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Just Energy Transition and Energy Demands: Regulatory and Technical Challenges in the Integration of Green Hydrogen and Data Centers

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ABSTRACT
This article examines the limits and potential of integrating green hydrogen and data centers within an energy transition framework that calls for sustainable and inclusive solutions capable of meeting growing electricity demands. The study followed a qualitative approach and relied on two research procedures: a literature review and a document-based investigation. The literature review brought together theoretical contributions on energy transition, regulation, and electrical infrastructure, while the document-based investigation involved the analysis of technical reports, regulatory instruments, and institutional guidelines. These procedures complemented each other and provided a consistent foundation for the discussions presented. The general objective was to analyze how the integration of green hydrogen and data centers can be implemented in a technically efficient and regulatory-compliant manner, aligned with the principles of a just energy transition and Brazil's increasing energy needs. The collected evidence indicates that such integration is feasible, provided that adequate policies, a coherent institutional framework, and technical solutions are established to ensure stability, reliability, and efficiency in high-load environments.

Keywords: *energy transition; green hydrogen; data centers; regulation.*

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I. INTRODUCTION

Integration of energy transition, green hydrogen, and data centers has emerged as one of the most strategic topics in contemporary discussions on sustainability and electrical security. The rapid growth of computational demand, combined with pressure for renewable sources that reduce emissions and promote social equity, places Brazil before structural decisions that will shape the future of its energy matrix. In this context, understanding how large energy-intensive consumers can be integrated into the electrical system in a balanced manner is essential to ensure an orderly, reliable, and socially fair expansion.

The development of the article followed a qualitative approach suited to the interpretation of complex phenomena and employed two research procedures: a literature review and a document-based investigation. The literature review brought together theoretical contributions on energy transition, regulation, and electrical infrastructure, while the document-based investigation involved the examination of technical reports, regulatory norms, and institutional guidelines. These procedures complemented each other and provided a consistent foundation for the discussions presented.

General objective: To analyze how the integration of green hydrogen (GH_2) and data centers can be implemented in a technically efficient and regulatory-compliant manner, aligned with the principles of a just energy transition and Brazil's increasing energy demands.

Specific objectives: To examine how a just transition can guide the expansion of energy demand, reducing waste and curtailment while ensuring equitable energy access for vulnerable populations. To identify the main regulatory challenges associated with connecting large loads, such as data centers and GH_2 facilities, to the Brazilian electrical system. To assess the technical and operational requirements for integrating data centers powered by green hydrogen, considering stability, reliability, and efficient use of electrical infrastructure.

Finally, the article was organized into four sections that structure the analytical process: the Introduction, which outlines the topic and objectives; the Materials and Methods section, which details the approach and procedures used; the Theoretical Framework, which consolidates the selected references; and the Final Considerations, which synthesize the analyses developed throughout the study.

II. MATERIAL AND METHODS

A qualitative approach was adopted in the study, appropriate for examining complex phenomena that involve social, technological, and regulatory dimensions. This type of approach makes it possible to clarify relationships, meanings, and dynamics that cannot be reduced to numerical expressions, as well as to analyze, in context, the factors that influence the integration of green hydrogen and data centers into the electrical system. The choice of method is grounded in the literature on qualitative research in education and the social sciences, which emphasizes its relevance for studies that seek to understand complex realities.

Two complementary methods were used: a literature review and a document-based investigation. Fifteen works from national and international scientific journals were examined, authored by researchers who address issues related to energy transition, sectoral regulation, and electrical infrastructure. This detailed review enabled the collection of consolidated interpretations in the literature, as well as the organization of distinct theoretical perspectives relevant to the research topic.

The document-based investigation relied on the analysis of institutional documents produced by national and international organizations, including reports from the IPCC, guidelines from ANEEL, studies by EPE, analyses from the IEA, and Brazilian regulatory instruments. This set of documents presented the technical and regulatory elements essential for understanding the institutional framework that shapes growing energy requests and the integration of large consumers. The document analysis was crucial for identifying operational guidelines, access rules, and energy planning standards.

The relevance of each procedure is justified by the complexity of the topic. The literature review provided the theoretical foundation needed for a critical analysis of the connections among a just transition, energy requirements, and technological demands. The document-based investigation, in turn, supplied regulatory and structural information that clarifies how the introduction of large loads into the electrical matrix is shaped by policies, regulations, and technical standards.

