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POTENTIAL ENERGY INFRASTRUCTURE FOR DATA CENTER DEPLOYMENT IN NORTHEASTERN BRAZIL: A TECHNICAL ANALYSIS OF RENEWABLE ENERGY SOURCES AND ELECTRICITY AVAILABILITY

INFRAESTRUTURA ENERGÉTICA POTENCIAL PARA IMPLANTAÇÃO DE DATA CENTERS NO NORDESTE BRASILEIRO: UMA ANÁLISE TÉCNICA DAS FONTES RENOVÁVEIS E DA DISPONIBILIDADE ELÉTRICA

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ABSTRACT

The expansion of digital services has increased demand for data centers, and establishing this type of facility requires an uninterrupted electricity supply and adequate operating conditions. In this context, the research was guided by the following question: to what extent can the potential for solar and wind power generation, combined with electricity transmission and distribution infrastructure, supply reliability, and cooling conditions, support the deployment of data centers in Northeastern Brazil, given their continuous energy demands and operational requirements? The general objective was to analyze the current state of the region's energy infrastructure in terms of its capacity to accommodate these facilities, considering the availability of renewable energy sources, supply reliability, electricity grid capacity, and requirements related to cooling and operational continuity. Methodologically, the study adopted a qualitative approach based on bibliographic and documentary research. The former, exploratory and descriptive in nature, focused on publications from 2018 to 2026, while the latter covered technical standards, reports, expansion plans, and institutional documents concerning the electricity sector and data center infrastructure. The material was organized into three thematic areas: renewable energy generation and integration; electricity infrastructure and supply reliability; and the energy demands and operational requirements of these facilities. The results indicate that Northeastern Brazil has favorable conditions, particularly due to the availability of solar and wind resources. This advantage, however, is not sufficient on its own: the feasibility of these facilities also depends on transmission and distribution capacity, supply reliability, and the efficiency of cooling and energy storage systems. It is concluded that the integrated planning of renewable energy generation, the electricity grid, and operational

requirements is the factor that effectively guides the deployment of data centers in the region.
Keywords: Data centers; Solar energy; Wind energy; Electricity infrastructure.

RESUMO

A expansão dos serviços digitais tem pressionado a demanda por data centers, e instalar um empreendimento desse tipo exige energia elétrica disponível sem interrupção e condições operacionais adequadas. Diante disso, a pergunta que orientou esta pesquisa foi: em que medida o potencial de geração solar e eólica, somado à infraestrutura de transmissão e distribuição de eletricidade, à confiabilidade do fornecimento e às condições de refrigeração, sustenta a implantação de data centers no Nordeste brasileiro, diante de suas demandas energéticas contínuas e exigências operacionais? O objetivo geral foi analisar em que condições se encontra a infraestrutura energética da região para receber esses empreendimentos, considerando a disponibilidade de fontes renováveis, a confiabilidade do fornecimento, a capacidade da rede elétrica e as exigências ligadas à refrigeração e à continuidade operacional. Metodologicamente, o trabalho seguiu uma abordagem qualitativa, desenvolvida por meio de pesquisas bibliográfica e documental: a primeira, de caráter exploratório e descritivo, concentrou-se em publicações do período de 2018 a 2026; a segunda cobriu normas técnicas, relatórios, planos de expansão e documentos institucionais referentes ao setor elétrico e à infraestrutura de data centers. O material foi organizado em três eixos temáticos, a saber: geração e integração de fontes renováveis, infraestrutura elétrica e confiabilidade do fornecimento, e demandas energéticas e operacionais dessas instalações. Os resultados indicam que o Nordeste reúne condições favoráveis, sobretudo pela

disponibilidade de recursos solares e eólicos. Essa vantagem, no entanto, não é suficiente isoladamente: a viabilidade desses empreendimentos está condicionada também à capacidade de transmissão e distribuição, à confiabilidade do fornecimento e à eficiência dos sistemas de refrigeração e de armazenamento de energia. Conclui-se que o planejamento integrado da geração renovável, da rede elétrica e das exigências operacionais é o fator que efetivamente orienta a implantação de data centers na região.
Palavras-chave: Data centers; Energia solar; Energia eólica; Infraestrutura elétrica.

1. INTRODUCTION

The expansion of digital technologies has increased the demand for infrastructure capable of processing, storing, and providing access to large volumes of information. Data centers support the operation of digital services, corporate systems, communication platforms, and artificial intelligence applications. However, their operation requires a continuous electricity supply, efficient cooling systems, and infrastructure that ensures stability and operational availability. Therefore, decisions regarding their location are not based solely on economic and technological criteria. The region's capacity for electricity generation, transmission, and distribution also plays an important role.

In Brazil, this discussion involves the Northeast, particularly because of the availability of natural resources favorable to solar and wind power generation. The existence of these energy sources, however, does not in itself ensure that the demands of large consumers can be met, since energy utilization depends on transmission capacity, grid connection conditions, and supply reliability. Data centers also

have their own energy requirements, including cooling, storage, and support systems for operational continuity. It is this combination of renewable resources, electricity infrastructure, and the technical requirements of data centers that determines the regional conditions for new developments.

Based on these considerations, the research was guided by the following question: to what extent can the potential for solar and wind power generation, combined with electricity transmission and distribution infrastructure, supply reliability, and cooling conditions, support the deployment of data centers in Northeastern Brazil, considering their continuous energy demands and operational requirements?

To address this question, the general objective was to analyze the conditions of the energy infrastructure in Northeastern Brazil for data center deployment, considering the regional availability of solar and wind power generation, electricity supply reliability, transmission and distribution capacity, and the energy requirements associated with cooling and operational continuity in these facilities. The specific objectives were to examine the availability and geographical distribution of solar and wind resources, as well as their potential integration into the energy supply of data centers; investigate whether the transmission and distribution infrastructure has the capacity to serve these facilities, considering grid connection, supply reliability, and location; and assess the energy and operational requirements involved, with particular attention to continuous electricity demand, cooling systems, energy storage, and operational continuity requirements.

Regarding the methodological procedures, a qualitative approach supported by bibliographic and documentary research was adopted. The bibliographic search, exploratory and descriptive in nature, prioritized studies published between 2018 and 2026. The documentary research, in turn, gathered technical standards, reports, expansion plans, and institutional publications related to the electricity sector and data center infrastructure. This reliance on secondary sources entails a limitation: the discussion of transmission capacity and supply reliability is based on data previously measured and published by third parties, rather than on original surveys of grid data. The collected material was organized and interpreted according to three analytical areas: renewable energy generation and integration; electricity infrastructure and supply reliability; and the energy demands and operational requirements of data centers.

