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HYBRID RENEWABLE ENERGY SYSTEMS APPLIED TO DATA CENTERS: CRITERIA FOR SIZING, ENERGY STORAGE, AND INTELLIGENT ENERGY SUPPLY MANAGEMENT

SISTEMAS HÍBRIDOS DE ENERGIA RENOVÁVEL APLICADOS A DATA CENTERS: CRITÉRIOS DE DIMENSIONAMENTO, ARMAZENAMENTO E GESTÃO INTELIGENTE DO SUPRIMENTO ENERGÉTICO

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ABSTRACT

Data centers require continuous electricity supply, and this demand increases in parallel with the volume of data processed and stored by these facilities. Integrating renewable energy sources into their electricity supply represents an approach to diversifying the energy mix and reducing dependence on a single centralized source. This study aimed to analyze the application of hybrid renewable energy systems to power data centers, considering the technical criteria for sizing photovoltaic and wind power sources, energy storage technologies, intelligent energy management systems, and the requirements for reliability, efficiency, and operational continuity imposed by these facilities. The research adopted a qualitative approach based on bibliographic and documentary surveys. An integrative review was not conducted; rather, the bibliographic survey followed an exploratory and descriptive approach, prioritizing publications from 2018 to 2026, while the documentary survey covered technical standards and institutional documents addressing energy storage, uninterruptible power supply systems, and energy efficiency in these facilities. The sources were selected according to their relevance to the subject, currency, clear bibliographic identification, and traceability to their original sources. They were subsequently organized into three analytical areas: the sizing of hybrid renewable energy systems; energy storage and electrical reliability; and intelligent energy management and operational efficiency. The results indicated that the implementation of hybrid renewable energy systems in data centers depends on the integration of three main elements: appropriate sizing of photovoltaic and wind power sources, energy storage technologies, and intelligent energy supply management. When properly integrated, this combination tends to enhance supply stability, cooling efficiency, and operational continuity, provided that power

capacity, autonomy, redundancy, and energy control requirements are met. The contribution of this study lies primarily in systematizing these criteria rather than empirically validating them, since the research is bibliographic and documentary in nature, and its findings constitute qualitative interpretations of the literature, without field measurements. Future research opportunities include the optimization of hybrid systems, energy storage, and the application of intelligent energy management techniques.
Keywords: Hybrid renewable energy systems; Data centers; Energy storage; Energy management.

RESUMO

Data centers dependem de energia elétrica o tempo todo, e essa dependência cresce junto com o volume de dados que essas instalações processam e armazenam; integrar fontes renováveis ao suprimento delas é uma forma de diversificar essa matriz e reduzir a dependência de uma única fonte centralizada. Este trabalho teve como objetivo analisar a aplicação de sistemas híbridos de energia renovável no suprimento de data centers, levando em conta os critérios técnicos de dimensionamento das fontes fotovoltaica e eólica, as tecnologias de armazenamento, os sistemas inteligentes de gerenciamento de energia e os requisitos de confiabilidade, eficiência e continuidade operacional que essas instalações impõem. A pesquisa seguiu abordagem qualitativa, apoiada em levantamento bibliográfico e documental. Não houve revisão integrativa: o levantamento bibliográfico assumiu um perfil exploratório e descritivo, priorizando publicações entre 2018 e 2026, e o levantamento documental cobriu normas técnicas e documentos institucionais sobre armazenamento de energia, sistemas de alimentação ininterrupta e eficiência energética dessas instalações. As fontes foram escolhidas pela pertinência ao tema, pela

atualidade, pela identificação bibliográfica clara e pela possibilidade de rastreá-las até a origem, e depois distribuídas em três frentes de análise: o dimensionamento dos sistemas híbridos renováveis, o armazenamento junto com a confiabilidade elétrica, e o gerenciamento inteligente de energia junto com a eficiência operacional. O que os resultados mostraram é que usar sistemas híbridos renováveis em data centers depende de articular três coisas: o dimensionamento adequado das fontes fotovoltaica e eólica, as tecnologias de armazenamento e o gerenciamento inteligente do suprimento. Bem articulada, essa combinação tende a favorecer a estabilidade do fornecimento, a eficiência da refrigeração e a continuidade operacional, desde que respeitados os requisitos de potência, autonomia, redundância e controle energético. A contribuição deste trabalho está mais na sistematização desses critérios do que numa validação empírica deles: a pesquisa é bibliográfica e documental, e os resultados são leituras qualitativas da literatura, feitas sem medição em campo. Ficam como possibilidades de pesquisa futura a otimização dos sistemas híbridos, o armazenamento e a aplicação de técnicas inteligentes de gestão energética.
Palavras-chave: Sistemas híbridos de energia renovável; Data centers; Armazenamento de energia; Gerenciamento energético.

1. INTRODUCTION

Digitalization, cloud computing, artificial intelligence, and digital services have increased the demand for information processing and storage capacity. Data centers have assumed a strategic position in contemporary technological infrastructure, as they house equipment and systems responsible for processing, storing, and transmitting large volumes of data. The operation of these facilities,

however, depends on a continuous electricity supply, both to keep information technology equipment operational and to power auxiliary systems, particularly cooling and environmental control systems. The availability of electricity for these systems can hardly be interrupted without jeopardizing the operation of the data center as a whole. These circumstances give rise to challenges related to energy consumption, operational efficiency, and supply reliability, which motivate this study.

The integration of renewable energy sources, particularly solar photovoltaic and wind power, represents an alternative for diversifying the energy supply mix of data centers and reducing dependence on conventional sources. However, solar and wind power generation are variable, and this variability is not easily compatible with a consumption profile that is, by definition, continuous. Hybrid systems, when combined with energy storage technologies and intelligent management mechanisms, enable the integration of different generation sources, the management of energy availability, and responses to fluctuations in demand. Nevertheless, their implementation must also account for cooling systems, which represent a significant share of electricity consumption and directly influence both the efficiency and operational continuity of these facilities.

The research question guiding this study was formulated as follows: how can the integration of hybrid renewable energy systems, combined with energy storage technologies and intelligent energy management systems, contribute to meeting the continuous electricity demands of data centers, considering supply reliability, cooling system efficiency, and operational continuity? This question was addressed by examining the technical foundations of hybrid

systems, energy storage alternatives, and energy management strategies, relating these components to the electricity availability and operational efficiency requirements of these facilities.

