

Impacts of data center expansion on global energy demand: Sustainability challenges in the age of artificial intelligence

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Abstract

Digital transformation and advances in artificial intelligence have driven the expansion of data centers and increased their share of global electricity demand. This article analyzes the impacts of this growth on power systems and discusses the main challenges to the sector's sustainability. The study adopts a qualitative, exploratory, and descriptive approach and was conducted through a bibliographic and documentary review of 18 sources published between 2019 and 2025. Technical reports, standards, regulatory acts, institutional studies, and specialized publications concerning data center energy consumption, artificial intelligence, electricity infrastructure, and energy supply alternatives were examined. The results indicate that global electricity demand associated with data centers, artificial intelligence, and cryptocurrencies may reach between 620 and 1,050 TWh in 2026, while data center electricity consumption in the United States may reach between 325 and 580 TWh in 2028. The comparative analysis shows that the impact does not result solely from the global volume of electricity consumed, but from the combination of rapid expansion, geographical concentration, continuous supply requirements, and the mismatch between the deployment timelines of digital and electricity infrastructure. It is concluded that the sector's sustainability will depend on anticipatory locational and energy planning, operational efficiency, data transparency, coordinated grid expansion, and diversification of low-carbon energy sources.

Keywords: Data centers; Artificial intelligence; Energy demand; Sustainability; Electricity infrastructure.

1. Introduction

The digital transformation of recent decades has profoundly changed the way data are produced, stored, processed, and transmitted. In this context, data centers have become essential components of the global technological infrastructure, supporting applications related to cloud computing, the Internet of Things (IoT), digital services, information storage, and Artificial Intelligence (AI) [1].

Recent advances in artificial intelligence have further increased the relevance of these facilities. The training and operation of complex computational models require large volumes of data processing, storage, and transfer. Consequently, the expansion of digital infrastructure has been accompanied by increased electricity consumption and new requirements related to the availability, reliability, and quality of the energy supply.

In recent years, investment in the construction of data centers has intensified, particularly in the United States, China, and the European Union. Companies such as Google, Microsoft, and Amazon have increased their investments in computing infrastructure to meet the growing demand for digital services and artificial intelligence applications. In

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2023, these companies' investments reached approximately 0.5% of the United States gross domestic product, exceeding investment by the country's oil and gas industry [2].

Although medium-sized data centers may have power demands ranging from 5 to 10 MW, hyperscale facilities may exceed 100 MW. The concentration of such facilities in certain regions has significant impacts on local power grids, even though the global share of data centers in total electricity consumption remains relatively limited [2].

The central issue lies not only in the aggregate volume of energy consumed, but also in the rate of load growth, the geographical concentration of projects, and the need for continuous operation. While a data center can be designed and built in approximately two or three years, expanding generation, transmission, and distribution systems may require considerably longer periods [1,3].

This mismatch can cause grid congestion, delays in connecting new projects, and the need for additional investment in generation and electricity infrastructure. Furthermore, the use of fossil fuels and diesel generators to ensure redundancy and operational continuity increases the sector's carbon footprint [4].

Against this background, it is necessary to assess how the growth of data centers influences global energy demand and which measures can reconcile the expansion of digital infrastructure with sustainability and decarbonization goals.

In the literature examined, consumption projections, reliability requirements, territorial impacts, and electricity infrastructure constraints are generally distributed across documents with different areas of focus. It therefore remains relevant to integrate these elements into an analysis capable of distinguishing global demand growth from the local effects caused by the concentration of large loads. The contribution of this article lies in articulating four dimensions of the problem: the rate of data center expansion, their geographical concentration, the need for continuous operation, and the time required to expand generation and grid systems.

The study was guided by the following research question: how does the expansion of data centers, intensified by advances in artificial intelligence, affect electricity demand and power system planning, and what conditions are required to reconcile this growth with energy sustainability?

Accordingly, this article aims to analyze the impacts of data center growth on global energy demand by identifying the main factors driving electricity consumption, the effects on electricity infrastructure, and the challenges associated with sustainable energy supply.