In addition to this introduction, the article is organized into three sections. The second presents the theoretical framework, divided into three topics: the solar and wind resources of Northeastern Brazil; electricity infrastructure and supply reliability; and the energy demands, cooling systems, and operational continuity of data centers. The third describes the methodological procedures adopted in the research. Finally, the fourth presents the concluding remarks, synthesizing the main evidence discussed, the contributions of the study, and possible directions for future research.

2. THEORETICAL FRAMEWORK

2.1. Potential Solar And Wind Resources In Northeastern Brazil And Their Application To Data Center Energy Supply

The increasing generation of electricity from renewable sources is creating growing opportunities to meet the needs of large consumers, such as data centers, which cannot tolerate interruptions in their electricity supply. The abundance of solar and wind resources in Northeastern Brazil makes the region suitable for the development of power generation projects, considering its climatic and geographical characteristics. However, assessing a region's energy conditions requires distinguishing among the availability of natural resources, installed generation capacity, and the electricity actually generated. According to Dantas et al. (2019), the expansion of this energy source also depends on territorial and socio-environmental conditions that must be considered when planning projects. The existence of favorable natural conditions for energy development does not, in itself, mean that sufficient electricity is available to supply data processing and storage facilities.

Wind power generation exhibits variability associated with changes in wind speed and direction, making it necessary to understand the temporal behavior of atmospheric resources to estimate electricity production. De Paula et al. (2020), by comparing machine learning models applied to long-term wind speed forecasting in wind farms in Northeastern Brazil, demonstrate the importance of predictive methods for characterizing the behavior of this energy source. From a complementary perspective, Ramos (2021), using high-resolution regional climate projections, investigates possible changes in wind regimes in Northeastern Brazil over different future periods. These contributions indicate that energy planning should not be restricted to current observed meteorological conditions, but should also consider interannual variability and potential climate change. For data centers, this assessment is particularly relevant because variable wind power generation must be coordinated with energy

procurement mechanisms, electrical integration, and complementary resources capable of sustaining the supply to a load that cannot depend exclusively on wind availability.

Solar energy availability in Northeastern Brazil varies spatially, according to the distribution of solar irradiation across different locations, and temporally, due to daily, seasonal, and meteorological fluctuations in photovoltaic generation. Thus, favorable solar radiation for installing power plants in the region does not, by itself, guarantee the amount of electricity actually delivered to the grid. Lima et al. (2025), when testing the forecast quality of the GFS-MOS and WRF-Solar global solar irradiance models, worked with data from 101 meteorological stations operated by INMET across different locations in Northeastern Brazil. GFS-MOS performed better than WRF-Solar, although the authors identified limitations under certain low-irradiance conditions, precisely when reliable forecasts are particularly important for planning purposes. In practice, weather forecasting helps plan photovoltaic generation and schedule energy supply, but it does not eliminate the uncertainties inherent in solar resource availability.

The variability of renewable energy sources is directly related to electricity supply continuity, particularly in facilities whose operation depends on an uninterrupted power supply. Silva et al. (2024, p. 02) provide the following characterization:

> *Among established renewable energy sources, some have an approximately constant supply, such as geothermal energy, hydropower with reservoir regulation, and biomass. However, others depend on meteorological variables and therefore exhibit high variability and low predictability. This is the case with wind, solar, and hydropower generation when no storage reservoir is available. These sources are referred to as intermittent.*

This distinction makes it possible to understand that the availability of solar and wind resources does not necessarily correspond to the capacity to ensure electrical power throughout all operating periods of a data center. Consequently, the contribution of these sources to supplying such facilities must be examined in conjunction with generation diversification, energy storage, and the use of the infrastructure of the interconnected power system.

The complementarity between solar and wind energy represents an opportunity to reduce temporal fluctuations in generation, provided that their respective production profiles exhibit patterns favorable to mutual compensation. Carpio and Guimarães (2024, p. 02) emphasize that:

> *Uncertainties in renewable energy generation, diurnal and seasonal variability, and the intermittency of certain natural resources have hindered the large-scale adoption of renewable energy. Despite these disadvantages, expanding renewable energy generation is a viable investment for a more sustainable world. The high penetration of intermittent sources can be supported by exploiting potential complementarities to increase the balance between electricity load and generation. Complementarity studies employ different methods according to their intended objectives. Some assess only the behavior of natural resources over different periods and seasons of the year, relying primarily on linear correlation calculations.*

When investigating the regional diversification of hydropower, wind, and solar sources in the Brazilian electricity system, the authors employ a mean-variance model to examine combinations capable of reducing generation variability. This approach helps demonstrate that complementarity depends on the correlation between production profiles and the geographical distribution of projects, and cannot be assumed merely because solar and wind farms are simultaneously present in a region.

In Northeastern Brazil, this complementarity can be assessed by combining statistical indicators with operational information from the power plants themselves, making it possible to identify periods when reduced generation from one source is offset by production from another. Silva et al. (2024) developed complementarity maps for intermittent sources in Northeastern Brazil, considering correlation indices over a representative year. Silva Filho et al. (2024), in a study specifically focused on hybrid power plants, examined the complementarity between wind and photovoltaic generation based

on the capacity factors of existing projects, using data provided by the Brazilian National Electric System Operator (ONS). They identified conditions under which solar generation compensates for periods of lower wind power production.

These findings are useful for developing energy diversification strategies, but caution is necessary when extrapolating them: complementarity between two sources does not, in itself, ensure continuous supply. For this purpose, generation levels, project scale, grid connection capacity, and, above all, the temporal correspondence between electricity production and data center demand must also be considered.

Another factor affecting the use of renewable generation concerns operational constraints that may prevent the full delivery of the electricity produced. Vieira et al. (2026, p. 02) state that:

> *The integration of wind and solar energy is essential for global decarbonization, but forced curtailment, characterized by reductions in renewable energy generation due to grid or market constraints, remains a significant barrier. High shares of Variable Renewable Energy (VRE) increase the risk of curtailment, leading to inefficiencies and economic losses. The financial impact is substantial: in the United Kingdom, billions of pounds have been paid in compensation to generators whose production was curtailed. At the same time, China has revised its regulatory framework in response to persistent curtailment challenges.*

Vieira et al. (2026), in their investigation of the Brazilian electricity system, identify different operating conditions associated with

generation curtailment, including the concentration of variable renewable energy sources in Northeastern Brazil and limitations related to the electricity system. Therefore, a power plant's installed capacity should not be confused with the electricity actually delivered to the system, since transmission, operational, and dispatch constraints may reduce the utilization of available production.