The convergence of results from both procedures supported a robust and coherent analysis aligned with the central focus of the study. The connection between scientific literature and official documents offered a holistic view of the multiple social, technical, and regulatory dimensions involved, helping ensure methodological rigor and consistency throughout the research process.

III. THEORETICAL FRAMEWORK

The theoretical framework was organized into three axes that support the analysis developed throughout the study. The first examines how a just transition aligns with growing energy demand and the efficient management of the electrical matrix, emphasizing the relationship among equity, supply security, and the reduction of waste. The second addresses the regulatory framework applicable to large consumers and the conditions required for their connection to the electrical system, considering the normative, tariff-related, and institutional requirements that shape this process. The third evaluates the electrical infrastructure associated with computational loads and discusses the technical criteria needed for the integration of data centers powered by green hydrogen, with attention to stability, reliability, and consistency with the dynamics of digitalization.

3.1 Just Transition, Energy Demand, and the Efficient Management of the Electrical Matrix

Recent literature has advanced the understanding of a just transition as a central pillar of energy planning. Costabile, Simões, and Costa (2025) argue that this process requires policies capable of harmonizing environmental goals with social protections, particularly in regions marked by historical inequalities. This perspective aligns with Eisenberg (2019), who interprets the transition as a political commitment that must safeguard workers and communities affected by the modernization of energy infrastructure.

The connection between these references allows for a synthesis of the elements that link a just transition, energy needs, and efficiency in electricity use. To support this discussion and organize the key concepts identified in the literature, Table 1 will be presented immediately after the second paragraph, compiling the analytical axes that guide the approaches examined here. This inclusion makes the reading more accessible and helps highlight the interconnections among social equity, technical planning, and sustainability in the management of the electrical matrix.

Table 1. Main analytical axes linking just transition, energy demand and power system efficiency

Analytical axis	**Contributions to the debate**
Distributive justice	Relates equity, energy access and the mitigation of social inequalities.
Energy planning	Integrates policies to reduce curtailment, improve efficiency and expand renewable generation.
Social participation	Highlights the involvement of affected communities in policy formulation.
Socio-environmental sustainability	Connects climate goals with the protection of vulnerable populations.
Regulation and governance	Examines regulatory instruments that reconcile innovation with social safeguards.

Source: developed from Costabile, Simões and Costa (2025); Eisenberg (2019); García-García, Carpintero and Buendía (2020); Wang and Lo (2021); EPE (2023); IPCC (2023).

Researchers who examine the social dimensions of the energy transition argue that, for it to be effective, it must rely on mechanisms that distribute benefits and risks in a fair manner. García-García, Carpintero, and Buendía (2020) contend that structural changes in the electricity sector are only beneficial when accompanied by income and employment policies, while Wang and Lo (2021) add that energy justice concerns both access and the participation of vulnerable groups in decisions that affect them. These perspectives converge on the importance of recognizing communities as active participants in shaping the policies that guide the electrical matrix.

The intensive use of renewable sources has also generated discussions on energy planning, especially regarding the technical challenges involved. Projections from EPE (2023) indicate that the expansion of renewable sources may increase curtailment rates in the absence of integrated flexibility. A scenario of this nature reinforces the IPCC's (2023) recommendation for policies that integrate efficiency, security of supply, and the reduction of social disparities. Distributive justice and efficient management are therefore connected to regulatory instruments that reconcile technological innovation with social responsibility.

The theme of energy equity also includes the need to avoid waste and optimize energy use in regions with high renewable generation. Costabile, Simões, and Costa (2025) emphasize that a just transition cannot materialize without policies that democratize access and reduce territorial asymmetries. This view aligns with the argument presented by García-García, Carpintero, and Buendía (2020), who maintain that system efficiency is tied to models that recognize accumulated vulnerabilities and ensure fair participation conditions in the sector.

