal costs. Additionally, Diniz and Gomes (2025) propose off-grid models that incorporate solar energy combined with batteries and local data centers, aimed at serving isolated communities. These configurations require integrated planning of both physical and digital infrastructure, through protocols that ensure interoperability and agile response to generation fluctuations. Before proceeding, Table 2 presents a comparative synthesis of the isolated and integrated applications of batteries and data centers for curtailment mitigation.

Table 2 – Comparison between Isolated and Integrated Applications of Batteries and Data Centers in Curtailment Mitigation

Technological Configuration	Operational Advantages	Technical Challenges	Applied Examples
Batteries (isolated)	Surplus storage, grid stability support	Installation cost, cycle degradation	Souza (2020), Schmidt et al. (2019)
Data Centers (isolated)	Load modulation, usage during surplus generation	High thermal demand, specialized infrastructure	Brito et al. (2023), Liu et al. (2020)
Batteries + Data Centers (integrated)	Synergy of storage and load flexibility	Systemic integration, regulatory and tariff model gaps	Diniz and Gomes (2025), Campos et al. (2022)

Source: Souza (2020); Schmidt et al. (2019); Brito et al. (2023); Liu et al. (2020); Diniz and Gomes (2025); Campos et al. (2022)

The connection between technological solutions and regulatory frameworks will be crucial to enable the effective operation of integrated storage and flexible consumption systems. The specialized literature emphasizes the importance of standardized metrics for performance evaluation, as well as protocols that facilitate the inclusion of these assets in the flexibility market. Accordingly, actions such as those mentioned by Correia et al. (2020) and Peng et al. (2022) indicate the implementation of platforms that respond to demand and adopt dynamic tariffs, based on criteria of energy efficiency and operational availability. These alternatives enable a more resilient network architecture, adapted to the demands of an increasingly complex renewable energy matrix.

Compensation Policies for Curtailment and Flexibility Remuneration: Lessons

The advancement of renewable energy sources in Brazil has underscored the urgent need for regulatory mechanisms that adequately address curtailment, especially due to its increasing occurrence in the Northern and Northeastern regions. As highlighted by Almeida, Losekann, and Pereira (2025), curtailment constitutes a structural challenge that directly impacts the financial predictability of projects and their attractiveness for new investments. Internationally, countries such as the United Kingdom and Germany have already implemented consolidated compensation models, known respectively as Constraint Payments and Einspeisemanagement. These mechanisms are based on the premise that systemic decisions to reduce generation should not harm the producer, ensuring proportional compensation for the energy that would have been supplied. In the Brazilian context, the absence of a formalized policy generates both legal and economic uncertainties, as analyzed by Souto Jr. (2024) and Faveret (2025).

Beyond direct compensation, models based on flexibility auctions and demand response mechanisms have demonstrated efficiency in practical cases, such as the United Kingdom's Balancing Mechanism and the United States' demand response programs promoted by Independent System Operators (ISOs) like PJM and CAISO. According to the analysis by Fitch Ratings (2025), Brazil faces structural limitations that exacerbate curtailment risk, making the implementation of solutions that ensure contractual fairness and technical efficiency essential. The report by ANEEL (2022) indicates that the absence of a structured compensation framework constitutes a significant regulatory obstacle, emphasizing the urgency of normative progress to secure investor confidence. Based on these examples, it is feasible to establish guidelines tailored to the particularities of the Brazilian power system, favoring the creation of regulatory instruments that are adaptable and financially sustainable.

It is relevant to consider Table 3 below before presenting the theoretical proposal of policies compatible with the national reality. This table organizes three compensation and flexibility mechanisms that could be adopted in Brazil, taking into account international experiences and ongoing regulatory research in the country. The present comparative analysis was developed from the contributions of ANEEL (2022), Almeida et al. (2025), Rolim (2025), and enriched by international studies such as those by Woodman and Mitchell (2011) and Heffron et al. (2021).

Table 3 – Proposed Mechanisms for Compensation and Flexibility in the Brazilian Context

Proposed Mechanism	Description	International Inspiration	Applicability in Brazil
Compensation for Non-Injected Energy (CPE-NI)	Financial compensation for energy not injected into the grid due to ONS curtailment. Based on real generation estimates.	Einspeisemanagement (Germany)	High, with technical and legal support (Law 10.848/2004)
Flexibility Auctions	Participation of data centers, batteries and flexible loads to consume or store excess energy.	Demand Response (USA) and Balancing Services (UK)	Moderate to high, requires specific regulation and price signals
Curtailment Market with Compensation Bids	Generators inform the minimum price for curtailment. ONS selects the most economic offers.	Balancing Mechanism (UK)	High, with a market structure managed by CCEE

Source: Based on ANEEL (2022), Almeida et al. (2025), Rolim (2025), Woodman and Mitchell (2011), Heffron et al. (2021).

The feasibility of these mechanisms is linked to the degree of institutional maturity and the capacity of the Brazilian electricity system to incorporate elements of predictability and regulatory fairness. The recent experience of curtailment exceeding 10% of renewable generation, as pointed out by Rolim (2025), underscores the urgency of structuring instruments that equitably redistribute risks. Furthermore, the presence of specific contractual clauses in Power Purchase Agreements (PPAs) and the proposals currently under review by ANEEL and CCEE demonstrate that there is both a technical and legal foundation for progress. Adopting a hybrid set of solutions — combining direct compensation, price signals, and active demand participation — represents a realistic and effective path to ensuring the continued expansion of renewable energy under regulatory certainty.

IV. Conclusion

The central objective of this investigation was to examine intelligent strategies for curtailment management in power systems with significant integration of renewable energy sources, by exploring the role of batteries and data centers as flexibility resources, in addition to comparing compensation policies implemented in Brazil with international experiences. The specific objectives were fully achieved: the first enabled the understanding of the structural causes of curtailment, especially in the most affected regions, such as Northeastern Brazil; the second outlined the technical and operational functionalities of the analyzed technologies; and the third made it possible to identify significant contrasts between national and international regulatory models, providing foundations for proposals aligned with efficiency and contractual fairness.

The findings highlight the relevance of integrated planning as a key element in preventing structural barriers, with renewable scenario forecasting being a recurrent practice in the literature reviewed. The combination of batteries and data centers revealed significant operational advantages, particularly when supported by public policies that promote systemic flexibility. The theoretical contributions are consolidated in the systematization of the main challenges and solutions, while the practical implications are reflected in the proposals for mechanisms adapted to the Brazilian context, such as the CPE-NI and flexibility auctions. By compiling, comparing, and systematizing a wide range of technical sources, the research contributes to a deeper understanding of the various variables involved in the management of intermittent energy surpluses.

The diversity of the sources analyzed and the methodological robustness employed were substantial. The investigation focused on guidelines derived from theoretical models, simulations, and documented institutional experiences. Furthermore, the ongoing evolution of the energy sector, accompanied by the recurrent emergence of disruptive technologies and regulatory changes, requires dynamic interpretations and periodic reassessments of the directions indicated in this study. These factors suggest that the results should be understood as part of a continuously evolving landscape.

Based on the analysis conducted, future research is recommended to focus on the practical application of hybrid architectures integrating batteries and data centers, as well as on the economic feasibility of various tariff models. It is also suggested to expand the international comparison to include emerging countries whose energy infrastructures share similarities with Brazil's. Finally, the material presented herein may prove valuable to policymakers, energy sector professionals, and researchers seeking to develop solutions aligned with the goals of energy transition, grid resilience, and sustainability of the national interconnected system's operational model.

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