2. Methodology

This study adopts a qualitative, exploratory, and descriptive approach based on a bibliographic and documentary review. This methodological procedure was selected because of the need to gather, organize, and analyze evidence available in literature on the expansion of data centers, the growth in energy demand driven by artificial intelligence, and its impacts on electricity infrastructure planning and sustainability.

The literature survey was conducted by selecting publications in Portuguese and English made available between 2019 and 2025. Priority was given to documents produced by recognized institutions in the fields of energy, energy efficiency, and digital infrastructure, including technical reports, institutional publications, technical standards, regulatory acts, and specialized studies addressing the relationship between data centers, electricity consumption, artificial intelligence, and energy planning.

The inclusion criteria covered documents presenting technical data, demand projections, regulatory aspects, energy efficiency indicators, or analyses related to the impact of data centers on power systems. Publications of an exclusively commercial nature, news items without a technical basis, duplicate documents, and materials not directly related to the objectives of the study were excluded.

The final review corpus comprised 18 documents effectively used in the preparation of this article, including technical reports, institutional publications, regulatory acts, energy efficiency standards, and specialized studies. The main sources consulted include publications from the International Energy Agency (IEA), the Brazilian Ministry of Mines and Energy (MME), Ireland's Commission for Regulation of Utilities (CRU), Lawrence Berkeley National Laboratory (LBNL), ASHRAE, FGV Energia, and the European Parliament, as shown in Table 1.

The selection of these publications sought to encompass different geographical and regulatory contexts, allowing international and national experiences related to data center expansion to be compared. Information concerning the United States, China, the European Union, Ireland, and Brazil was therefore analyzed, as these regions represent relevant contexts in terms of digital infrastructure growth, electricity consumption, and energy planning strategies.

The documents were analyzed through critical reading and comparison of the information presented in the different sources, with the aim of identifying convergences and divergences regarding the evolution of electricity demand, infrastructure expansion challenges, energy efficiency measures, and energy supply alternatives. Based on this comparative analysis, the results were organized into thematic categories, allowing the main impacts of data center expansion on power systems and their implications for energy planning to be discussed.

Table 1 characterizes the documentary corpus used in the study, providing transparency regarding the source selection process and allowing readers to understand the composition of the documentary basis of the review.

Table 1 Characterization of the documentary corpus used in the study.

Document	Institution	Year	Document type	Main topic
Application of Small Modular Reactors for Supplying Energy to Data Centers	FGV Energia	2024	Technical report	SMRs and data centers
ASHRAE Standard 90.4-2022 – Energy Standard for Data Centers	ASHRAE	2022	Technical standard	Data center energy efficiency
CGIEE Resolution No. 1/2024 – Approves the Regulatory Agenda of the Management Committee for Energy Efficiency Indicators and Levels for the 2024–2026 Period	MME	2024	Legislation	Energy efficiency
CRU Direction to the System Operators Related to Data Centre Grid Connection	CRU	2021	Regulatory document	Data center grid connection
Data Centres & Networks	IEA	2023	Institutional publication	Digital infrastructure
Directive (EU) 2023/1791 of the European Parliament and of the Council on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast)	European Parliament	2023	Legislation	Energy efficiency
Electricity 2024	IEA	2024	Technical report	Global electricity demand
Electricity Market Report	IEA	2023	Technical report	Global electricity market trends and outlook
Energy Demand from AI	IEA	2025	Institutional publication	AI and energy demand
Explainer: How China Is Managing the Rising Energy Demand from Data Centres	Eco-Business	2025	Specialized publication	China
Global Energy and Climate Model	IEA	2024	Technical report	Energy modeling
MME and EPE Map Solutions to Meet the Growing Demand from Data Centers in Brazil	MME	2024	Institutional publication	Brazilian energy planning
Nuclear Energy: In the Race to Power AI, Angra 3 Will Be Only the Beginning	Startups	2024	Specialized news article	AI and nuclear energy
Nuclear Power in a Clean Energy System	IEA	2019	Technical report	Nuclear energy

United States Data Center Energy Usage Report	LBNL	2024	Technical report	Data center electricity consumption in the United States
What the Data Centre and AI Boom Could Mean for the Energy Sector	IEA	2024	Institutional publication	AI growth
Why AI and Energy Are the New Power Couple	IEA	2023	Institutional publication	AI and energy
World Energy Outlook 2024	IEA	2024	Technical report	Energy scenarios

Source: Author (2026).