The interpretation of regional energy conditions therefore requires distinguishing among five complementary dimensions: the available natural resource, corresponding to solar irradiation and wind conditions; the technical generation potential, which considers the possibilities of converting these resources into electricity; installed capacity, expressed in units of power, such as megawatts (MW); the energy actually produced and made available, expressed in megawatt-hours (MWh); and firm power, which refers to the capacity to meet demand under previously established availability and reliability conditions. This distinction is particularly important for data center planning because a facility may have high and continuous electricity consumption even during periods of low solar or wind generation. Tyaquiçã et al. (2026), when analyzing winds at a height of 100 meters in Northeastern Brazil using ERA5 reanalysis data for the period from 1980 to 2025, identified interannual variability patterns and climate trends relevant to wind power planning. Their results reinforce the need to consider the evolution of natural resources and climate resilience when assessing projects, without confusing regional wind availability indicators with estimates of actual generation at specific locations.

The systematization of these contributions makes it possible to relate the characteristics of solar and wind resources to the

conditions required for their use in supplying data centers. To facilitate this understanding, Table 1 brings together the main dimensions examined, their implications for electricity supply planning, and the corresponding scientific contributions, distinguishing natural generation conditions from the limitations that affect the actual availability of electricity.

Table 1. Assessment Dimensions of Solar and Wind Potential and Their Contribution to Data Center Energy Supply in Northeastern Brazil

Dimension analyzed	Aspects considered in the assessment	Scientific contribution (author and abbreviated title of the work)
Wind resource availability	Territorial conditions, wind characteristics, and socio-environmental aspects of wind farm development.	Dantas et al. (2019). Wind power on the Brazilian Northeast Coast.
Wind predictability	Wind speed variability and the application of predictive models.	De Paula et al. (2020). Predicting long-term wind speed in wind farms of northeast Brazil.
Climate variability	Climate projections and possible future changes in wind regimes.	Ramos (2021). Projeções climáticas regionais em alta resolução.
Regional complement arity	Temporal correlation between renewable sources and geographical distribution of energy resources.	Silva et al. (2024). Análise da complementaridade de fontes intermitentes no nordeste brasileiro.
Energy diversification	Combination of hydropower, solar, and wind sources to reduce generation fluctuations.	Carpio and Guimarães (2024). Regional diversification of hydro,

		wind, and solar generation potential.
Solar-wind integration	Capacity factors and compensation between generation profiles in hybrid power plants.	Silva Filho et al. (2024). Análise de complementaridade solar em usinas híbridas.
Generation constraints	Renewable energy curtailment resulting from operational limitations and electricity system constraints.	Vieira et al. (2026). Characterizing wind and solar curtailment in Brazil.
Solar predictability	Solar irradiance forecasting models and differences in performance across locations in Northeastern Brazil.	Lima et al. (2025). Evaluation of the short and medium-term forecast quality of global solar irradiance.
Wind resource resilience	Climate trends, interannual variability, and wind behavior at a height of 100 meters.	Tyaquiçã et al. (2026). Climate drivers and long-term trends of 100 m winds in Northeast Brazil.

Source: Prepared by the authors (2026), based on the works of Dantas et al. (2019), De Paula et al. (2020), Ramos (2021), Silva et al. (2024), Carpio and Guimarães (2024), Silva Filho et al. (2024), Vieira et al. (2026), Lima et al. (2025), and Tyaquiçã et al. (2026).

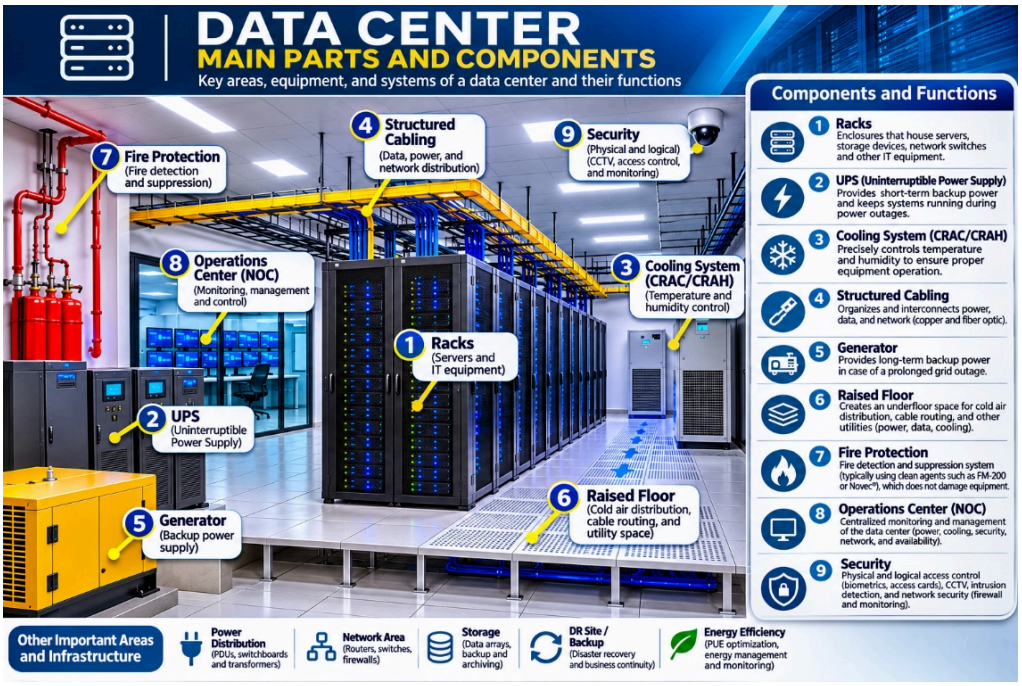
Finally, the analysis of solar and wind generation conditions makes it possible to recognize that the contribution of these sources to data center deployment in Northeastern Brazil depends on the integration of natural resource availability, production predictability, energy complementarity, and effective utilization of the electricity generated. Although diversifying energy sources can reduce supply variability, the operational continuity of these facilities requires that the contracted or generated electricity be effectively available during

periods of demand, including when renewable generation reductions occur. Therefore, characterizing solar and wind resources constitutes the first dimension in assessing the region's energy infrastructure and must be complemented by an investigation of transmission and distribution capacity, grid connection conditions, and electricity supply reliability, which are addressed in the following section.

2.2. Electrical Infrastructure, Transmission Capacity, And Supply Reliability For Data Centers

The deployment of data centers in a given region does not depend exclusively on the availability of electricity in terms of generation capacity or on the existence of a predominantly renewable energy mix. These facilities require a continuous power supply, the capacity to accommodate high electrical loads, voltage and frequency stability, and connections compatible with their operational scale. Therefore, the assessment of electrical infrastructure must jointly consider generation capacity, the performance of transmission and distribution systems, grid connection conditions, and the resources allocated to ensuring continuity of supply. The Energy Research Office (EPE) emphasizes that data centers represent large electrical loads whose accommodation directly affects transmission expansion planning and requires advance information on the power demand of these facilities (EPE, [s. d.]). Figure 1 provides an overview of the main components of a data center.

