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From Abundance to Energy Waste: Context Architecture and Regulatory Instruments for Mitigating Curtailment in the Brazilian Energy Transition

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ABSTRACT

The accelerated expansion of renewable energy sources in the Brazilian electric power system has increased the supply of clean energy while simultaneously exposing operational, regulatory, and institutional constraints related to the absorption of this generation. In this context, curtailment has become a central issue in the debate on system efficiency and the rational indication of energy use, as it reveals situations of waste associated with transmission constraints, lack of flexibility, and misalignments between generation and demand. The analysis of this phenomenon therefore requires an integrated perspective that considers not only technical aspects but also regulatory and economic arrangements embedded in the energy transition process. The methodology adopted was based on a qualitative approach, suitable for understanding complex and interdependent phenomena. To develop the research, bibliographic and documentary research procedures were used in a complementary manner, enabling the articulation of consolidated theoretical frameworks with technical and institutional documents related to planning, operation, and regulation of the electric power sector. The general objective of the study was to analyze how context architecture, combined with regulatory and economic instruments, can contribute to mitigating curtailment in the Brazilian electric power system within the scope of the energy transition, considering the integration of renewable generation, transmission, energy storage, and new demand vectors. In an integrated manner, the research demonstrated that curtailment mitigation cannot be treated as an isolated or purely technical issue. It constitutes a challenge that requires coordination among sectoral planning, economic regulation, and institutional design, guided by a context architecture capable of aligning incentives, technologies, and energy flows. By shifting the focus toward a systemic perspective, the study contributes to the debate on efficiency, economic rationality, and responsible energy use in the energy transition process.

Keywords: *Curtailment; Energy transition; Context architecture; Electric power system.*

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I. INTRODUCTION

Brazil's energy transition has been marked by the accelerated expansion of variable renewable energy sources, particularly wind and solar power, driven by technological advances, cost reductions, and environmental commitments. This process has significantly increased the supply of clean energy while also exposing structural limitations of the national electric power system, especially with regard to transmission capacity, operational flexibility, and coordination between generation and demand. In this context, curtailment has emerged as a recurring phenomenon associated with the compulsory reduction of renewable generation, revealing tensions between energy abundance and systemic constraints.

The increasing occurrence of curtailment challenges the traditional logic of planning and operating the electric power sector, as it highlights situations in which available energy cannot be fully utilized. This scenario reinforces the need for approaches that move beyond fragmented analyses and consider the electric power system in an integrated manner, articulating technical, regulatory, and economic dimensions. The concept of context architecture is situated within this debate by proposing a systemic perspective capable of linking infrastructure, regulation, market instruments, and new demand vectors, thereby contributing to the mitigation of energy waste in the transition process.

In this context, curtailment assumes a relevant analytical role as an indicator of coordination failures among planning, regulation, and system operation, rather than being understood merely as a technical event. International literature has pointed out that power systems with a high penetration of variable renewable energy sources face similar challenges, requiring institutional arrangements capable of internalizing variability and redistributing risks among market agents. IRENA (2025) emphasizes that the increase in curtailment is a recurring phenomenon in systems undergoing transition, particularly when the expansion of generation capacity is not accompanied by regulatory flexibility and adequate infrastructure. Accordingly, the Brazilian debate is situated within a global agenda that links systemic efficiency, energy governance, and the rational use of renewable resources.

The methodology adopted in this study was based on a qualitative approach, appropriate for understanding complex phenomena involving multiple interdependent dimensions within the Brazilian energy transition. This methodological choice made it possible to analyze curtailment not merely as an operational event, but as an expression of systemic arrangements, regulatory decisions, and planning strategies. Two complementary research procedures were employed: bibliographic research and documentary research, which enabled the articulation of theoretical frameworks with technical and institutional documents relevant to the subject.