3. Data centres and energy consumption

3.1. Structure and operation of data centers

Data centers are facilities designed to house servers, storage systems, network equipment, and auxiliary components required for data processing and transmission [5].

Servers are responsible for performing calculations and processing information. These devices may use central processing units and specialized accelerators, such as graphics processing units. In modern data centers, servers may account for approximately 60% of electricity demand, although this share varies according to the type of facility and the nature of the activities performed. Storage systems, in turn, are used to maintain and protect large volumes of data, while network equipment, such as switches, routers, and load balancers, enables communication between devices and the transmission of information [5].

Another important component is the cooling and environmental control system. Electronic equipment generates heat during operation, making it necessary to control temperature and humidity to prevent failures and performance losses. In more efficient hyperscale facilities, cooling may account for approximately 7% of total electricity consumption. In less efficient enterprise data centers, this share may exceed 30% [5].

In addition, data centers use uninterruptible power supplies, batteries, and emergency generators. Although these systems are activated only under specific conditions, they are essential for maintaining operational continuity during failures or interruptions in the external power supply. The share of each component in total consumption depends on equipment efficiency, computing density, climatic conditions, cooling system architecture, and the data center's usage profile [6].

3.2. Artificial intelligence and the growth of computational demand

Artificial intelligence has increased the demand for data processing because of the development of increasingly large and complex models. Training these models requires large numbers of computing devices to operate simultaneously, while their continuous use also requires infrastructure to process user requests [5].

Different applications have different energy intensities. Image and video generation, for example, tend to require greater computing capacity than applications focused exclusively on text generation. The evolution of energy consumption will therefore depend not only on the number of users, but also on the types of applications developed and how frequently they are used [2].

The architecture of artificial intelligence models and the efficiency of algorithms also directly influence electricity demand. The development of more efficient chips makes it possible to perform more calculations with lower energy consumption per operation. The energy efficiency of chips designed for artificial intelligence has doubled, on average, every two and a half years to three. Despite these gains, growth in the number of devices, users, and applications may outpace efficiency improvements. This occurs when the reduction in consumption per operation is offset or exceeded by growth in the total number of operations performed [2].

The lack of transparency regarding data center consumption also makes it difficult to produce accurate projections. Some companies do not disclose detailed information on installed capacity, electricity consumption, server utilization, and cooling system efficiency. Consequently, estimates are subject to significant uncertainty [2,7].

4. Global expansion and impacts on energy demand

4.1. Global projections

Advances in artificial intelligence, cloud computing, and other digital applications have significantly increased the electricity demand associated with data centers. According to the International Energy Agency, global electricity consumption related to data centers, artificial intelligence, and cryptocurrencies may reach between 620 and 1,050 TWh in 2026, with the reference scenario estimated at approximately 800 TWh, compared with about 460 TWh recorded in 2022. These projections represent an increase of between 160 and 590 TWh in only four years. Under the highest scenario, this increase is approximately equivalent to the annual electricity consumption of a large economy [7].

In addition to growing consumption, digital infrastructure is highly geographically concentrated. According to the International Energy Agency, more than 8,000 data centers are operating worldwide, approximately 33% of which are in the United States, 16% in Europe, and 10% in China. This distribution shows that data center expansion occurs predominantly in regions with well-established technological infrastructure, high connectivity, energy availability, and greater investment capacity [7].

Although data centers account for a growing share of electricity demand, they are not the only factor driving the expansion of global energy consumption. The electrification of transport, industrial growth, the spread of air-conditioning systems, and economic expansion itself will continue to exert a significant influence on electricity demand in the coming decades [3]. However, the data center sector has characteristics that distinguish it from other major energy consumers. The rapid deployment of new projects, the high territorial concentration of loads, and the need for continuous supply intensify their impacts on local power systems, requiring advance planning of generation, transmission, and distribution infrastructure [2].