The general objective of this article was to analyze the application of hybrid renewable energy systems to the energy supply of data centers, considering the technical criteria for sizing photovoltaic and wind power sources, energy storage technologies, intelligent energy management systems, and the reliability, efficiency, and operational continuity requirements of these facilities. This objective was divided into three areas of investigation. The first involved examining the technical foundations and sizing criteria of hybrid renewable energy systems applied to data centers, focusing on photovoltaic and wind power integration, generation variability, and electricity demand profiles. The second investigated energy storage technologies and integration mechanisms with hybrid renewable energy systems in terms of supply stability, power availability, and operational continuity. The third analyzed intelligent energy management strategies in hybrid systems applied to data centers, including consumption optimization, cooling efficiency, electrical reliability, and operational continuity.

The study adopted a qualitative approach based on bibliographic and documentary research. The bibliographic survey followed an exploratory and descriptive approach, prioritizing scientific publications from 2018 to 2026. It did not constitute an integrative review, and the procedures specific to this type of review were not adopted. The documentary investigation covered technical standards and institutional documents addressing energy storage technologies, uninterruptible power supply systems, and energy efficiency parameters applicable to data centers. The selection of

sources considered their relevance to the subject, currency, bibliographic identifiability, and verifiability of provenance. The collected material was subsequently organized into three analytical areas: sizing of hybrid renewable energy systems; energy storage and electrical reliability; and intelligent energy management and operational efficiency.

In addition to this introduction, the article is organized into three further sections. The second presents the theoretical framework, structured around three topics: hybrid renewable energy systems and their sizing criteria; energy storage technologies and electricity supply reliability; and intelligent energy management, cooling efficiency, and operational continuity in data centers. The third section describes the methodological procedures adopted in the investigation. The fourth and final section presents the concluding remarks, revisiting the research objectives and summarizing the main conclusions drawn from the bibliographic and documentary analysis.

2. THEORETICAL FRAMEWORK

2.1. Hybrid Renewable Energy Systems And Sizing Criteria For Data Centers

Data centers have been expanding in number, accompanied by an increasing demand for information processing and storage, which places additional pressure on the electricity supply of these facilities. They must operate continuously and reliably while reducing their dependence on fossil fuel sources. In this context, combining different renewable energy sources, particularly solar photovoltaic and wind power, represents a technical alternative through

configurations that may also incorporate energy storage, grid connection, and conventional backup units. There is no single standard architecture, as the appropriate configuration depends on local energy resources, the consumption profile of each facility, and the level of operational continuity required. The International Energy Agency (IEA, 2025) has drawn attention to the growing electricity demand associated with data centers and the contribution of renewable sources to meeting this consumption, reinforcing the need for supply strategies that consider both generation expansion and actual energy availability.

In photovoltaic-wind configurations, the objective is precisely to take advantage of the differences between these two sources to increase the temporal complementarity of electricity generation. Photovoltaic production depends on solar irradiance and is concentrated during daylight hours, whereas wind power generation responds to wind speed and consistency, with production patterns that may differ considerably throughout the day and across seasons. It is important to emphasize, however, that combining these sources does not eliminate their inherent variability nor does it independently guarantee the full supply of the electrical load. This limitation is often overlooked in more optimistic discussions of the subject. Anoune et al. (2018) approach the configuration of these systems as a problem involving the joint assessment of components, implementation costs, and reliability parameters. The authors emphasize that configuration selection must consider different sizing criteria and optimization strategies to reconcile energy performance with the required investments.

The sizing of a hybrid system cannot be determined simply by adding the nominal power ratings of its generators. The literature

addresses this issue differently depending on the application context, but converges on one point: the actual power delivered depends on the demand being supplied, the availability of natural resources at each moment, converter characteristics, losses associated with each conversion stage, the contribution of energy storage when available, and grid connection conditions. These factors, when considered together, can result in a final capacity substantially different from that suggested by a simple sum of nominal power ratings. Bansal (2022, p. 05) explains that:

> *Standard sizes of hybrid renewable energy systems (HRES) range from a few kW to hundreds of kW, depending on the load they supply. According to current trends, the main research areas in HRES can be divided into four groups: size optimization, meteorological parameter forecasting, controller design, converter design, and performance evaluation.*

This approach makes it possible to understand sizing as an integrated process in which equipment power ratings must be assessed in relation to load behavior and system operating conditions. In data centers, this issue assumes specific characteristics because the concentration of information technology equipment is accompanied by a requirement that admits no exceptions: uninterrupted operation. The electricity demand of these facilities is never limited to server consumption. It also includes cooling and ventilation systems, internal power conversion and distribution, lighting, monitoring, and various auxiliary equipment, all of which operate continuously.

Therefore, the sizing criteria for a hybrid system intended for these facilities must be based on the total energy consumption of the

infrastructure rather than solely on the IT load, while also accounting for the operational variations in this consumption.

The IEA (2025) has already associated the expansion of data centers with the growth of global electricity demand, while energy planning studies indicate that renewable generation must be compatible with the hourly availability of electricity, rather than being assessed exclusively in terms of total energy production.

Evaluating the load profile in this context means considering both the power required during different periods and the energy consumed throughout operation. These are two distinct parameters that cannot be adequately captured by sizing based solely on nominal capacity.

The integration of renewable energy sources also depends on adequate infrastructure for electrical energy conversion and control. In hybrid systems, DC-DC, DC-AC, and AC-DC converters enable the compatibility of different voltage levels and current forms, allowing the interconnection of photovoltaic modules, wind turbines, energy storage systems, and electrical loads. According to Seidu et al. (2025, p. 08):

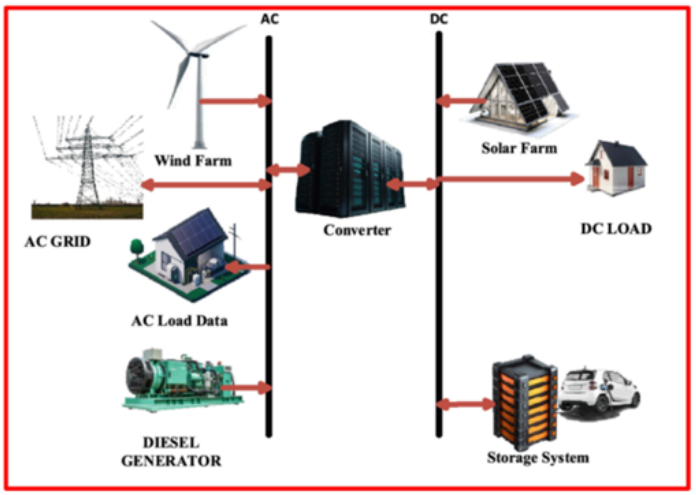
> *Power electronic interfaces, including DC-DC, DC-AC, and AC-DC converters, facilitate the seamless integration of various energy sources and loads within an EMF. These converters enable different types of power systems, whether renewable, storage-based, or conventional, to operate harmoniously by converting energy into compatible forms for efficient distribution and utilization. This adaptability allows effective energy management and stability within EMFs, facilitating flexible demand response and ensuring reliable operation across diverse energy sources and consumption requirements.*

These devices therefore serve as interfaces between subsystems, contributing to electrical compatibility and the control of energy flows. Figure 1 brings together, within a single architecture, the components that a hybrid installation integrating generation, grid connection, conversion, storage, and electrical loads must coordinate.