3.2 Regulatory Framework for Large Consumers and Their Connection to the Electrical System

The debate on the regulatory classification of large loads in Brazil shows that their connection to the electrical system is shaped by norms that have been refined over time in response to modernization needs. Lima and Ribeiro (2024) examine how Brazilian regulation has attempted to incorporate innovation and sustainable principles, noting that the sector still faces challenges in aligning its guidelines with the pace of technological change. Baptista, Silva, and Fonseca (2022) also contribute to this discussion by analyzing the legal nature of distributed generation and the limits it faces within the sector's regulatory structure.

Organizing the regulatory elements discussed throughout this section requires a concise presentation of the factors that structure the connection of large consumers to the electrical system. For this purpose, Table 2 is presented at this point, supporting the analysis before the discussion moves toward operational and institutional implications. Its inclusion helps clearly articulate the regulatory requirements, adjustment costs, and technical conditions addressed in the references examined.

Table 2. Key regulatory and operational factors for integrating large consumers into the Brazilian power system

Factor	**Description**
Regulatory compliance	Alignment with ANEEL resolutions and sectoral legislation governing access conditions and consumer classification.
Grid adequacy requirements	Technical demands for upgrading grid infrastructure to accommodate high-load facilities.
Tariff and compensation rules	Application of PRORET guidelines and tariff structures that influence cost allocation and consumer obligations.
Flexibility and curtailment management	Integration strategies that reduce curtailment and improve operational efficiency in regions with high renewable penetration.
Legal and institutional coordination	Interaction among ANEEL, ONS and MME in defining responsibilities and ensuring regulatory coherence.

Source: developed from Lima and Ribeiro (2024); Baptista, Silva and Fonseca (2022); ANEEL (2012; 2021); Brazil (2022); EPE (2021); Gomes et al. (2025).

The number of regulations governing network access is clearly reflected in ANEEL's resolutions, such as REN 482/2012, which establishes general conditions for the connection of micro- and mini-generators. In addition, PRORET Module 7.1, approved by REN 912/2021, sets out tariff definitions and access criteria, complementing this framework for various consumer categories. These documents show that the connection of large consumers is subject to specific requirements related to quality, safety, and infrastructure adequacy, which is particularly relevant for data centers and GH_2 facilities.

From a legal standpoint, new elements are introduced by Law 14.300/2022, which addresses the framework for distributed microgeneration and minigeneration. Although it does not apply directly to large loads, it highlights the sector's trend toward expanding compensation mechanisms and establishing clearer rules for interactions between consumer units and the grid. The relationship among this legislation, ANEEL's resolutions, and the guidelines issued by the Ministry of Mines and Energy reveals a segmented regulatory structure that often does not align with the demands posed by large-scale projects.

Discussions on energy efficiency also offer valuable insights for understanding the technical requirements associated with grid connection. The Energy Efficiency Atlas published by EPE (2021) shows the need for stronger mechanisms within the electrical system to manage consumption fluctuations and reduce structural losses. Gomes et al. (2025) indicate that the combination of data centers and GH2 facilities may contribute to curtailment management in regions with high renewable penetration, provided that appropriate compensation and flexibility policies are in place.

3.3 Electrical Infrastructure, Computational Demand, and the Integration of Green-Hydrogen-Powered Data Centers

There are several specific requirements for the operation of data centers that directly affect the performance of the electrical system. According to Gomes et al. (2025), such facilities play an important role in scenarios with high penetration of renewable sources, since their continuous demand can support curtailment management. As noted by Stacciarini and Gonçalves (2025), data centers have become essential to the digital economy and require uninterrupted energy flows, which increases the need for connection to sources capable of ensuring stability and security.

The text you shared contains misunderstandings and imprecise explanations, and it is important to clarify these points. A proper approach to defining the meaning of each term is essential to identify what has been misinterpreted or inaccurately presented.

The IEA (2024) projects that the growth of computational loads will place increasing pressure on electrical systems in several countries as digital services expand and advanced artificial intelligence models are deployed. This highlights the need to understand the electrical characteristics of these infrastructures, which, according to Brito, Matai, and Santos (2023), follow strict standards of efficiency and thermal management. Chatterjee and Venugopal (2023) point out that the high density of equipment in clusters dedicated to AI applications significantly raises the requirements for power supply, redundancy, and thermal control.