4.2. United states

The United States accounts for the largest share of existing data centers. According to a report prepared by Lawrence Berkeley National Laboratory, the electricity load associated with these facilities tripled over the past decade and may double or triple again by 2028 [8].

Electricity consumption by data centers in the United States increased from approximately 58 TWh in 2014 to 176 TWh in 2023. Values ranging from 325 to 580 TWh are projected for 2028. The share of these facilities in the country's total electricity consumption, estimated at approximately 4.4% in 2023, may reach between 6.7% and 12% in 2028. This growth is associated with artificial intelligence, the expansion of cloud computing, the electrification of economic activities, and the resurgence of certain industrial sectors. The concentration of data centers in some U.S. states increases pressure on local generation and transmission systems [8].

4.3. China and the European union

In China, the expansion of 5G networks, the Internet of Things, and digital services has driven the energy consumption of data centers. The projections analyzed indicate that these facilities may consume approximately 300 TWh in 2026 and more than 400 TWh by 2030 [9,10].

In the European Union, data centers consumed approximately 100 TWh in 2022, equivalent to about 4% of the bloc's electricity demand. This consumption may reach approximately 150 TWh in 2026, with facilities concentrated in technology hubs such as Frankfurt, London, Amsterdam, Paris, and Dublin [7].

Although the absolute figures are significant, the most substantial impacts may occur in smaller countries with a high concentration of projects. In Ireland, data centers accounted for approximately 17% of electricity demand in 2022. Projections indicate that this share may reach approximately 32% in 2026. This case demonstrates that the impact of data centers should not be assessed exclusively at the global level. Regional concentration can compromise the availability of electricity capacity, require grid reinforcement, and affect national energy planning [7].

4.4. Prospects for Brazil

Data centers have expanded in Brazil, mainly because of advances in artificial intelligence and the growing demand for data storage, processing, and distribution. These facilities consume large amounts of electricity, particularly for equipment cooling, and require robust connections to the transmission system. In response to this demand, the Ministry

of Mines and Energy, together with the Energy Research Office, has conducted planning studies to address the expected growth [11].

Data from the Ministry of Mines and Energy indicate that the projected load from data centers may reach 2.5 GW by 2037, considering only new projects in the states of São Paulo, Rio Grande do Sul, and Ceará. These studies are important for planning the Brazilian electricity sector, mitigating risks, and developing evidence-based policies [11].

This consumption is expected to increase with the emergence of new projects and technologies, such as cryptocurrency mining. According to the Ministry of Mines and Energy, this consumption profile requires continuous energy availability, redundancy in circuits connected to the Basic Grid, and emergency generators because of the importance and high value of the data handled by these facilities [11].

Given the prospect of increased digital investment and the need to reinforce electricity supply, government initiatives aimed at establishing minimum energy efficiency levels for equipment and buildings are becoming increasingly important. In February 2024, the Ministry of Mines and Energy issued CGIEE Resolution No. 1/2024, which approved the regulatory agenda of the Steering Committee for Energy Efficiency Indicators and Levels for the 2024-2026 period, helping to preserve the national power grids and reduce the country's carbon footprint [12].

Considering these data, energy availability at the national level does not eliminate the possibility of regional constraints. The concentration of new projects in a small number of states may shift the problem to substations, transmission corridors, and specific points of connection, requiring electricity capacity assessments to consider the location and schedule of each project rather than only the country's aggregate generation balance [11].

The Brazilian case therefore highlights the importance of anticipating grid access studies, grid reinforcements, redundancy requirements, and efficiency criteria before loads are connected. This approach reduces the risk that digital infrastructure will expand without coordination with the planning and implementation time frames of the electricity sector [11,12].

The evidence presented for the different international contexts allows the main challenges faced by power systems in response to data center expansion to be compared. Table 2 summarizes these differences and their implications for energy planning.