Wind and photovoltaic generation units supply AC and DC buses, which are interconnected through converters. The electrical grid, an AC load, a DC load, a diesel generator, and an energy storage system are also connected to this central arrangement.

Although this figure does not specifically represent a data center, the configuration of its components provides a useful basis for understanding how a hybrid system can be assembled to supply loads requiring high levels of availability.

Figure 1: An Overview of Current Optimization Approaches for Hybrid Energy Systems Combining Solar Photovoltaic and Wind Technologies



Source: Seidu et al. (2025)

The optimization criteria are therefore established through a joint assessment of technical, economic, and operational aspects. Ajiboye et al. (2023) discuss how the selection of hybrid configurations requires consideration of parameters such as reliability, costs, energy performance, and environmental impacts. This perspective is particularly important for data centers, since the most economical electricity generation option will not necessarily be the one best suited to their electricity availability requirements. Nasser and Ehsani (2025) investigated the integration of photovoltaic and wind power generation with lithium-ion batteries and hydrogen storage in a DC microgrid for a 1 MW data center facility. Similarly, Guo et al. (2026) examined the integrated planning of solar and wind power generation, energy storage, and grid connection for data centers, considering hourly supply constraints. These studies highlight the need for a joint assessment of generation, storage, conversion, and grid connection conditions, rather than limiting system sizing to the nominal power ratings of the energy sources.

A brazilian reference for this discussion is the mission-critical microgrid at the Alcântara Launch Center, whose design and sizing were presented by Castelo Branco et al. (2022). The configuration

examined comprises a 1.25 MWp photovoltaic power plant, a lithium-ion battery storage system with a power rating of 1 MW and an energy capacity of 1 MWh, three diesel generator sets, and a connection to the electrical grid. The project considers both grid-connected and islanded operation, with particularly stringent continuity requirements during launch campaigns. In this case, resource capacity was also determined according to the ability to withstand single contingencies involving generation or storage, rather than solely on the basis of demand under normal operating conditions. Although the application is not a data center and does not include wind power generation, this case provides a reference for discussing how load criticality and failure scenarios influence power supply configuration.

It is important, however, to distinguish the design study from subsequent implementation records. The article by Castelo Branco et al. (2022) presents the microgrid design and simulation results. Subsequently, an institutional publication by the Brazilian Air Force (2024) reported the use of the microgrid in the Center's activities and stated that its photovoltaic power plant, an integral component of the energy microgrid, had been inaugurated in June 2023. This record complements the design study by documenting the implementation of the solution, whereas a quantitative assessment of its field performance requires specific operational data.

Based on these contributions, Table 1 summarizes the main components and technical criteria that should be considered when evaluating hybrid renewable energy systems for supplying data centers, linking each aspect to the contributions of the cited publications.

Table 1. Components and technical criteria for analyzing hybrid renewable energy systems applied to data centers

Analytical dimension	Components or technical criteria	Application to data center power supply	Author and abbreviated title of the publication
Integration of renewable energy sources	Photovoltaic and wind power generation; temporal complementarity; resource variability	Combination of sources with different generation patterns to increase energy availability	Anoune et al. (2018), Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system
Generation sizing	Installed capacity; load profile; meteorological forecasting; capacity optimization	Matching generation capacity with the facility's electricity requirements	Bansal (2022), Sizing and forecasting techniques in photovoltaic-wind based hybrid renewable energy system
Sizing for critical loads	Load criticality; grid-connected and islanded operation; generation and storage availability under N−1 contingencies	Assessment of the capacity of remaining resources to supply critical loads when a generation or storage unit is unavailable	Castelo Branco et al. (2022), Mission Critical Microgrids: The Case of the Alcântara Space Center
Optimization criteria	Reliability; costs; energy performance; environmental impacts	Assessment of configurations that reconcile technical performance, economic	Ajiboye et al. (2023), A review of hybrid renewable energies optimisation

		feasibility, and supply continuity	
Electrical conversion and integration	DC-DC, DC-AC, and AC-DC converters; direct and alternating current buses	Electrical compatibility among generation sources, storage systems, the electrical grid, and consumer loads	Seidu et al. (2025), An overview of current optimization approaches for hybrid energy systems
Demand characterization	IT equipment consumption; cooling; auxiliary systems; continuous demand	Identification of total energy requirements and operational requirements of data centers	IEA (2025), Energy and AI
Generation-storage integration	Photovoltaic and wind power generation; batteries; hydrogen; DC microgrid	Coordination of renewable energy sources and storage systems to supply data center loads	Nasser and Ehsani (2025), Two-stage optimization of a DC microgrid with green hydrogen
Integrated planning	Generation capacity; energy storage; grid connection; hourly energy balance	Analysis of actual energy availability and the conditions for meeting demand over time	Guo et al. (2026), Integrated planning of wind-solar-storage-grid systems
Large-scale power supply requirements	Hourly demand; photovoltaic and wind power capacity; energy storage	Assessment of generation and storage requirements for large-scale data centers	Michaelides (2026), Renewable energy and energy storage requirements for hyperscale data centers

Source: Prepared by the author, based on Anoune et al. (2018), Bansal (2022), Ajiboye et al. (2023), Seidu et al. (2025), IEA (2025), Nasser and Ehsani (2025), Guo et al. (2026), Michaelides (2026), and Castelo Branco et al. (2022).

The criteria examined thus far point to a central consideration underlying the entire sizing process: a hybrid system applied to data centers should not be evaluated component by component, but rather through the combined assessment of generation capacity, load profile, conversion resources, available storage, and electrical grid connection conditions. In examining the power supply requirements of a large-scale data center, Michaelides (2026) demonstrates that the key factor is the hourly alignment between demand, renewable generation, and energy storage. Guo et al. (2026) address the other side of the problem: having sufficient renewable energy on an annual basis does not mean that this energy will be available during every operating period. Considered together, these studies indicate that sizing criteria must simultaneously account for the required power capacity and the energy effectively available over time, without overlooking the physical limitations of the power supply infrastructure itself.