Figure 1. Main infrastructure components and systems of a data center.



Source: Prepared by the authors with the assistance of ChatGPT (OpenAI, 2026).

The integration of renewable energy sources into large-scale power systems also requires coordinated planning between generation and energy transmission infrastructure. Carpio and Guimarães (2024, p. 05) state that:

> *Some studies have analyzed the impact of the progressive increase in renewable energy sources on energy security and transmission and distribution networks, concluding that the optimal allocation of renewable energy sources is an important task in energy system expansion planning. This study proposes a sustainable approach to smoothing the variability of hydropower, wind, and solar generation by analyzing the potential for regional complementarity, taking into account the heterogeneity of the regional generation potential of these sources, as well as the existing correlations between atmospheric conditions across regions. The objective is to identify a way for power systems to become predominantly composed of renewable energy sources over the coming decades, thereby reducing excessive dependence on fossil fuels and increasing security of supply.*

In the Brazilian context, increasing the share of renewable energy sources must be accompanied by investments in transmission lines, substations, and electrical control equipment. The Ten-Year Energy Expansion Plan 2034 recognizes that wind and photovoltaic expansion poses new challenges for transmission planning, particularly because of the varying locations of these projects and the need to transmit regionally generated electricity (EPE, 2025).

In the Northeast, this relationship between generation expansion, transmission capacity, and the supply of new loads is particularly relevant in the states of Ceará and Piauí. The PAR/PEL 2025, prepared by the Brazilian National Electric System Operator (ONS), identifies voltage stability constraints along the Rio Grande do Norte, Ceará, and Piauí corridor and presents the so-called “Ponte Solution,” designed to enable the connection of up to 3 GW of new large

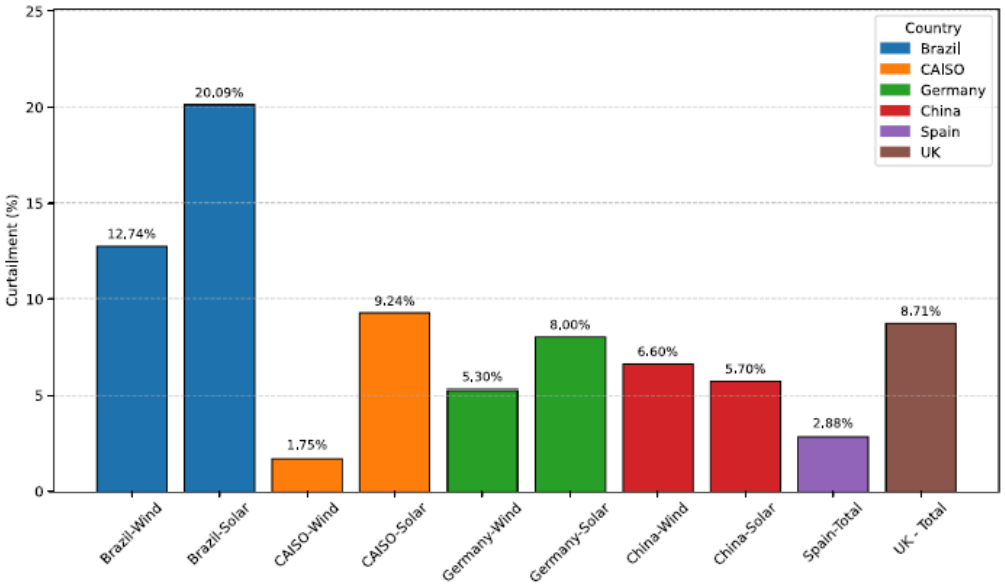
consumers in these states in the medium term. The proposal includes the installation of five synchronous condensers at the Açu III, Ceará Mirim II, Morada Nova, and Quixadá substations, with the aim of strengthening electrical stability margins and ensuring the transmission of regional renewable energy generation (ONS, 2025).

The need to ensure that load expansion is compatible with operational security is also evident in the generation constraint data presented by Vieira et al. (2026, p. 02), who report that:

> *Recent data highlight that Brazil has some of the highest generation curtailment rates among major power systems. Figure 2 shows that, in the first half of 2025, Brazil's average generation curtailment rate exceeded those of Germany, Spain, the United Kingdom, China, and the California Independent System Operator (CAISO). For comparison, China recently increased its maximum tolerated curtailment rate from 5% to 10%, while Spain recorded an increase following a blackout in April 2025. In terms of renewable energy penetration, Germany leads with 65.9% of wind and solar energy in its installed energy mix in 2024, followed by Spain (54.7%), the United Kingdom (46.8%), China (43.8%), CAISO (36.6%), and Brazil (35%).*

The comparison presented in Figure 2 illustrates the extent of generation curtailment recorded in Brazil relative to the selected power systems, providing a basis for discussing transmission capacity constraints and the need to strengthen transmission infrastructure.

Figure 2. Comparison of average generation curtailment rates in the first half of 2025 across different countries and power systems.



Source: Vieira et al. (2026).

The expansion of transmission infrastructure is one of the conditions for increasing the capacity to serve large consumers. The Energy Transmission Report of the Ten-Year Energy Expansion Plan 2035 (PDE 2035), prepared by the Ministry of Mines and Energy and the Energy Research Office (EPE), estimates investments of approximately BRL 120 billion in the transmission system by 2035. This figure already accounts for, among other factors, the growth of renewable energy sources and the connection of new large-scale loads, including data centers and hydrogen production facilities using electrolysis (Brasil, 2025). The PAR/PEL 2025 follows the same direction by forecasting new transmission lines and transformers, as well as reinforcements to interregional interconnections, suggesting that transfer capacity between subsystems is likely to play an increasingly important role in meeting future demand (ONS, 2025).

However, planned investments should not be confused with guaranteed electricity supply. Assessing supply reliability also involves operational and power quality indicators. The Brazilian National Electric System Operator (ONS) provides metrics on the robustness of the Basic Grid, the duration and frequency of load interruptions, and unsupplied energy. These indicators make it

possible to monitor system performance and identify vulnerabilities that could affect large consumers (ONS, 2026). At the distribution level, ANEEL Normative Resolution No. 956/2021 establishes the Distribution Procedures (PRODIST), which include procedures for expansion planning, user connections, system operation, and supply quality. These regulatory parameters provide the basis for examining the technical conditions of grid connections and the performance of the network supplying consumer facilities (ANEEL, 2021).