Table 1 International comparison of the impacts of data center expansion on power system planning.

Region	Current situation ⁱ	Projection	Main implication
United States	176 TWh (2023)	325-580 TWh (2028)	Expansion of generation and transmission to keep pace with load growth.
China	Growth associated with AI, IoT, and 5G	>400 TWh (2030)	Alignment of digital expansion with energy efficiency and decarbonization targets.
European Union	100 TWh (2022)	150 TWh (2026)	Strengthening transparency, energy efficiency, and the management of regional concentration.
Ireland	17% of national demand (2022)	32% (2026)	Mitigation of the systemic risk arising from the high share of data centers in national electricity demand.
Brazil	New projects concentrated in three states	2.5 GW (2037)	Anticipation of grid access studies, Basic Grid reinforcements, and the adoption of energy efficiency criteria.
Global overview	>8,000 data centers and 460 TWh (2022)	620-1,050 TWh (2026)	Integrated planning of digital expansion and electricity infrastructure.

Source: Prepared by the author based on [7–11].

The comparison shows that the problem takes different forms. In the United States and China, the absolute growth in consumption is most prominent; in Ireland, the main risk lies in the high share of data centers in national demand; in the European Union, transparency and decarbonization are particularly important; and in Brazil, the central challenge is to anticipate the connections and reinforcements required for a load that is still expanding. In all cases, territorial concentration makes an analysis based solely on aggregate national indicators insufficient.

5. Impacts on electricity infrastructure

The rapid deployment of data centers creates significant challenges for generation, transmission, and distribution infrastructure. While a digital facility can be built within a few years, new generation and transmission projects frequently face longer planning, licensing, financing, and construction processes [7].

This difference in time frames may result in insufficient capacity for new connections. In some regions, system operators and authorities have already imposed restrictions or suspended the approval of new data centers because of inadequate electricity infrastructure [7,13].

Another important aspect is the continuous load profile. Unlike consumers whose demand varies significantly throughout the day, data centers must operate continuously. This requires energy sources capable of providing firm power and backup systems prepared to begin operating immediately [14].

The concentration of facilities in the same region also reduces the possibility of distributing impacts across the grid. A single large data center may consume an amount comparable to that of an energy-intensive industrial facility. When several projects are located close to one another, the effects on substations, transmission lines, and distribution systems become more pronounced [2].

In addition, data center operators require high levels of supply quality and reliability. Even brief interruptions can cause data loss, service unavailability, and financial losses. For this reason, redundant systems, batteries, and diesel generators are used [5].

Although emergency generators increase reliability, their use contributes to atmospheric emissions and may cause local environmental impacts. Data center expansion therefore requires solutions capable of combining operational continuity with reduced dependence on fossil fuels [4].

6. Sustainability challenges

6.1. Dependence on fossil fuels

The expansion of data centers increases electricity demand and consequently reinforces their dependence on the energy mix of the regions in which these facilities are connected. Although many companies adopt renewable energy targets and emission-offset mechanisms, data center operations remain physically connected to local power systems, which in many countries are still supplied by coal, natural gas, and other fossil fuels. The carbon intensity associated with the operation of these facilities therefore depends directly on the composition of the regional electricity mix and, on the mechanisms used to contract or offset the energy consumed. In systems with a high share of fossil fuels, the growth of digital infrastructure may contribute to increased power sector emissions and make it more difficult to meet decarbonization targets [15].

Among fossil fuels, natural gas offers greater operational flexibility for serving continuous loads, an important characteristic for the uninterrupted operation of data centers. However, its use still produces significant greenhouse gas emissions and is subject to price volatility. Coal, in turn, has a higher emissions intensity and faces increasingly stringent regulatory restrictions because of its environmental impacts. In this context, reducing dependence on fossil fuels and increasing the share of low-carbon sources are essential for reconciling data center expansion with sustainability, energy security, and the transition to less emissions-intensive power systems [15].