In this regard, photovoltaic-wind hybrid systems can be understood as configurations whose suitability depends on the integration of natural resources, demand profiles, electrical conversion, energy storage, and grid connection, with none of these elements being sized independently. In a data center, this integration must also account for the consumption of cooling systems and auxiliary equipment, since operational continuity can only be ensured by meeting the total load of the facility, rather than merely the computational load of its servers. This is the basis provided by the

reviewed literature for discussing the technical sizing criteria, which are addressed here without original engineering calculations or simulations. The following section builds on this foundation to examine energy storage technologies and electricity supply reliability.

2.2. Energy Storage Technologies And Electricity Supply Reliability In Data Centers

A data center cannot afford to stop operating, and meeting this requirement depends on the electrical infrastructure supporting it. This infrastructure must ensure that loads remain supplied even when the external grid experiences fluctuations or failures and when demand itself varies sharply. It is in this context that energy storage plays a role extending beyond supplying the facility during emergencies. Within this framework, storage technologies also contribute to load management, renewable energy integration, and supply stability. These functions complement their original backup role and, in more demanding facilities, become equally important.

Among the currently available alternatives, battery energy storage systems (BESS) occupy a central position, particularly when based on lithium-ion cells, whose combination of available power, rapid response, and operational flexibility is difficult to match with other technologies. This does not mean, however, that they are suitable for every application. Their selection depends on the conditions of each facility, the duration of interruptions that must be covered, and the continuity requirements of the loads being supplied.

This planning process has become more challenging with the expansion of data centers dedicated to artificial intelligence. The

computational activities associated with these applications produce rapid and substantial variations in electricity consumption, requiring storage systems to accommodate a considerably less predictable load profile than that of traditional facilities. This imposes sizing requirements that previous projects simply did not anticipate. According to Rahman and Khan (2026, p. 634):

> *AI data centers differ significantly from traditional data centers in terms of electricity consumption. Traditional data centers hosting cloud storage or web servers generally exhibit relatively stable loads throughout the day. In comparison, AI data centers operate with highly dynamic load profiles due to the much higher power densities of their racks. Traditional server racks typically operate in the range of 4 kW to 12 kW, whereas high-density racks can operate at up to 20 kW. In contrast, modern AI training racks generally consume between 50 kW and 200 kW, highlighting the substantial power requirements of systems based on graphics processing units (GPUs). This power demand can fluctuate rapidly depending on whether training or inference tasks are running, resulting in significant variations in both electricity consumption and cooling demand. These rapidly changing loads can also introduce power quality issues, such as harmonic distortion and voltage fluctuations. To maintain the reliable operation of sensitive computing equipment, these power quality issues must be addressed.*

Lithium-ion batteries are not all identical, and these differences have considerable implications when sizing an energy storage system for a data center. Rahman and Khan (2026) discuss technologies that address requirements ranging from immediate support for computational loads to longer-duration energy supply, considering power, capacity, efficiency, service life, and safety. The performance

of lithium iron phosphate (LFP) and nickel manganese cobalt oxide (NMC) chemistries differs in several respects, including energy density, thermal response, durability, and discharge capability. The report Chemistry Options for Lithium-Ion UPS and BBU (2022) indicates that selecting between these alternatives requires consideration of the required backup power duration, discharge rate, battery operating temperature, and facility safety requirements. Nominal capacity alone provides limited information; what ultimately matters is the suitability of battery performance under actual operating conditions.

Battery chemistry, however, does not encompass the entire issue. The application of BESS requires an assessment of the relationship between available power and energy storage capacity, which address distinct operational requirements: power determines how much of the instantaneous demand the system can assume, whereas energy capacity determines how long that load can be supplied. Zhang et al. (2024) investigated the use of batteries both as backup power sources and as load regulation resources in data centers. Their findings demonstrate a point that may seem obvious only after it has been stated: the reliability of the external electricity supply directly influences the technical and economic assessment of energy storage, since this reliability determines how much backup capacity is actually required. The same authors emphasize the importance of battery state of charge, operating cycles, accumulated degradation, and replacement costs, factors that tend to be overlooked when the discussion focuses exclusively on energy cost savings. This leads to a consideration that is often underestimated: using batteries to reduce electricity expenses must be coordinated with the preservation of sufficient reserve capacity for supply

interruptions, since both functions compete for the same stored energy.

Installing batteries alone is therefore insufficient to guarantee electrical reliability. What matters is the design of the power supply architecture and how protection and supply resources operate together. UPS systems, generator sets, energy storage systems, and redundant circuits can perform complementary functions, provided that they are properly sized and coordinated.

Parise, Allegri, and Parise (2020, p. 3397) explain that:

> *The design of critical power systems must provide topologies that enable operational performance and service continuity, such as protection selectivity, immunity to interference between system areas, efficient maintenance of all system components, flexibility, and scalability. Mission-critical systems include hospitals, data centers, nuclear power plants, institutional buildings, road tunnels, among others; business-critical systems include shopping centers, airports, railway stations, ports, container terminals, among others. In power systems, loads classified as critical (CL), preferential (PL), normal (NL), or shedable (SL) have different service continuity requirements, which an efficient topology must ensure with an appropriate level of integrity. Relevant mission-critical loads are generally incorporated into a complex power system consisting of a primary medium-voltage (MV) distribution circuit, sometimes several secondary MV circuits, and multiple MV/LV transformer substations. Local power generation systems, such as generator sets (GS), uninterruptible power supply systems (UPS), and energy storage systems (ESS), are essential power sources for ensuring the continuity of electricity supply to critical loads, which are normally supplied through an electrical distribution system (EDS).*

The Alcântara microgrid study provides further insight into the coordination of these resources. In the islanded operation modeled by Castelo Branco et al. (2022), the BESS preferably assumes the role of establishing the microgrid's voltage and frequency reference, a function known as grid-forming operation. If this resource becomes unavailable, one of the generator sets assumes this function. The study examined contingencies involving the loss of the battery energy storage system (BESS), photovoltaic generation, or a diesel generator set, with the remaining resources reallocating their

contributions to meet demand. This case demonstrates why storage assessments must also consider the possibility of storage system unavailability: batteries contribute to supply continuity, but their presence does not eliminate the need for alternative resources and an operating strategy for post-failure conditions.