With regard to the objectives, the general objective of the research was to analyze how context architecture, combined with regulatory and economic instruments, can contribute to mitigating curtailment in the Brazilian electric power system within the scope of the energy transition, considering the integration of renewable generation, transmission, energy storage, and new demand vectors. The specific objectives were to examine curtailment as a manifestation of systemic inefficiencies in the Brazilian energy transition in light of the accelerated expansion of variable renewable sources; to evaluate existing regulatory and economic instruments, as well as those that could be implemented, aimed at compensating or remunerating renewable energy producers during periods of curtailment; and to analyze the role of batteries and data centers as structuring elements of context architecture, capable of reducing energy losses and increasing system flexibility.

The study is structured into four main sections. In addition to this introduction, the materials and methods section details the methodological procedures adopted. The theoretical framework then develops the main concepts and analyses related to curtailment, regulatory architecture, and technical solutions associated with context architecture. Finally, the concluding remarks synthesize the main findings of the study and indicate directions arising from the research conducted.

II. MATERIAL AND METHODS

The present study adopted a qualitative approach, as it is aimed at understanding complex phenomena involving technical, regulatory, and institutional dimensions within the Brazilian energy transition. This methodological choice made it possible to analyze curtailment not merely as an operational event, but as an expression of systemic arrangements, normative decisions, and planning strategies, in line with the epistemological foundations of scientific research discussed by Rattner (1979) and Gil (2021).

To develop the study, two complementary research procedures were employed: bibliographic research and documentary research. Bibliographic research played a structuring role in the construction of the theoretical framework, enabling the identification, organization, and articulation of concepts related to curtailment, context architecture, and the regulatory and economic instruments associated with the mitigation of energy losses. This procedure followed well-established methodological guidelines, as discussed by Gil (2021) and by Rodrigues and

Neubert (2023), who emphasize bibliographic research as an indispensable stage for the conceptual and analytical grounding of scientific investigations.

Documentary research was used with the purpose of examining technical documents, institutional reports, and official publications produced by agencies and entities directly involved in the planning and operation of the electric power system. This procedure allowed access to primary and secondary information on generation curtailment, renewable energy integration, energy storage, and the evolution of generation costs, thereby contributing to the empirical analysis of the phenomenon under investigation. The use of documentary research followed the methodological assumptions presented by Cellard (2008), who highlights the relevance of this type of source for understanding institutional practices, technical guidelines, and normative contexts.

With regard to documentary sources, the analysis was based primarily on reports and studies prepared by the National Electric System Operator, the Energy Research Company, the International Renewable Energy Agency, and joint publications by GIZ and the Ministry of Mines and Energy, which directly address issues such as generation curtailment, the integration of distributed generation, energy storage systems, and regulatory best practices. These documents provided essential technical and institutional inputs for understanding curtailment in the Brazilian context.

Taken together, the combination of bibliographic and documentary research enabled the articulation between theoretical foundations and institutional evidence, ensuring methodological consistency throughout the study. In total, more than fifteen scientific and technical works were consulted, contributing to the analytical robustness of the research and to the alignment between the methodological procedures adopted and the proposed objectives, in accordance with classical methodological guidelines for qualitative scientific research.

III. THEORETICAL FRAMEWORK

The theoretical framework was organized to construct a progressive and articulated reading of the curtailment phenomenon within the context of the Brazilian energy transition. Initially, Section 3.1 is dedicated to understanding curtailment as an expression of systemic inefficiencies, situating the issue within the scenario of accelerated expansion of renewable energy sources and the structural limitations of the electric power system. Subsequently, Section 3.2 deepens the analysis from an institutional perspective by examining the regulatory architecture and existing economic compensation mechanisms, as well as their implications for cost allocation and incentive structures among sector agents. Finally, Section 3.3 shifts the focus to technical and organizational solutions, discussing the role of batteries and data centers as elements of context architecture capable of enhancing system operational flexibility and reducing losses associated with energy waste, thereby concluding the theoretical framework with an integrative approach that connects regulation, technology, and planning.