There is, moreover, an issue that undermines any optimistic assessment based solely on installed infrastructure: major disturbances in the National Interconnected System demonstrate that the availability of grid infrastructure does not, in itself, eliminate the risk of interruptions or instability. The audit conducted by the Federal Court of Accounts (TCU) concerning the event of August 15, 2023, examined the causes and consequences of the disturbance that affected electricity supply in different regions of the country. The analysis identified issues related to the performance of protection systems, voltage control, and the operation of generation and transmission equipment. It also drew particular attention to coordination among the agents involved and to the compatibility between the models used in electrical studies and the actual behavior of the equipment (TCU, 2025).

In view of these issues, the assessment of the available electrical infrastructure for data centers was organized around complementary dimensions: the physical capacity of the grid, connection conditions, operational stability, supply quality, and expansion prospects. Table 2 brings together these dimensions and indicates, for each one, what the institutional and scientific references used in this discussion effectively provide.

Table 2. Dimensions for assessing electrical infrastructure and its suitability for serving data centers in Northeastern Brazil

Dimension analyzed	Aspects considered	Contribution to data center deployment	Author and abbreviated title of the work
Electrical expansion planning	Demand projections, generation expansion, transmission lines, and substations.	Makes it possible to assess whether planned expansion keeps pace with the growth of large-scale loads.	EPE, *Ten-Year Energy Expansion Plan 2034*.
Transmission capacity	Length of transmission lines, transformer capacity, and interchange limits between subsystems.	Indicates the conditions for transmitting electricity to the facilities' connection points.	ONS, *PAR/PEL 2025: Medium-Term Electrical Operation Plan for the SIN*.
Connection of large consumers	Availability of connection points, supply capacity, and reinforcements required to integrate new loads.	Makes it possible to identify technical constraints and interventions required to connect data centers.	ONS, *PAR/PEL 2025: Executive Summary, 2026–2030 cycle*.
Electricity supply to data centers	Power requirements, energy consumption, and regional concentration of loads.	Supports grid expansion planning according to the characteristics of the facilities.	EPE, *Data Center Consumption*.
Supply quality and	Robustness of the Basic Grid,	Makes it possible to assess supply	ONS, *Supply Quality*.

continuity	duration and frequency of interruptions, and unsupplied energy.	reliability and the risks of operational interruptions.	
Structural expansion of transmission infrastructure	Investments, new transmission lines, substations, and reinforcements to regional interconnections.	Indicates prospects for increasing the capacity to serve large consumers.	MME and EPE, *PDE 2035: Energy Transmission Report*.
System security	Disturbances, performance of protection systems, voltage control, and system restoration.	Highlights operational vulnerabilities and the need for preventive and corrective measures.	TCU, *Audit of the disturbance in the National Interconnected System*.
Voltage stability and integration of large loads	Synchronous compensation, stability margins, and transmission constraints along the RN-CE-PI corridor.	Identifies technical solutions to enable new connections in Ceará and Piauí.	ONS, *PAR/PEL 2025: Connection of Large Consumers in Ceará and Piauí*.
Regional integration of renewable energy sources	Complementarity among hydropower, wind, and solar generation, as well as regional correlations.	Links renewable energy expansion to energy security and transmission planning.	Carpio and Guimarães, *Regional Diversification of Hydro, Wind, and Solar Generation Potential*.
Renewable generation curtailment	Curtailment, grid limitations, and operational	Demonstrates that the existence of renewable generation does	Vieira et al., *Characterizing Wind and Solar*

	conditions of power systems.	not, by itself, ensure its availability for consumption.	*Curtailment in Brazil*.
Technical distribution requirements	Expansion planning, connection procedures, operation, and supply quality.	Establishes regulatory parameters for assessing grid connections and distribution network performance.	ANEEL, *Normative Resolution No. 956/2021*.

Source: Prepared based on EPE (2025; [s. d.]), ONS (2025; 2026), Brasil (2025), TCU (2025), Carpio and Guimarães (2024), Vieira et al. (2026), and ANEEL (2021).

The assessment of electrical infrastructure in Northeastern Brazil for data center deployment must therefore go beyond identifying regional generation capacity and consider the actual capacity for grid connection, electricity transmission, system stability, and continuity of supply.

In Ceará and Piauí, the provision for connecting up to 3 GW of new large consumers, subject to reinforcements in voltage stability along the RN-CE-PI corridor, constitutes concrete evidence that the expansion of these facilities depends on specific interventions in the grid.

Thus, the electrical feasibility of these projects must be examined based on the integration of energy planning, power availability, transmission and distribution capacity, supply quality, and redundancy solutions. These factors condition the continuous

operation of data centers and their integration into the regional energy infrastructure.

2.3. Energy Demand, Cooling, Storage, And Operational Continuity Of Data Centers

The growing use of digital services, cloud computing, and artificial intelligence applications has increased global electricity demand in data centers. The International Energy Agency (IEA) reported that these facilities consumed approximately 415 TWh in 2024, representing around 1.5% of global electricity consumption, and this figure is expected to increase to approximately 945 TWh by 2030.

This trend demonstrates that the deployment of new facilities requires energy planning compatible with high and continuous electrical loads, particularly because supply interruptions can compromise digital services, information processing, and data storage (IEA, 2025).

The energy consumed by a data center extends beyond the servers used for data processing. Total demand also includes storage equipment, communication and networking devices, uninterruptible power supply (UPS) systems, power distribution units, transformers, cooling and air-conditioning equipment, fans, pumps, lighting, and monitoring and security systems.

Depending on the facility's scale, computing density, technology, and operating conditions, each component plays a distinct role. In this regard, the efficiency of information technology equipment also affects the sizing of auxiliary systems, since lower energy consumption by servers results in a smaller thermal load that must

be dissipated by the cooling system (IEA, 2025; Van Geet and Sickinger, 2024).

Among auxiliary systems, cooling is undoubtedly one of the most critical, since data processing equipment converts a large proportion of the electricity it consumes into heat, which must be continuously dissipated to keep electronic components operating under optimal conditions.