The scope of this analysis, however, must be clearly defined. In the Alcântara study, N−1 contingencies refer to the unavailability of one generation or storage resource at a time. Failures involving internal electrical distribution feeders and branch circuits were not included in the model. Furthermore, the control strategy assumes that the response times of the remaining resources are compatible with maintaining the electricity supply (Castelo Branco et al., 2022). When discussing its application to data centers, it is also necessary to consider load supply paths, protection selectivity, transfer times, and the operation of UPS systems. Source redundancy, therefore, constitutes one component of reliability assessment and must be coordinated with the integrity of the electrical distribution infrastructure, as discussed by Parise, Allegri, and Parise (2020).

Based on these contributions, Table 2 summarizes the main technologies and reliability mechanisms discussed in the literature, relating their characteristics to the functions they can perform in the electricity supply of data centers.

Table 2. Energy storage technologies and electricity supply reliability mechanisms in data centers

Technology or mechanism	Technical characteristics	Contribution to reliability and operational continuity	Author and abbreviated title of the publication

Lithium-ion batteries (BESS)	Energy capacity, power, state of charge, efficiency, service life, and degradation	Electricity supply during interruptions and regulation of electricity demand	Zhang et al. (2024), Reliability and economic evaluation of energy storage
LFP and NMC chemistries	Energy density, discharge rate, thermal stability, service life, and safety	Suitability of batteries for different power requirements and backup supply durations	Chemistry Options for Lithium-Ion UPS and BBU (2022)
UPS and BBU systems	Energy conversion, uninterruptible power supply, and fault response	Temporary maintenance of electricity supply to critical loads during disturbances or interruptions	Chemistry Options for Lithium-Ion UPS and BBU (2022)
Redundant architectures	Independent circuits, protection selectivity, generators, and alternative sources	Reduction of electrical system vulnerability and maintenance of priority load availability	Parise, Allegri, and Parise (2020), Electrical integrity resilience of data centers and critical loads
Microgrid coordination under contingencies	Grid-forming operation by the BESS or generator set; power redistribution following the loss of a generation or storage resource	Coordination of remaining resources to maintain the supply to critical loads during islanded operation	Castelo Branco et al. (2022), Mission Critical Microgrids: The Case of the Alcântara Space Center
Multiscale energy storage	Batteries at equipment, rack, facility, and grid	Mitigation of load variations and support for	Mohammadi et al. (2026), Grid

	levels; fuel cells and thermal storage	data center integration with the electrical grid	integration of AI data centers
BESS-generator hybrid systems	Coordinated operation of batteries and generator sets	Combination of rapid storage response with longer-duration emergency power supply	Zhang et al. (2024), Reliability and economic evaluation of energy storage
Management of behind-the-meter batteries	State-of-charge control, reliability-constrained dispatch, and outage forecasting	Reconciliation of electricity cost reduction with the maintenance of backup reserves for critical loads	Iqbal and Sarwat (2026), Reliability-constrained behind-the-meter BESS dispatch
UPS performance requirements	Performance classification, testing, and operational requirements	Technical guidance for the specification and assessment of uninterruptible power supply systems	IEC (2021), IEC 62040-3
Energy storage for artificial intelligence loads	Rapid power variations, dynamic demand, and response requirements	Accommodation of consumption fluctuations and support for electrical power quality	Rahman and Khan (2026), Energy Storage Systems for AI Data Centers

Source: Prepared by the author, based on Zhang et al. (2024), Chemistry Options for Lithium-Ion UPS and BBU (2022), Parise, Allegri, and Parise (2020), IEC (2021), Mohammadi et al. (2026), Rahman and Khan (2026), Iqbal and Sarwat (2026), and Castelo Branco et al. (2022).

The analysis of the technologies presented makes it possible to understand that electricity supply reliability in data centers results from the combination of energy storage, uninterruptible power supply systems, emergency generation, and infrastructure redundancy. Mohammadi et al. (2026) emphasize the importance of coordination among different storage levels, whereas Iqbal and Sarwat (2026) examine the need to preserve energy availability for critical loads during unexpected interruptions. In this context, energy storage must be integrated into the facility's energy planning, considering both backup requirements and the possibilities for demand regulation and renewable energy integration. This coordination provides the foundation for understanding how intelligent management systems can coordinate generation, storage, and consumption, an issue addressed in the following section.

2.3. Intelligent Energy Management, Cooling Efficiency, And Operational Continuity In Data Centers

The growth of cloud computing, the Internet of Things, and, particularly, artificial intelligence applications has increased the demand for data processing and storage, turning data centers into energy-intensive facilities. Managing this consumption can no longer be restricted to the electricity used by servers, as cooling, electrical distribution, and operational support systems must also be considered. Kahil et al. (2025) observe that the increase in computational loads has significant financial and environmental implications, meaning that computational performance, energy efficiency, and service continuity can no longer be addressed as separate issues. The authors summarize this context by stating:

> *The digitalization of society and the emergence of new AI technologies have increased the overall demand for computational power. This growth has made data centers a critical infrastructure supporting our modern digital ecosystems. The increased use of technologies such as the Internet of Things (IoT), cloud computing, big data, and artificial intelligence (AI) has increased the workload of data centers, which now require even greater computational resources to meet demand. Data centers form the backbone of modern digital infrastructure, and their high energy consumption has substantial financial and environmental implications (Kahil et al., 2025, p. 02).*

In this context, Energy Management Systems (EMS) emerge as the element that connects the other components. They enable the monitoring and coordination of renewable energy generation, storage, electricity supplied by the grid, and the energy consumption of the facilities themselves. In practice, an EMS can integrate information from meters, thermal sensors, electrical equipment, and supervisory systems. Operational decisions are then grounded in this information, which is collected under actual operating conditions. Sá Ferreira et al. (2026) address this interface by discussing the combination of machine learning and optimization methods as a means of bringing forecasting and decision-making closer together in energy management. The relevant point is that this integration makes it possible to account for demand variations, renewable energy availability, and the operational constraints of each application, without assuming that a single algorithm is suitable for every facility.

This coordination can also be examined through changes in operational priorities under different operating modes. In the Alcântara case, Castelo Branco et al. (2022) developed distinct strategies for grid-connected operation, involving the local electricity utility, and islanded operation. In the former, energy management uses photovoltaic generation and storage to reduce electricity purchases, including during periods of higher tariffs. In the latter, supply security determines the dispatch strategy, which must comply with resource availability, battery state-of-charge limits, and generator constraints. The simulations also show situations in which photovoltaic generation must be curtailed to preserve the power balance when the storage system has limited capacity to absorb energy and there is no connection to the external grid. For data centers, this approach provides a management principle: opportunities for cost savings and renewable energy utilization must be assessed within the conditions required to maintain the continuity of critical loads. Applying this principle requires recognizing that, in these facilities, continuity requirements remain in effect throughout their entire operation.