The literature indicates that global corporations have sought to reposition their data centers in relation to renewable sources. Calma (2024) notes that the industry is increasingly locating new facilities near solar and wind farms to reduce emissions and increase the direct use of clean energy. Alonso (2024) argues that, for information technology to align effectively with renewable matrices, robust regulatory frameworks and an infrastructure capable of supporting large loads are indispensable.

This discussion gains further relevance when the use of green hydrogen as an energy source is considered. The production of GH_2, when integrated with energy-intensive consumers, may contribute to greater system stability while supporting decarbonization strategies. In this context, it becomes important to systematize some of the main factors that guide this convergence. To that end, Table 3 is presented in a clear and concise manner, allowing a synthetic view of the technical requirements that structure the integration of GH_2-powered data centers before the text advances to the subsequent operational discussions.

Table 3. Technical requirements for integrating H_2V-powered data centers into electrical infrastructure

Requirement	**Description**
Continuous and stable power supply	Capacity to deliver uninterrupted energy compatible with high computational workloads.
Redundancy and reliability standards	Electrical architectures that ensure backup systems, low-failure configurations and robust operational continuity.
Power quality and harmonics control	Mitigation of disturbances caused by high-density equipment and electronic converters.
Cooling and thermal management integration	Compatibility between electrical supply strategies and advanced cooling systems required by dense IT loads.
Hydrogen-based energy interface	Conditions for coupling H2V production systems with large-scale computing infrastructures.

Source: developed from Gomes et al. (2025); Stacciarini and Gonçalves (2025); Brito, Matai and Santos (2023); Chen et al. (2022); Chkirbene et al. (2018); Choi et al. (2022); IEA (2024); Calma (2024).

Modern electrical distribution architectures have been the focus of research as a means to improve the efficiency of these facilities. Chen et al. (2022) examine the operation of large-scale data centers equipped with direct-current distribution systems and highlight advantages related to reduced losses and increased power density. As shown by Chkirbene et al. (2018), the energy consumption of telecommunications infrastructures is strongly influenced by traffic-optimization techniques and network-management strategies, underscoring the need for an integrated approach that connects computing and electrical engineering.

Models based on artificial intelligence have also been studied to enhance thermal and electrical efficiency in data centers. As discussed by Choi et al. (2022), adaptive systems can improve operations by adjusting dynamically to variations in load and temperature, which reduces instability and increases system reliability. These findings contribute to the analytical basis supporting the use of green hydrogen as an alternative for power supply and for sustaining essential operations.

IV. DISCUSSION AND CONCLUSION

The growing search for cleaner energy systems has brought renewed attention to the idea of integrating green hydrogen and data centers, especially when the goal is to balance new energy-intensive loads, social equity, and operational security. This reinforces the need to investigate solutions capable of meeting rising electricity demand without compromising fairness or system efficiency.

All of the objectives established for the study were successfully met. The research examined the intersection between a just transition and the expansion of large loads, addressed the regulatory challenges that shape the connection of major consumers, and explained the technical requirements governing the operation of data centers powered by green hydrogen.

The first table organized the analytical axes that link distributive justice, energy planning, social participation, socio-environmental sustainability, and governance, showing how these elements are essential for understanding a just transition in contexts of growing demand. This synthesis demonstrated that expanding energy capacity cannot be separated from social, climatic, and institutional criteria.

The second table presented the regulatory and operational factors that condition the entry of large loads into the electrical system. Regulatory compliance, grid adequacy, tariff rules, flexibility management, and institutional coordination revealed that the interconnection between data centers and hydrogen facilities is an issue that demands solid technical-legal arrangements.

The third table addressed the technical requirements for interconnecting data centers powered by green hydrogen, emphasizing continuous energy supply, reliability, quality and harmonic control, thermal integration, and the coupling interfaces between hydrogen production and electrical infrastructure. These elements illustrate the need for alignment between digital technologies and renewable energy matrices to ensure effective operation.

The data collected throughout the study suggest that integrating green hydrogen and data centers is feasible, provided that appropriate policies, a consistent institutional framework, and technical solutions capable of ensuring stability, reliability, and efficiency in high-load environments are in place.

Future research could focus on simulation models that incorporate land-use planning, smart grids, demand response, and storage dynamics, as well as comparative analyses of international strategies for integrating green hydrogen into large-scale digital services.

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