6.2. Renewable energy sources and intermittency

Solar and wind power are essential to the decarbonization of power systems. However, their output depends on weather conditions and varies over time. This intermittency presents a challenge for facilities that require continuous supply. For variable sources to fully serve data centers, they must be combined with storage, complementary generation, demand management, or connection to diversified power systems [15].

Batteries can mitigate some variations and provide support during short interruptions. However, maintaining a large facility for extended periods would require substantial storage capacity, increasing project costs and complexity. Sustainable data center supply therefore tends to depend on a combination of energy sources, storage technologies, energy contracts, and improvements to electricity infrastructure [15].

6.3. Energy efficiency

Energy efficiency is one of the main measures for reducing the impact of data centers. Advances in processors, storage systems, algorithms, and cooling technologies can reduce the energy required to perform a given number of operations [2,6]. However, the contribution of each system to total electricity consumption varies according to the type of data center. Hyperscale facilities concentrate most of their consumption in information technology equipment, whereas enterprise data centers have a relatively higher share associated with cooling systems and supporting infrastructure.

As shown in Figure 1, information technology equipment accounts for the largest share of electricity consumption, particularly in hyperscale data centers, whereas cooling systems have a greater share in enterprise and colocation facilities. This distribution indicates that energy efficiency strategies should consider the operating characteristics of each data center category and prioritize interventions in the components with the greatest energy impact.

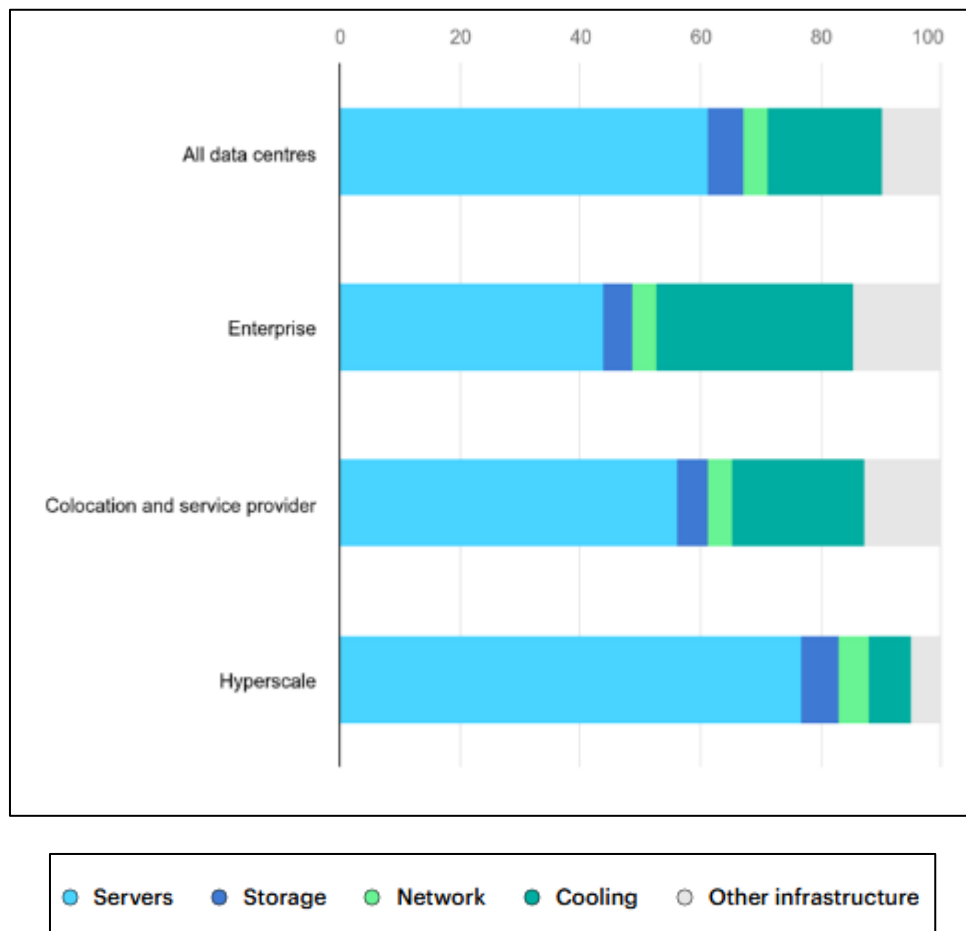


Figure 1 Distribution of electricity consumption by equipment category across different types of data centers.