Among intelligent strategies, reinforcement learning has been investigated as a means of dynamically adjusting operating parameters, particularly in cooling systems and information technology infrastructure. Kahil et al. (2025) report applications of this approach in cooling control and in the management of computational systems, while emphasizing that the results must be evaluated in light of the experimental conditions and performance indicators adopted in each study. Lin et al. (2024), from a complementary perspective, examine energy-saving methods and thermal models that connect computational load management with cooling control. Integration between these two areas is not

merely a secondary consideration: changes in the distribution of processing workloads alter the amount of heat generated and, consequently, the cooling requirements.

Thermal management requires continuous monitoring of environmental conditions and airflow circulation within facilities. When airflow is poorly distributed, hot air recirculates, cold air is diverted, and areas with unfavorable thermal conditions emerge. This increases the load on cooling equipment and may ultimately compromise operational stability. Du et al. (2023) advocate predicting, evaluating, and controlling the thermal environment, noting that airflow distribution indicators help both identify problems and establish operating strategies. The authors explain that:

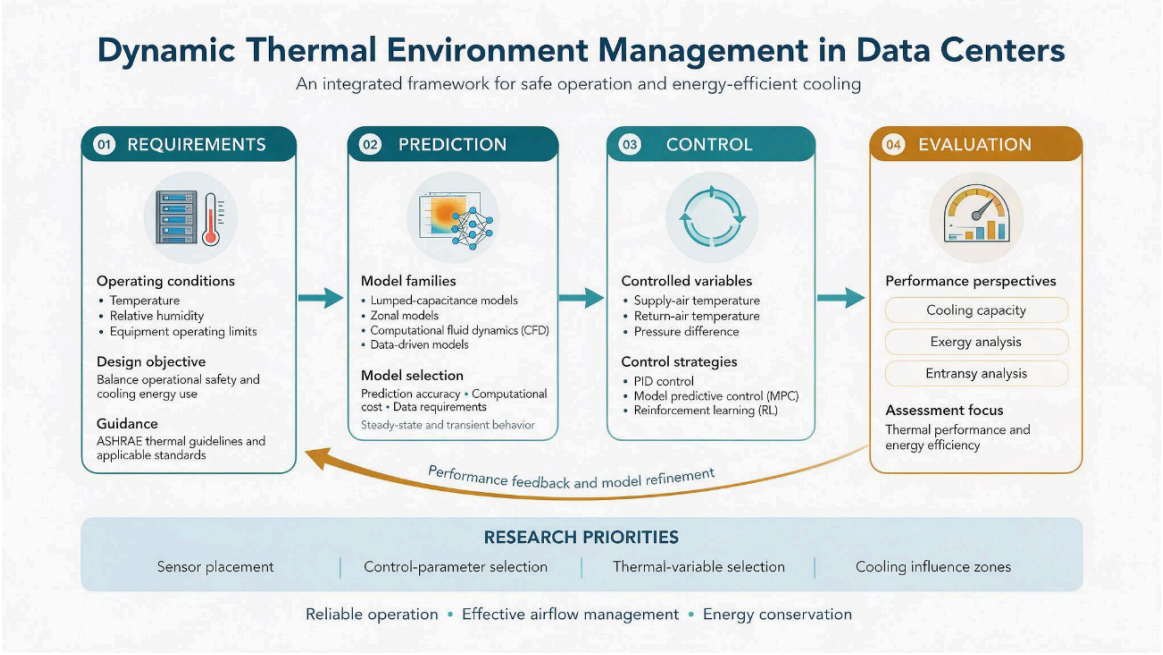
> *To guide data center operations more effectively, the assessment of thermal environment management is essential. Improper airflow organization mainly includes short-circuiting, recirculation, and negative-pressure air mixing. Air recirculation means that hot air enters the cold aisle and mixes with the inlet air. Bypass airflow refers to cold air leaking into the hot aisle or returning directly to the computer room air handling units (CRAHs), potentially accounting for up to 60% of the total cold air supply. Negative-pressure airflow refers to airflow caused by the Venturi effect in the space between the raised floor and the ground, generally resulting from low pressure and the adsorption effect near a high-velocity fluid. Many studies have proposed corresponding indices from different perspectives to evaluate airflow distribution in data centers. Appropriate evaluation indices can characterize the actual airflow distribution conditions in data centers and assist in determining the most suitable guidelines for thermal environment control (Du et al., 2023, p. 03).*

Monitoring, forecasting, and control do not function as isolated stages in this context but rather as a continuous flow of information: the operational state provides input for predictive models, which in turn guide adjustments to cooling systems. Figure 2 illustrates this sequence, encompassing thermal requirements, model selection, the variables to be controlled, and performance assessment. The diagram clearly places greater emphasis on thermal environment management, but its relationship with the logic of EMS remains relevant, since temperature, airflow, and cooling demand directly influence the overall electricity consumption of the facility.

Figure 2 organizes the dynamic thermal management of data centers into four interconnected stages: identification of operating

conditions, prediction of thermal behavior, control of environmental variables, and performance assessment. Monitoring temperature, relative humidity, and equipment operating limits provides input for selecting predictive models and control strategies, which include both conventional methods and intelligent techniques.

Figure 2. Integrated Framework for Dynamic Thermal Environment Management in Data Centers



Source: Prepared by the authors (2026), based on Lin et al. (2024), Du et al. (2023), Kahil et al. (2025), and Sá Ferreira et al. (2026).

The assessment of data center efficiency cannot rely on a single metric because design and operational decisions affect different dimensions of energy and thermal performance, and each dimension requires its own indicator to be examined with an appropriate degree of rigor. Power Usage Effectiveness (PUE) relates the total energy consumed by the facility to the energy used by information technology equipment, indicating the extent to which supporting infrastructure contributes to overall consumption. ISO/IEC 30134-2:2026 establishes how this indicator must be defined, measured, calculated, and reported. Water Usage Effectiveness

(WUE), in turn, follows ISO/IEC 30134-9:2022 and measures water consumption during data center operations. Van Geet and Sickinger (2024) add three indicators to this set: Energy Reuse Effectiveness (ERE), Energy Reuse Factor (ERF), and Renewable Energy Factor (REF), which shift the analysis toward energy reuse and the contribution of renewable sources. The combined interpretation of these metrics provides a more comprehensive understanding of the actual effects of energy and thermal management decisions, since each indicator, when considered individually, captures only one aspect of the problem.