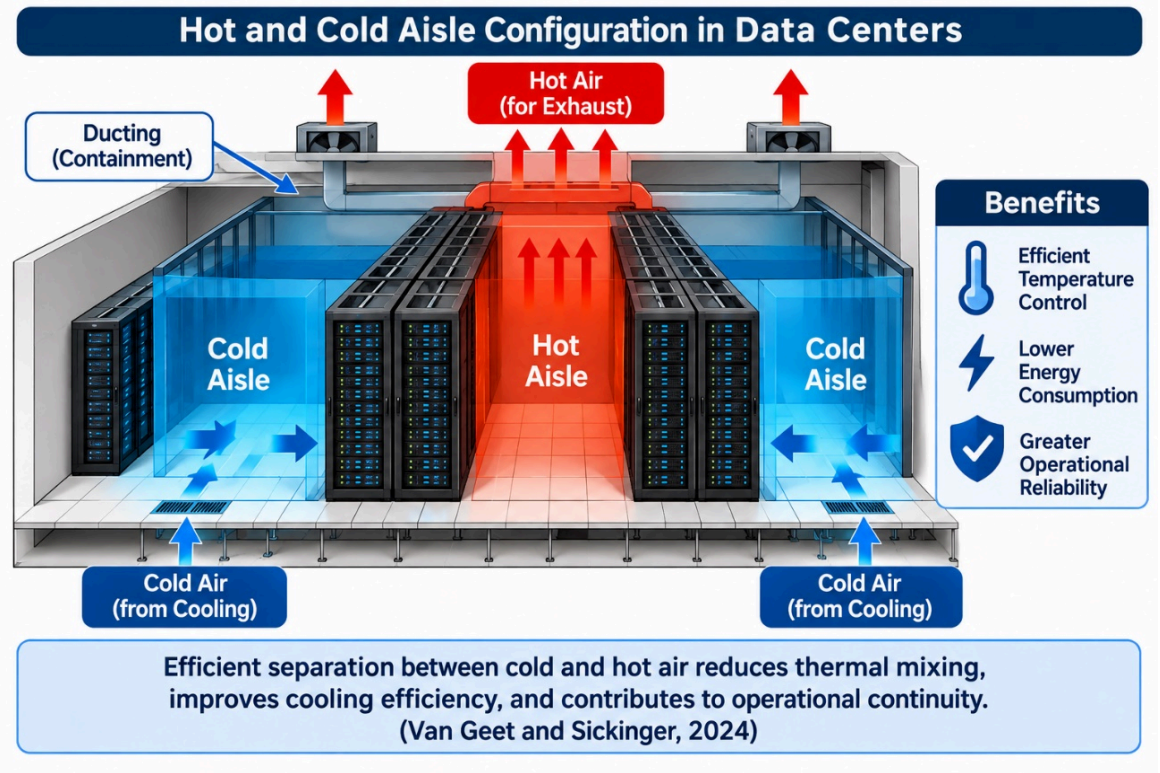
The selection of cooling technology must take into account rack thermal density, aisle arrangement, airflow dynamics, ambient temperature and humidity, as well as the efficiency of chillers, fans, and pumps. Thermal management should not be considered in isolation, as the literature demonstrates that equipment layout and airflow management directly affect the energy consumption of mechanical systems and the operational stability of the facility (Lin et al., 2024; ASHRAE, 2021).

With the wide range of cooling technologies available, thermal infrastructure can be adapted to the specific characteristics of the equipment and the environment in which the facility is located. According to Chang et al. (2024, p. 02),

> *Data center cooling is crucial for safeguarding equipment functionality and improving energy efficiency, and is primarily categorized into air-cooling and liquid-cooling systems. Air-cooling methods, including direct cooling, indirect cooling, and evaporative cooling, improve efficiency through optimized airflow management. Liquid-cooling methods, such as cold-plate cooling, immersion cooling, and spray cooling, directly cool components using liquid, increasing server efficiency and stability while reducing energy consumption and noise.*

To illustrate one of the thermal management strategies mentioned, Figure 3 presents the separation of hot and cold aisles, a configuration that reduces the mixing of heated air discharged by equipment with the cooled air supplied to server inlets.

Figure 3. Hot and Cold Aisle Configuration in Data Centers.



Source: Prepared by the authors (2026).

Note: Artificial intelligence (ChatGPT, OpenAI) was used as an auxiliary tool in the preparation and visual design of the figure. The technical content and cited reference (Van Geet and Sickinger, 2024) were retained by the authors.

The efficiency of a cooling system is determined not only by the technology selected but also by how that technology interacts with the climate in which it will operate. In their study, Liu et al. (2021) found that adjusting chilled water supply and return temperatures according to the climate of each region significantly reduced the annual energy consumption of cooling systems. Focusing on facilities with multiple chillers, Zhang, Li, and Wang (2024) add that the load is not static: it increases progressively throughout the facility's service life, and designs that fail to account for this factor do not age well. Taken together, these contributions indicate that, in Northeastern Brazil, thermal system sizing must be based on local temperature and humidity conditions, water availability, and variations in computational load. Otherwise, standardized solutions may be adopted without ever having been assessed against the actual environmental conditions of the facility.

Thermal modeling and integrated equipment control represent another approach to reducing energy consumption without compromising operational safety. The study by Lin et al. (2024) examines methods that combine three areas: computational workload distribution, thermal management, and cooling control. The practical value of this integration lies in preventing overcooling, which directly results in wasted electricity. Along the same lines, Chang et al. (2024) address control strategies and performance indicators for these systems. For facilities in the Northeast, the value of these approaches is tangible: they make it possible to compare solutions that reconcile energy efficiency with the control of thermal conditions under environmental and operational variations that an imported solution simply does not anticipate.

Operational continuity also depends on the availability of resources capable of responding to failures in the electricity supply or cooling equipment. UPS systems provide temporary power to critical equipment during interruptions or transitions between power sources, while emergency generators can sustain operations for longer periods, depending on their capacity, autonomy, and fuel availability. Peng et al. (2024) examine UPS architectures with energy storage and control strategies that expand the functions of these units, including applications in electricity demand management. In the field of thermal management, Ma, Zhang, and Zou (2022) investigate the integration of a closed-loop thermosyphon with latent thermal energy storage, experimentally demonstrating the possibility of keeping servers operational for approximately six minutes after the conventional cooling system is interrupted, with the potential to extend this period through adjustments to the materials used.

The integration of these resources requires the project to address three closely related issues from the initial design stage: redundancy, autonomy, and compatibility between electrical and thermal systems. The technical guide by Van Geet and Sickinger (2024) recommends assessing both the loads expected at the beginning of operations and those projected for the future, verifying the efficiency of power distribution equipment, examining UPS performance under different loading levels, and considering the available thermal storage alternatives. ASHRAE (2021) addresses another aspect of the problem by establishing the environmental operating conditions for data processing equipment, with temperature and humidity ranges defined according to each equipment class. Neither document, on its own, guarantees operational continuity. Attributing continuity solely to the presence of generators or batteries is an oversimplification because maintaining safe facility operation requires the simultaneous availability of electrical power, cooling, monitoring, and the necessary control systems.

The assessment of energy performance requires indicators capable of relating the consumption of information technology equipment to the facility's total demand. In this context, ISO/IEC 30134-2:2026 establishes the criteria for defining, measuring, calculating, and reporting Power Usage Effectiveness (PUE), an indicator obtained by dividing the total energy consumed by the data center by the energy used by its information technology equipment. The edition published in January 2026 updates measurement requirements, addresses on-site electricity generation, and incorporates guidance for facilities located in mixed-use buildings. However, PUE should not be interpreted in isolation as a measure of reliability, renewable energy availability, or water efficiency. It is therefore advisable to

associate it with other performance and operational continuity indicators (ISO; IEC, 2026).