3.1 Curtailment and Systemic Inefficiencies in the Brazilian Energy Transition

Curtailment has become one of the most evident manifestations of the systemic inefficiencies associated with the Brazilian energy transition, particularly in the context of the accelerated expansion of variable renewable energy sources. In the electric power sector, the term refers to the compulsory reduction of generation even when the primary energy resource is available, due to technical, operational, or institutional constraints. In Brazil, this phenomenon has recurrently affected wind and solar generation, highlighting the mismatch between the pace of renewable supply growth and the system's capacity to integrate it in a coordinated manner. As indicated by the National Electric System Operator, generation curtailment has ceased to be an episodic occurrence and has taken on a structural character, with direct impacts on the efficiency of the national electric power system (ONS, 2024).

From a technical and operational perspective, the causes of curtailment are strongly associated with transmission bottlenecks, the spatial concentration of renewable projects, and dispatch restrictions imposed by the operation of the National Interconnected System. The lag between the commissioning of new power plants and the expansion of transmission infrastructure creates situations in which available energy cannot be fully absorbed by the system. The diagnosis prepared by the ONS (2024) shows that a significant share of curtailment events results less from isolated failures and more from persistent structural limitations, exacerbated by operational security criteria and the need to maintain system reliability.

Beyond technical aspects, curtailment also exposes economic and regulatory weaknesses. The absence of consolidated compensation mechanisms for generation cuts increases risk perceptions among market agents and undermines the predictability of revenue streams, thereby affecting the investment environment. In this regard, the public consultation opened by the Ministry of Mines and Energy, analyzed by Caixeta (2025), represents an institutional acknowledgment of the problem and of the need for instruments capable of redistributing, in a more balanced manner, the costs associated with curtailment. Nevertheless, as emphasized by Almeida, Losekann, and Pereira (2025), regulatory responses have progressed at a slower pace than the expansion of renewable sources, perpetuating a condition of structural misalignment. Table 1 provides a synthesis of the main causes and impacts of curtailment in the Brazilian context, in light of institutional diagnoses and the selected academic analyses.

Table 1 – Curtailment in the Brazilian electric power system: causes and systemic impacts

Analyzed dimension	Main elements associated with curtailment
Technical and operational	Transmission bottlenecks, dispatch restrictions, operational security criteria
Economic	Reduction in generators' revenues, increased regulatory risk, impacts on investment decisions
Institutional	Absence or fragility of compensation mechanisms, limitations in coordination between planning and operation
Systemic	Misalignment between the expansion of renewable generation, transmission, energy storage, and new demand vectors

Source: Authors' elaboration, based on ONS (2024), Caixeta (2025), Almeida, Losekann, and Pereira (2025), and Fonseca and Michellis Jr. (2025).

An integrated reading of these dimensions shows that curtailment should not be understood as a merely technical problem, but rather as a symptom of broader failures in the organization of the electric power sector. Gomes et al. (2025) argue that the absence of a context architecture capable of articulating generation, transmission, energy storage, and demand contributes to the reproduction of these inefficiencies, as the different elements of the system are treated in a fragmented manner. In this scenario, generation cuts emerge as a direct consequence of disconnected decisions between long-term planning, system operation, and the available regulatory instruments.

From a comparative perspective, international studies indicate that curtailment tends to increase in the early stages of the energy transition, particularly in countries with a strong geographical concentration of renewable generation and delayed expansion of transmission infrastructure. According to the International Renewable Energy Agency – IRENA (2025), the absence of flexibility mechanisms and adequate economic signaling converts renewable surpluses into systemic losses, thereby undermining the overall efficiency of the electricity system. This assessment reinforces the interpretation that Brazilian curtailment does not constitute an exception, but rather a specific manifestation of a structural challenge shared by power systems undergoing transition.