These indicators are meaningful, however, only when linked to technical design, operation, and maintenance criteria. ANSI/ASHRAE Standard 90.4-2025 establishes minimum energy efficiency requirements for new data centers, expansions, and modifications, addressing aspects ranging from non-renewable and renewable energy consumption to water use and greenhouse gas emissions. Van Geet and Sickinger (2024) follow the same approach by compiling recommendations on the efficiency of information technology equipment, airflow management, cooling, electrical systems, and heat recovery. Equipment automation addresses only part of the problem. The remaining aspects depend on well-defined design criteria, appropriate instrumentation, data quality, the establishment of operational limits, and periodic performance assessment. This is why energy management in data centers requires decisions that simultaneously reconcile electrical efficiency, thermal performance, water use, and operational reliability. The following Table 3 is based on this integrated approach: hybrid renewable systems, energy storage, and intelligent control mechanisms operating together to supply these facilities.

Table 3. Intelligent management strategies, thermal efficiency, and performance indicators in data centers

Analysis dimension	Strategies and aspects considered	Related indicators or parameters	Author and abbreviated title of the work
Intelligent energy management	Integration of machine learning and optimization methods for energy forecasting and decision-making.	Demand forecasting, electricity consumption, and operational performance.	Sá Ferreira et al. (2026), *Integrating machine learning and optimization methods for green data center energy management*.
Energy management subject to operational safety constraints	Coordinated dispatch of generation and storage in grid-connected and islanded modes, considering costs, operational limits, and contingencies.	BESS state of charge, available power, generation-demand balance, generator limits, and energy procurement costs.	Castelo Branco et al. (2022), *Mission Critical Microgrids: The Case of the Alcântara Space Center*.
Reinforcement learning	Application of algorithms to optimize cooling systems and information technology loads.	Energy consumption, cooling performance, and computational efficiency.	Kahil et al. (2025), *Reinforcement learning for data center energy efficiency optimization*.
Thermal modeling	Use of models to relate computational loads, heat generation, and	Temperature, thermal distribution, and energy consumption.	Lin et al. (2024), *Thermal modeling and thermal-aware energy saving*

	the energy consumption of cooling systems.		*methods for cloud data centers*.
Thermal environment control	Airflow monitoring, prediction of thermal conditions, and cooling control.	Temperature, recirculation, air bypass, and airflow distribution.	Du et al. (2023), *Dynamic thermal environment management technologies for data center*.
Facility energy efficiency	Assessment of total energy consumption in relation to the energy used by information technology equipment.	PUE.	ISO/IEC (2026), *ISO/IEC 30134-2:2026: Power usage effectiveness*.
Water usage efficiency	Monitoring of water consumption associated with data center operations.	WUE.	ISO/IEC (2022), *ISO/IEC 30134-9:2022: Water usage effectiveness*.
Energy reuse and renewable energy contribution	Assessment of energy recovery and the contribution of renewable sources to operations.	ERE, ERF, and REF.	Van Geet and Sickinger (2024), *Best practices guide for energy-efficient data center design*.
Design and operational efficiency requirements	Compliance with minimum energy efficiency requirements for new projects, expansions, and modifications.	Renewable and non-renewable energy consumption, water consumption, and emissions.	ASHRAE (2025), *ANSI/ASHRAE Standard 90.4-2025: Energy standard for data centers*.

Source: Prepared by the authors based on Kahil et al. (2025), Du et al. (2023), Lin et al. (2024), Sá Ferreira et al. (2026), Van Geet and Sickinger (2024), ISO/IEC (2022, 2026), ASHRAE (2025), and Castelo Branco et al. (2022).

Finally, operational continuity depends on coordinating computational and thermal demand without exceeding equipment safety limits. Predictive models and optimization strategies can help adjust cooling according to variations in workload, while indicator monitoring makes it possible to identify efficiency losses and guide interventions. It is worth emphasizing, however, that reducing consumption must not compromise either the recommended environmental conditions or service availability.

3. METHODOLOGY

The research is qualitative and theoretical-documentary in nature, as it focuses on interpreting scientific knowledge, technical information, and regulatory documents related to the application of hybrid renewable energy systems in data centers. The aim is not to measure each variable separately, but rather to understand how photovoltaic and wind power generation are combined with energy sizing, storage methods, intelligent management, cooling efficiency, and operational continuity, as well as the technical conditions that influence this integration. As Lakatos and Marconi (2020) explain, the definition of methodological procedures must be aligned with the research problem and objectives so that the choices made are compatible with the nature of the knowledge to be produced. A problem concerning how technical components interact calls for an interpretive examination of what has already been published and standardized on the subject, rather than a series of measurements.

The study relied on two complementary procedures: bibliographic research and documentary research. The former involved gathering and examining scientific articles, literature reviews, and technical publications related to hybrid renewable systems, energy storage technologies, and energy management in data centers. The latter considered technical standards and institutional documents intended to establish requirements, parameters, and guidelines applicable to energy efficiency, uninterruptible power supply, and performance assessment in these facilities. Combining these two procedures was appropriate because an energy solution for a data center cannot be assessed according to a single criterion: it must simultaneously ensure efficiency, safety, and supply availability (Lakatos; Marconi, 2020). Furthermore, comparing academic discussions with regulatory and technical references broadened the understanding of the research subject.

As a complementary reference for supplying critical loads, the study examined the work by Castelo Branco et al. (2022) on the power microgrid at the Alcântara Launch Center, in the state of Maranhão, Brazil. Its use focused on resource configuration criteria, contingency management, and energy management strategies for critical electrical loads, while explicitly distinguishing between aerospace applications and data centers. The institutional publication by the Brazilian Air Force (2024) was used to contextualize the implementation and operation of the power microgrid. Accordingly, the simulation results presented in the scientific article, subsequent institutional reports, and interpretations of their relevance to the subject of this research were treated separately.

The bibliographic component was exploratory and descriptive in nature and was not configured as an integrative literature review. Its

exploratory dimension involved mapping technologies, concepts, and strategies associated with the research subject, making it possible to identify both approaches to sizing photovoltaic and wind power systems and alternatives for energy storage and management methods. The descriptive dimension involved organizing and presenting the technical characteristics of these solutions, including autonomy, response time, storage capacity and power, efficiency, generation variability, service life, cooling control, and performance indicators. Neubauer and Eckert (2025) describe bibliographic research as a methodological procedure for constructing scientific knowledge through the identification and examination of previously published works. It is therefore important to clarify that no integrative review protocol was adopted, nor was an integrative synthesis of primary study results intended. Instead, the relevant publications were identified, selected, read, interpreted, and thematically organized in accordance with the research objectives.