Table 3 brings together the main components of energy consumption and the technical resources required to ensure thermal efficiency and operational continuity in data centers, relating each dimension to the contributions of the works used in this theoretical framework.

Table 3. Energy demand components and efficiency and operational continuity requirements for data centers

Dimension analyzed	**Technical aspects considered**	**Relevance to deployment in Northeastern Brazil**	**Author and abbreviated title of the work**
Global energy demand	Electricity consumption by data centers and projections for demand growth.	Supports planning for the energy supply capacity required by new facilities.	IEA, Energy and AI.
IT equipment consumption	Servers, storage, network equipment, and computational processing.	Makes it possible to identify the share of demand associated with the facility's core activities.	Lin et al., Thermal Modeling and Thermal-Aware Energy Saving Methods for Cloud Data Centers.
Air and liquid cooling	Direct, indirect, and evaporative cooling, cold plates, immersion, and spray cooling.	Guides the selection of cooling technologies according to thermal density and	Chang et al., Optimization Control Strategies and Evaluation Metrics of Cooling Systems in Data Centers.

		environmental conditions.	
Airflow management	Hot and cold aisle separation, ventilation, and airflow control.	Reduces thermal recirculation and contributes to the efficiency of cooling systems.	Van Geet and Sickinger, Best Practices Guide for Energy-Efficient Data Center Design.
Climate adaptation of cooling systems	Chilled water temperature, humidity, wet-bulb temperature, and environmental conditions.	Makes it possible to adapt cooling systems to the climatic characteristics of each location.	Liu et al., Optimal Setting Parameters of Cooling System under Different Climate Zones.
Chiller performance	Equipment efficiency, partial-load operation, and variations in thermal demand.	Contributes to the appropriate sizing of cooling systems throughout their service life.	Zhang, Li, and Wang, Energy Performance Analysis of Multi-Chiller Cooling Systems.
Thermal energy storage	Thermosyphons, phase-change materials, and cold energy storage.	Provides temporary cooling support during failures or interruptions of the conventional system.	Ma, Zhang, and Zou, Thermal Performance of a Loop Thermosyphon Integrated with Latent Thermal Energy Storage.
Uninterruptible power supply	UPS systems, batteries, electrochemical storage, and control strategies.	Maintains power supply to critical equipment during interruptions in the external electricity supply.	Peng et al., Energy Storage Type of UPS and Its Control Method in Internet Data Centers.

Environmental conditions for equipment	Permissible temperature and humidity ranges and thermal operating requirements.	Guides the environmental control required to preserve equipment reliability.	ASHRAE, Thermal Guidelines for Data Processing Environments.
Energy efficiency indicator	Ratio between total facility energy consumption and IT equipment energy consumption, as defined by PUE.	Makes it possible to assess overall energy efficiency and identify opportunities to reduce auxiliary energy consumption.	ISO/IEC, ISO/IEC 30134-2:2026: Power Usage Effectiveness (PUE).

Source: Prepared based on IEA (2025), Liu et al. (2021), Lin et al. (2024), Chang et al. (2024), Zhang, Li, and Wang (2024), Ma, Zhang, and Zou (2022), Peng et al. (2024), ASHRAE (2021), Van Geet and Sickinger (2024), and ISO/IEC (2026).

In view of the energy and operational requirements, data center deployment in Northeastern Brazil will only be viable if the infrastructure can simultaneously accommodate computational loads, auxiliary systems, cooling, and equipment designed to protect against failures. The climatic characteristics and availability of local energy resources in Ceará, Piauí, and all other states in the Northeast must be taken into account when selecting cooling and storage technologies. Assessing efficiency through PUE, in conjunction with reliability indicators and redundancy requirements, makes it possible to establish technical criteria for comparing different deployment alternatives. Thus, the regional availability of renewable energy sources must be integrated with the efficiency of internal systems and the maintenance of continuous operations, so that data

center expansion takes place within a framework that is energy-secure and environmentally sustainable.

3. METHODOLOGY

The research adopts a qualitative, theoretical-documentary approach and focuses on interpreting scientific, technical, regulatory, and institutional information concerning the energy infrastructure required for data center deployment in Northeastern Brazil. This approach is appropriate because the availability of renewable energy sources, electricity expansion planning, grid connection capacity, supply reliability, and the efficiency of these facilities' internal systems do not exist in isolation. Understanding this set of factors requires examining how they relate to one another and the implications of these relationships for regional energy planning, which cannot be achieved solely through variable measurement or scenario simulation (Risemberg; Wakin; Shitsuka, 2026).

The study relied on two complementary procedures: bibliographic research and documentary research. The former was exploratory and descriptive in nature and sought to gather scientific contributions on solar and wind power generation, the integration of intermittent energy sources, electrical infrastructure, and the energy requirements of data centers. It was exploratory insofar as it identified concepts, approaches, and issues relevant to the research problem, and descriptive because it organized and presented the characteristics and contributions of the selected studies. This procedure, however, does not constitute an integrative literature review, since no protocol for the systematic integration of findings

from primary studies was applied, nor was the production of an integrative synthesis of this nature intended (Arantes, 2025).

The bibliographic search prioritized publications from 2018 to 2026, a period encompassing most of the sources used, without excluding older references that retained conceptual or regulatory relevance. The selection criteria included the direct relationship between the publications and the research topic and objectives, identification of authorship and editorial responsibility, availability of verifiable metadata, and the scientific or technical relevance of the content. Priority was given to studies on solar and wind power generation in the Northeast, complementarity among renewable energy sources, generation forecasting, transmission constraints, power system expansion, cooling, energy storage, and data center energy efficiency. Materials lacking a substantive connection to the research subject, records with insufficient bibliographic identification, and texts that did not contribute to the established objectives were excluded. Each reference was recorded with its authorship, title, year, journal or institution, volume, issue, pages or article identifier, and DOI or official electronic address, when available, to ensure the traceability of the material. It should be noted that the DOI was treated as an identification resource, rather than as independent evidence of editorial quality.

The documentary research was based on technical, regulatory, and institutional documents related to the research subject: the *Thermal Guidelines for Data Processing Environments* manual, published by ASHRAE (2021); the *Ten-Year Energy Expansion Plan 2034*, published by the Energy Research Office (EPE, 2025); the *PAR/PEL 2025*, 2026–2030 cycle, published by the Brazilian National Electric System Operator (ONS, 2025), including its Executive Summary; EPE

information on data center consumption; ONS supply quality indicators (2026); the *PDE 2035 Energy Transmission Report*, published by the Ministry of Mines and Energy and EPE; documentation from the Federal Court of Accounts (TCU) on disturbances in the National Interconnected System; ANEEL Normative Resolution No. 956/2021; the *Energy and AI* report, published by the International Energy Agency (IEA, 2025); and ISO/IEC 30134-2:2026, the standard concerning the Power Usage Effectiveness (PUE) indicator. These sources were selected based on their relevance to energy planning, power system operation, the connection of large consumers, supply quality, and the technical requirements of data centers.