Source: [5]

Liquid cooling is one of the alternatives under development for facilities with high computing density. This technology can remove heat more efficiently than conventional systems based exclusively on air circulation. Artificial intelligence algorithms may also be used to control temperature, ventilation, and the distribution of computing loads. Continuous monitoring makes it possible to adjust equipment operation to actual conditions and reduce waste. However, efficiency should not be assessed only at equipment level. The location of the data center, climatic conditions, water availability, the regional energy mix, and proximity to transmission infrastructure also affect its environmental performance [6].

In addition to electricity consumption, some cooling systems use large volumes of water. In water-stressed regions, data center development may intensify competition for this resource and generate social and environmental impacts. Sustainability assessments should therefore consider energy consumption, water use, emissions, and local impacts simultaneously. Reducing one variable should not come at the expense of worsening another [16].

7. Regulation and transparency

The lack of detailed data hinders power sector planning. Information on computing capacity, energy consumption, water use, and operational efficiency is required to estimate the effects of new projects.

In the European Union, Directive 2023/1791 established obligations related to the disclosure of energy consumption, efficiency, water use, and emissions. The regulation also encourages the recovery of waste heat produced by these facilities [16].

In Ireland, the criteria for connecting new data centers began to consider available grid capacity, the existence of on-site generation or storage, and the possibility of load flexibility when requested by the system operator [13].

These initiatives indicate a trend toward the adoption of sector-specific policies. Data center expansion cannot be assessed solely as a private investment decision because its effects extend to electricity infrastructure, the use of natural resources, and the achievement of climate targets.

8. Discussion of results

The review identified four main findings. First, data centers can be deployed faster than electricity infrastructure can normally be expanded. Second, territorial concentration can produce more severe impacts than global consumption percentages suggest. Third, equipment-level efficiency gains do not guarantee a reduction in total demand when processing volumes grow rapidly. Fourth, the sector's sustainability depends on a combination of locational planning, grid expansion, transparency, efficiency, and supply diversification.

The first finding arises from the difference between the deployment cycles of digital and electricity infrastructure. Data centers can be designed and built within a few years, whereas transmission lines, substations, and new generation units are subject to longer planning, licensing, financing, and implementation stages. Consequently, requests to serve new loads may arise before the power system is ready to absorb them, increasing connection queues, regional constraints, and the costs associated with the required reinforcements [1,7].

This difference in time frames makes anticipation a technical requirement for energy planning. Power system planning must incorporate not only projects that are already connected, but also projects under development, their expected commissioning dates, and the required levels of redundancy. Without this coordination, the expansion of digital infrastructure may be limited by the lack of available energy and grid capacity.

In addition to the timing mismatch, the second finding shows that the global share of data centers in electricity consumption may conceal significant local pressures. Ireland exemplifies a system in which digital loads account for a large share of national demand, while the United States has a strong concentration of data centers in certain states and technology hubs. In Brazil, the projected development of new projects in São Paulo, Rio Grande do Sul, and Ceará indicates that supply capacity must be assessed at specific points of connection rather than only through national indicators of energy availability [7,8,11].

Consequently, national supply and demand indicators are necessary but insufficient for assessing the impacts of this expansion. The analysis must consider substation capacity, transmission line loading, available transformation capacity, the hourly load profile, the need for redundant supply, and the possibility of physically expanding the grid at the sites selected for the projects.

The third finding concerns the limits of energy efficiency gains. More efficient processors, cooling systems, and algorithms reduce the amount of energy required per computing operation. However, expansion in the number of users, models, and applications may increase total electricity consumption. Energy efficiency therefore remains essential, but it should not be treated as an isolated solution to the growth in loads associated with data centers [2,5,6].