The literature search prioritized works published between 2018 and 2026, a period encompassing most of the selected references, without excluding earlier texts that made relevant technical or regulatory contributions. The selection included materials that met the following criteria: a direct relationship with at least one of the research's three thematic areas; verifiable authorship and title; publication in a scientific journal, academic publishing house, or responsible institution; availability of a DOI, publisher's website address, or institutional record; and technical or conceptual information relevant to the research problem. The currency of the content and its applicability to the reality of data centers were also considered in the selection process. Conversely, the study excluded texts with unidentifiable authorship or provenance, materials without a substantive relationship to the research objectives,

bibliographic records too incomplete to verify publication details, and promotional or commercial content lacking verifiable technical substantiation.

The identification details of each publication were recorded, including, whenever available, authorship, title, year, journal or responsible institution, volume, issue, page numbers or article number, DOI, and electronic address. This verification process involved consulting scientific publishers' websites, DOI records, and official repositories of the institutions responsible for the standards and technical documents examined. The documentary research included, among other materials, IEC 62040-3:2021, concerning performance and testing requirements for uninterruptible power systems; ISO/IEC 30134-2:2026 and ISO/IEC 30134-9:2022, concerning the PUE and WUE indicators; ANSI/ASHRAE Standard 90.4-2025; and the Best Practices Guide for Energy-Efficient Data Center Design, published by the National Renewable Energy Laboratory in 2024. The analysis of these documents considered their institutional authorship, purpose, publication context, and the relevance of their provisions to the research problem, in accordance with the methodological perspective discussed by Salge, Oliveira, and Silva (2021). The DOI was used solely to identify and locate publications, never as independent evidence of scientific quality or journal indexing.

After selection, the materials underwent analytical reading and were organized into three thematic areas, corresponding to the topics addressed in the theoretical framework: hybrid renewable energy systems and sizing criteria; energy storage technologies and electricity supply reliability; and intelligent energy management, cooling efficiency, and operational continuity. The information was

compared and integrated according to its contribution to the specific objectives, distinguishing between what the studies technically describe, what the standards require, and what the institutional documents recommend. No experiments, original measurements, interviews, field studies, mathematical sizing of facilities, or computer simulations were conducted. The findings therefore derive from the qualitative interpretation and systematization of the selected bibliographic and documentary sources.

4. FINAL CONSIDERATIONS

Data centers have expanded alongside digital infrastructure and now require a continuous electricity supply that the conventional grid alone cannot always guarantee with the level of reliability these facilities demand. This has created opportunities for combining renewable energy sources, particularly solar and wind power, with energy storage and intelligent management systems. This approach diversifies the electricity supply and, in principle, improves facility performance. Implementing it, however, involves more than selecting and installing a particular technology. It requires technical planning that simultaneously considers generation variability, the load profile to be served, available storage capacity, cooling system efficiency, and reliability requirements, rather than addressing each of these aspects in isolation. This study examined these dimensions collectively, seeking to discuss energy solutions that reconcile operational safety, efficiency, and sustainability with the expansion of digital services.

The research was guided by a straightforward question: how can the integration of hybrid renewable energy systems, combined with

storage and intelligent management, contribute to continuously meeting the electricity demand of data centers? This question was addressed by bringing together the technical aspects examined throughout the study, rather than relying on any single finding. The analysis showed that this integration helps ensure energy availability and supply stability, but only under three conditions: appropriate system sizing, storage strategies aligned with the actual load profile, and control mechanisms capable of coordinating generation, consumption, and cooling. If any of these elements is lacking, diversification of the energy mix no longer provides such assurance, since operational reliability depends less on any specific technology than on how the components of the energy system interact with one another and with the supporting and redundancy arrangements that underpin the entire infrastructure.

Regarding the proposed objectives, the general objective and the three specific objectives were achieved through the analysis of the technical foundations of hybrid systems, energy storage technologies, and intelligent management strategies applied to data centers. The study examined the sizing criteria for photovoltaic and wind power sources, generation variability, and its relationship with the electricity demand profile. It also investigated energy storage technologies and their contributions to supply stability, power availability, and operational continuity. Finally, it analyzed monitoring and control strategies aimed at optimizing consumption, improving cooling efficiency, and ensuring electrical reliability. Addressing these three areas collectively made it possible to bring together, within an integrated perspective on energy supply, technical requirements that are usually examined separately.

The first topic of the theoretical framework made clear that configuring a hybrid photovoltaic-wind power system requires consideration of the complementarity between energy sources, the availability of natural resources at the site, temporal generation variability, and the consumption profile of data centers. In this respect, system sizing goes beyond the installed capacity of generators. It also involves matching energy production to demand, meeting the power requirements during periods of peak consumption, and considering the conditions for integration with the electricity grid. Combining renewable sources therefore expands the range of possibilities for meeting energy demand, but only when the system configuration is determined according to the facility's operational characteristics and electricity supply availability requirements.

The second topic made clear that energy storage technologies do not all perform the same function within the electrical system. Each serves a different purpose, and this is precisely why they complement one another in sustaining the power supply. Batteries, particularly lithium-ion batteries, help meet load variations, regulate power, and maintain supply during interruptions. In practice, however, this depends on careful sizing of capacity, power, efficiency, service life, response time, and autonomy. The analysis also showed that storage does not operate in isolation. Its integration with renewable sources, uninterruptible power supply (UPS) systems, emergency generators, and redundancy mechanisms is what ensures continuity of supply.

In the third topic, intelligent management emerged as the element that makes it possible to coordinate generation, storage, and consumption. Monitoring, forecasting, and control strategies adjust

equipment operation as operating conditions change. Cooling efficiency, in turn, depends directly on thermal management and on how airflow is organized within the facility, while indicators such as PUE, WUE, ERF, and REF provide complementary parameters for assessing the energy and water performance and energy recovery of these facilities.

As a contribution, this study brought together in a single framework the technical criteria and relationships among hybrid renewable generation, energy storage, intelligent management, cooling, and operational continuity. This framework may serve as a reference for those planning the energy infrastructure of data centers. The discussion also indicates that the efficiency of these facilities must be assessed from an integrated perspective, encompassing both the energy consumed by information technology equipment and the demand of supporting systems.

At least four areas remain open for future research: comparative studies of hybrid photovoltaic and wind power configurations; assessments of different storage capacities and technologies; management strategies based on artificial intelligence; and coordination between computational loads and cooling systems. Techno-economic analyses and scenario simulations are also relevant, considering variations in demand, power supply interruptions, and the efficiency indicators discussed above, in order to determine the operating conditions under which these solutions are genuinely justified.

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