The examination of the documents considered institutional authorship, purpose, publication context, technical or regulatory nature, and the relevance of their content to the research objectives. As Cellard (2019) points out, this procedure requires consideration of the conditions under which documents were produced, their authors, and their context; otherwise, their records may be interpreted in isolation. The material was examined through reading and identification of relevant information, which was subsequently organized into three thematic areas: availability and integration of renewable energy sources; electrical infrastructure, transmission, distribution, and supply reliability; and energy demand, cooling, storage, and operational continuity. Information from institutional documents was then compared with contributions from the scientific literature to identify areas of convergence and technical conditions affecting data center deployment in the Northeast. Traceability was maintained through bibliographic information and official web addresses.

The study thus focused on the qualitative interpretation of scientific literature and technical and institutional documents, integrating information on renewable generation, electrical infrastructure, and the operational requirements of data centers. The combination of exploratory and descriptive bibliographic research with documentary research made it possible to examine the problem from different perspectives while maintaining a distinction between scientific evidence, regulatory guidelines, and institutional planning information.

4. FINAL CONSIDERATIONS

Data centers require an uninterrupted power supply, which makes the expansion of these facilities primarily an electrical infrastructure issue. As demand for digital information processing, storage, and transmission continues to grow, so does the pressure for a continuous and reliable electricity supply that meets the stringent operational requirements of this type of facility. In this context, Northeastern Brazil offers relevant conditions for discussion, particularly because of the region's availability of solar and wind resources and the investments being directed toward regional electrical infrastructure. Examining these conditions is of scientific and strategic interest because it makes it possible to determine the extent to which renewable generation can be integrated with existing transmission and distribution networks and the technical requirements of data centers. This directly contributes to the debate on where new facilities should be located and how regional energy supply should be organized.

The research question guiding this study concerned the extent to which solar and wind power generation, combined with

transmission and distribution infrastructure, supply reliability, and cooling conditions, can support data center deployment in Northeastern Brazil. This question was addressed throughout the investigation. The analysis provides a qualified answer: the region has favorable renewable energy resources, a finding confirmed by the examination without reservations. However, resource availability alone does not determine the feasibility of a data center. Supplying these facilities also depends on the capacity for integration into the electricity grid, connection conditions, supply stability, and the systems designed for thermal management and operational continuity. Decisions regarding deployment must therefore involve an equally thorough assessment of the different components of this energy infrastructure rather than examining each one in isolation.

The general objective and the three specific objectives were achieved through the analysis of renewable generation conditions, electrical infrastructure, and the energy and operational requirements of data centers. Regarding solar and wind energy sources, the study characterized the availability of natural resources and discussed how this energy can be integrated into the electricity supply. Electrical infrastructure, in turn, was examined in terms of its transmission and distribution capacity, the procedures through which large consumers connect to the grid, and supply reliability. The assessment of operational requirements considered continuous electricity consumption, cooling, energy storage, and the mechanisms necessary to maintain operations. None of these three areas, considered independently, would have been sufficient to answer the research question. It was their integration that made it possible to fulfill the purpose of the study without restricting the analysis to a single dimension of the problem.

The first topic addressed in the theoretical framework concerned the renewable energy potential of Northeastern Brazil. The region has favorable natural conditions for solar and wind power generation, although the geographical distribution and availability of these resources vary according to local geography and meteorological conditions. The study also found that the intermittency of both sources requires integration and planning strategies that align generation periods with consumption requirements. Their complementarity tends to reduce fluctuations in electricity production, while generation forecasting and energy storage increase the scope for supply management. One qualification underlies this entire discussion: the availability of natural resources does not mean that electricity is effectively delivered to consumers, since generation depends on grid connection, transmission capacity, and power system operating conditions.

The second topic focused on the path electricity follows to reach consumers. The analysis showed that data center deployment cannot be addressed solely through installed generation capacity. Transmission and distribution infrastructure must also be capable of delivering electricity to consumer facilities. When assessing potential locations, the existence of grid connections, the capacity to serve large loads, electrical stability, and supply quality are decisive factors. The study also found that transmission constraints and renewable generation curtailment can compromise the utilization of the electricity produced, even in areas with abundant natural resources. This highlights the importance of grid expansion planning and the assessment of specific connection conditions when identifying suitable areas for these facilities, particularly in Ceará and Piauí.

The third topic examined the internal systems of data centers. The energy demand of these facilities is not limited to servers and other information technology components. Cooling, ventilation, internal power conversion and distribution, lighting, monitoring, and operational support systems also account for a significant share of total energy consumption. In the discussion of cooling, particular attention was given to airflow management, hot and cold aisle separation, and the adaptation of thermal solutions to local climatic conditions, all of which directly affect facility energy performance. To preserve operational continuity in the event of power interruptions or fluctuations, energy storage, uninterruptible power supply (UPS) systems, and emergency power sources were also considered. Indicators such as Power Usage Effectiveness (PUE), defined according to the criteria established by ISO/IEC 30134-2:2026, make it possible to assess the overall energy performance of these facilities.

As a contribution, this study brought together, within a single analysis focused on Northeastern Brazil, three dimensions that are often addressed separately: renewable energy availability, electrical infrastructure conditions, and the internal energy consumption and cooling requirements of data centers. The resulting analysis provides a set of insights for researchers, public administrators, professionals in the electricity sector, and other stakeholders involved in planning digital infrastructure projects. Future research could include comparative studies among states and municipalities in the Northeast, investigations into the grid connection capacity of specific locations, examinations of the complementarity between solar and wind generation during different periods, and assessments of energy storage and cooling alternatives compatible with the regional climate. Technical and economic feasibility studies and analyses of demand expansion scenarios are also relevant. Such

studies should consider the development of transmission infrastructure and the reliability requirements established by data center operators.

Northeastern Brazil does indeed have favorable conditions for integrating data center expansion with electricity generation from renewable energy sources. However, this potential can only be realized if accompanied by electricity planning, effective grid connection availability, adequate transmission and distribution capacity, and appropriate operational solutions. Without these conditions, the region's natural potential has limited practical significance. By systematizing the main technical factors that should guide this assessment, the study demonstrated that the region's energy attractiveness results from the interaction among natural resources, supply infrastructure, and the efficiency of facilities' internal systems. The deployment of these facilities should therefore be guided by integrated assessments that consider not only electricity supply but also its quality, continuity, and efficient use.

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