Finally, the institutional impacts of curtailment extend beyond the strictly technical domain and reach the legal and regulatory debate of the electric power sector. Fonseca and Michellis Jr. (2025) warn of the risk of naturalizing curtailment as a recurrent practice, which may undermine the credibility of the regulatory environment and intensify conflicts between market agents and the granting authority. Thus, understanding curtailment as an expression of systemic inefficiencies constitutes a necessary step to reposition the issue at the center of the Brazilian energy transition, reinforcing the need for solutions that promote greater coherence among infrastructure, regulation, and new demand arrangements.

3.2 Regulatory Architecture and Economic Compensation Mechanisms in Curtailment Mitigation

The intensification of curtailment in the Brazilian electric power system has shifted the debate beyond technical limitations, placing regulatory and economic instruments aimed at compensating affected agents at the center of the analysis. In this context, curtailment is interpreted not only as an operational failure, but also as a signal of system maturation in the face of the growing participation of variable renewable energy sources. Takeda (2025) notes that, in power systems undergoing transition, generation cuts tend to emerge as a result of regulatory structures that are still insufficiently adapted to intermittency and the decentralization of supply, reinforcing the need for mechanisms that provide economic recognition of such events.

The discussion on financial compensation gains relevance as the increase in curtailment affects the predictability of revenues for renewable energy developers. Víctor (2025) emphasizes that the absence of clear remuneration instruments during periods of curtailment contributes to the perception of energy waste and to the amplification of regulatory risk. In parallel, international studies systematized by IRENA (2025) indicate that more mature markets have relied on combinations of differentiated tariffs, long-term contracts, and risk-sharing mechanisms as a means of preserving the economic viability of renewable projects, even under conditions of systemic constraints.

Within the regulatory domain, models such as capacity markets, availability payments, and remuneration for ancillary services have been mobilized as alternatives to mitigate the economic effects of curtailment. The literature suggests that these instruments allow the partial decoupling of remuneration from actual energy generation, recognizing the systemic value of installed capacity and operational flexibility. As analyzed by Lobo et al. (2026), international experiences show that well-designed policies for managing renewable surplus tend to reduce conflicts among agents and to create incentives more closely aligned with the safe and efficient operation

of the electric power system. Table 2 presents a summary of the main regulatory and economic mechanisms associated with curtailment mitigation, in light of the national and international experiences discussed in the literature.

Table 2 – Regulatory and economic instruments associated with curtailment mitigation

Instrument	Main characteristics	References
Financial compensation for curtailment	Partial or full compensation for energy not dispatched due to systemic constraints	Takeda (2025); Víctor (2025)
Capacity markets	Remuneration for plant availability regardless of actual generation	IRENA (2025)
Ancillary services	Payment for flexibility, frequency control, and grid support	IRENA (2025); Lobo et al. (2026)
Surplus management and differentiated tariffs	Incentives for local consumption, energy storage, and demand response	Lobo et al. (2026); EPE (2024)

Source: Authors' elaboration, based on Takeda (2025), IRENA (2025), Víctor (2025), Lobo et al. (2026), and EPE (2024).

The analysis of the table shows that the effectiveness of these instruments depends on their integration within a coherent regulatory architecture capable of articulating generation, network infrastructure, and consumption. In the Brazilian case, studies by the Energy Research Company (EPE, 2024) indicate that the integration between distributed generation, distribution networks, and new tariff arrangements is still in a process of consolidation, which limits the full application of these mechanisms. Consequently, curtailment mitigation requires not only the isolated adoption of economic instruments, but also their coordination within a context architecture that aligns regulatory incentives, sectoral planning, and economic signals, thereby reducing distortions and strengthening the energy transition.

International experience shows that mitigating the economic effects of curtailment depends on the explicit incorporation of systemic risk into regulatory instruments. Lobo et al. (2026) demonstrate that surplus management policies, when integrated with capacity markets and ancillary services, reduce regulatory conflicts and enhance predictability for renewable energy investors. In the Brazilian case, the absence of consolidated compensation mechanisms reinforces the need for regulatory evolution aligned with the specific characteristics of the national energy transition.