This result reinforces the need to monitor absolute consumption indicators together with performance metrics, such as computing efficiency and infrastructure energy use. A reduction in unit consumption will translate into a lower systemic impact only if it is not entirely offset by growth in processing volumes.

Finally, the fourth finding demonstrates that no single measure can meet the requirements of reliability, low carbon emissions, competitive cost, and rapid deployment. European regulation and the criteria adopted in Ireland indicate

that factors such as transparency, location, load flexibility, on-site generation, and energy storage can be incorporated into data center connection and licensing processes [13,16].

The main planning implication is that data centers should be treated as strategic, energy-intensive loads. Decisions regarding their location and deployment must integrate energy availability, power grid capacity, water use, the emissions profile, and supply alternatives. This approach is necessary to prevent technological expansion from transferring disproportionate costs or risks to the power system, other consumers, and communities in the regions where these facilities are developed.

9. Alternatives and prospects for energy supply

The sustainability of data centers will require a combination of measures. The first is to reduce consumption through more efficient equipment, improvements in cooling systems, and algorithm optimization [2,6].

The second involves contracting and integrating low-carbon energy sources. Solar, wind, and hydropower can make a significant contribution, provided they are combined with mechanisms capable of compensating for their variability or geographical constraints. Hybrid systems, energy storage, and flexible load management can increase the integration of renewable sources. Some computing activities that do not require immediate processing can be shifted to periods of greater clean energy availability [15].

Firm low-carbon sources may also play an important role. Nuclear power has a high-capacity factor, low operational emissions, and the ability to supply electricity continuously. However, its adoption involves high initial costs, long deployment periods, regulatory requirements, waste management, and issues related to public perception. Its contribution should therefore be assessed together with grid capacity, renewable sources, storage, and the specific conditions of each project [17,18].

Small modular reactors are an emerging technology that may eventually offer greater deployment flexibility and capacity compatible with different consumption profiles. However, their large-scale commercial application still depends on technological, regulatory, and economic advances. In this article, SMRs are considered one prospective option among several alternatives rather than an exclusive solution. The choice of supply model should consider facility size, location, the energy mix, available infrastructure, climatic conditions, and reliability requirements [4].

10. Conclusion

The results demonstrate that the energy impact of data centers cannot be explained solely by growth in global electricity consumption. The central issue lies in the combination of rapid expansion, territorial concentration, continuous operation, and the difference between the deployment time frames of digital and electricity infrastructure.

The regional comparison showed that the phenomenon takes different forms. The United States and China exhibit strong absolute growth in consumption; Ireland highlights the risk associated with the high relative share of data centers in national demand; the European Union is advancing transparency and efficiency requirements; and Brazil faces the challenge of anticipating grid access studies and reinforcements for projects that are still expanding.

The analysis also showed that improvements in the efficiency of processors, algorithms, and cooling systems are essential, but may not prevent total demand from increasing when processing volumes grow more rapidly. Policies focused exclusively on equipment efficiency therefore do not replace supply, grid, and locational planning for new loads.

In the Brazilian context, the projection of approximately 2.5 GW in new projects in the states analyzed reinforces the need for coordination among developers, the Ministry of Mines and Energy, the Energy Research Office, grid operators, and regulatory agencies. This coordination should take place before the projects begin operating and should consider connection capacity, redundancy, reinforcement schedules, energy efficiency, and environmental impacts.

It is concluded that reconciling digital expansion with sustainability requires anticipatory locational and energy planning, transparency of operational data, coordinated expansion of electricity infrastructure, water-use management, energy efficiency, and diversification of low-carbon sources. No single source or technology meets all reliability, cost, time, and decarbonization requirements.

Future research should deepen the technical, economic, and environmental comparison of renewable sources, energy storage, hybrid generation, and nuclear power, as well as develop scenarios specific to the Brazilian power system. Future studies may also assess siting and connection criteria applicable to large data centers, including regional impacts on transmission, distribution, water resources, and emissions.

Compliance with ethical standards

Disclosure of conflict of interest

All authors declares that she has no financial or non-financial conflicts of interest related to the publication of this manuscript or to any institution, product, or service mentioned in the study.

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