3.3 Batteries and Data Centers in the Context Architecture of the Energy Transition

The incorporation of batteries and data centers into the context architecture of the Brazilian energy transition has gained central importance as curtailment intensifies as a collateral effect of the expansion of variable renewable energy sources. These elements are increasingly understood as structuring components capable of absorbing generation surpluses and providing greater operational flexibility to the electric power system. Gomes et al. (2025) emphasize that the integration between energy storage and energy-intensive demands, such as those associated with data centers, creates technical and regulatory conditions to reduce energy losses and to realign the relationship between supply and consumption in environments characterized by high variability.

With regard to energy storage, batteries play a relevant role in curtailment mitigation by enabling the temporal shifting of surplus generation. Large-scale technologies, such as vanadium redox flow batteries, have been analyzed as suitable alternatives for power systems with high penetration of renewables, due to their durability and operational response capacity. Aluko and Knight (2023) point out that these systems contribute to grid stabilization and to the reduction of operational constraints, especially in contexts where transmission expansion does not keep pace with the growth of renewable generation.

In the Brazilian context, the diffusion of energy storage systems still faces regulatory and economic challenges, although recent advances indicate a trajectory toward greater institutionalization. The EPE Monitoring Report (2022) shows that the use of batteries in micro- and mini-distributed generation systems has increased self-consumption capacity and reduced the injection of surplus energy during critical hours, which directly relates to curtailment mitigation. Complementarily, the Best Practices Manual on Energy Storage Systems, prepared by GIZ

in partnership with the Ministry of Mines and Energy, highlights the need for clear regulatory frameworks to enable the large-scale deployment of these technologies (GIZ/MME, 2025).

In parallel, data centers have emerged as vectors of intensive and relatively flexible demand, capable of absorbing renewable surpluses when integrated in a coordinated manner into the system architecture. Arbache (2024) argues that, despite the costs associated with the installation and operation of these facilities, their strategic location and continuous consumption profile can contribute to regional balancing between generation and load. Guedes (2024) adds that technological advances in data centers have expanded their possibilities for interaction with the electric power system, including through load management strategies and differentiated energy contracting arrangements. Table 3 synthesizes the role of batteries and data centers in curtailment mitigation, based on the technical, economic, and regulatory contributions discussed in the literature.

Table 3 – Batteries and data centers as elements of context architecture in curtailment mitigation

Element	Function within the context architecture	Contributions to curtailment reduction	References
Energy storage batteries	Temporal shifting of energy and support for system operation	Absorption of surpluses, reduction of operational constraints, increased flexibility	Aluko and Knight (2023); EPE (2022); GIZ/MME (2025)
Data centers	Intensive and adjustable demand	Local consumption of renewable surpluses, regional balancing between generation and load	Arbache (2024); Guedes (2024); Gomes et al. (2025)

Source: Authors' elaboration, based on Gomes et al. (2025), Arbache (2024), Guedes (2024), Aluko and Knight (2023), EPE (2022), and GIZ/MME (2025).

The joint analysis of the table shows that batteries and data centers operate in a complementary manner within the context architecture, articulating storage, consumption, and flexibility. While batteries act primarily on the temporal dimension, data centers influence the spatial distribution of demand, creating new arrangements for the absorption of renewable surpluses. This combination makes it possible to reduce exclusive reliance on transmission expansion as a response to curtailment, while simultaneously requiring regulatory adjustments capable of recognizing and remunerating these systemic services.

Recent literature indicates that coordination between energy storage and energy intensive loads represents a qualitative advance in the management of renewable surpluses. Gomes et al. (2025) argue that data centers, when integrated into a context architecture guided by appropriate regulatory signals, can function as flexibility anchors, simultaneously reducing energy losses and alleviating pressures on transmission expansion. This approach reinforces the role of such facilities not merely as passive consumers, but as active agents in the energy transition.

Finally, the coordinated integration of batteries and data centers reinforces the need for an integrated regulatory approach that simultaneously considers generation, networks, storage, and demand. As argued by Gomes et al. (2025), the absence of such coordination tends to reproduce inefficiencies and limit the positive effects of these technologies on the electric power system. In this sense, context architecture is consolidated as an analytical reference for understanding how these elements can contribute, in an articulated manner, to curtailment reduction and to the advancement of the Brazilian energy transition.

IV. DISCUSSION AND CONCLUSION

Brazil's energy transition, marked by the rapid expansion of variable renewable energy sources, has increasingly exposed the operational, regulatory, and economic limits of the national electric power system. In this context, curtailment ceases to be an episodic phenomenon and becomes a clear signal of misalignment between energy supply, available infrastructure, and the institutional mechanisms that guide sector operation. This study is situated within this scenario by addressing the problem from a systemic perspective, grounded in the concept of context architecture.

The results obtained allow us to state that the research fully met all the proposed objectives. The general objective was achieved by demonstrating that the articulation between context architecture, regulatory instruments, and economic mechanisms offers consistent pathways for mitigating curtailment in Brazil, particularly when renewable generation, transmission, energy storage, and new demand vectors are considered in an integrated manner. Likewise, the specific objectives were addressed coherently and in an articulated way throughout the theoretical framework.

In the first axis, dedicated to the analysis of curtailment as an expression of systemic inefficiencies, the findings showed that the problem stems less from isolated failures and more from a structural arrangement that

has not kept pace with the expansion of renewable generation. Table 1 provided an organized synthesis of the main causes of curtailment in the Brazilian electric power system, as well as its technical, economic, and institutional impacts, reinforcing the understanding that energy waste is directly associated with transmission bottlenecks, operational constraints, and regulatory rigidity.

The second axis, focused on regulatory architecture and economic compensation mechanisms, demonstrated that the instruments currently available still have limited reach given the complexity of the phenomenon. The analysis revealed normative gaps and asymmetries in the way curtailment costs are distributed among sector agents. Table 2 contributed to the systematization of these instruments, making it possible to clearly visualize their purposes, limitations, and effects on generation agents, while also highlighting the need for greater coherence between regulation, planning, and system operation.

In the third axis, the investigation of batteries and data centers as elements of context architecture showed that these components play a relevant role in reducing energy losses and increasing system flexibility. When incorporated as vectors of storage and intelligent demand, these elements contribute to the absorption of surplus renewable generation and to the alleviation of operational constraints. Table 3 consolidated this analysis by relating functions, systemic benefits, and challenges associated with the integration of these resources within the Brazilian energy transition.

Taken together, the research demonstrated that curtailment mitigation cannot be treated as an isolated or purely technical issue. It is a challenge that requires coordination among sectoral planning, economic regulation, and institutional design, guided by a context architecture capable of aligning incentives, technologies, and energy flows. By shifting the focus toward a systemic perspective, the study contributes to the debate on efficiency, economic rationality, and the responsible use of energy in the energy transition process.

As a further development, future research is encouraged to advance empirical analyses of comparative regulatory models, to investigate the economic feasibility of different large-scale storage arrangements, and to explore in greater detail the role of energy-intensive flexible loads, such as data centers, in the operation of the Brazilian electric power system. Studies that integrate operational simulations, regulatory assessments, and economic analyses may further expand understanding of the available pathways to reduce energy waste and to improve governance in the country's energy transition.

Finally, the study contributes to the advancement of academic and regulatory debate by proposing the context architecture as an analytical and normative instrument for mitigating curtailment in Brazil. By integrating regulation, technology, and new demand vectors, the research broadens the understanding of energy waste as a systemic issue rather than a merely operational one. This framing engages with the international literature on systemic flexibility and the governance of the energy transition, as discussed by IRENA (2025) and Lobo et al. (2026), and offers substantive inputs for improving public policies and the institutional design of the Brazilian electricity sector.

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