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Energy Curtailment And Data Centers: Technological Strategies For Consumption Optimization In Renewable Energy-Based Systems

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Abstract:
Background: *The growing energy demand associated with data centers and the expansion of renewable energy sources have intensified scientific discussions concerning energy efficiency, sustainability, and operational stability in high-capacity digital infrastructures. Within this context, the present study aims to comprehensively examine technological strategies designed to optimize energy consumption in data centers operating within renewable energy-based systems, considering the impacts of energy curtailment on operational efficiency, sustainability, and the stability of energy supply in these infrastructures.*
Materials and Methods: *This study adopted a qualitative methodological approach, as the research sought to interpret and understand phenomena related to energy curtailment and technological strategies applied to energy management in data centers. Methodologically, a bibliographic review was employed as the primary research strategy, enabling the systematic organization and critical analysis of scientific publications associated with the investigated topic.*
Results: *The findings demonstrated that technical and operational factors directly influence the occurrence of curtailment in renewable energy-based systems, affecting the energy stability of data centers. Furthermore, the results indicated that technologies such as artificial intelligence, automation, and energy storage contribute to greater efficiency in computational workload management and to the reduction of energy waste.*
Conclusion: *It was concluded that the integration between intelligent technological solutions and renewable energy sources promotes greater operational sustainability, energy efficiency, and reliability in the operation of data centers with high computational demand.*
Key Word: *Energy curtailment; Data centers; Renewable energy; Energy efficiency.*

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I. Introduction

Over the last decades, an accelerated advancement of the phenomenon known as digital transformation has been observed, a process that has significantly increased dependence on computational infrastructures characterized by high-performance standards. In this context, data centers have assumed a strategic role in the storage, processing, and distribution of large volumes of data, becoming essential for the efficient operation of activities that require large-scale information management. Simultaneously, the growth in energy consumption associated with digital activities has intensified scientific and technological debates concerning the sustainability of these operations and the diversification of the energy sources employed in such infrastructures. Within this scenario, renewable energy sources have gained increasing prominence in strategies aimed at reducing the environmental impacts generated by human activities, while also contributing to the development of more sustainable energy models focused on long-term environmental preservation. Nevertheless, the intermittency inherent to renewable energy generation, particularly in wind and solar systems, remains a significant technical challenge for ensuring stability in electricity supply, especially in computational environments characterized by high energy demand.

One of the principal challenges associated with the efficient integration between data centers and renewable energy sources concerns the phenomenon known as energy curtailment. This phenomenon refers to the reduction of energy generation resulting from operational, structural, or demand-related limitations, particularly when there is a mismatch between the volume of generated energy and real-time electricity consumption. Such a scenario may produce significant consequences, including energy losses, reductions in operational efficiency, and interruptions in electricity supply that directly affect computational systems operating continuously. These impacts may compromise both overall performance and operational continuity. Consequently, the development of technological innovations aimed at intelligent and efficient energy management has progressively become a topic of substantial relevance within both scientific and technological domains. Current debates increasingly emphasize the search for alternatives capable of improving the operational efficiency of energy systems while mitigating the impacts arising from the intrinsic fluctuations of renewable energy sources. In this regard, solutions based on artificial intelligence, automation, and energy storage technologies emerge as relevant and innovative proposals for strengthening energy stability in data centers.

The present article aims to examine, in detail, the technological strategies designed to optimize energy consumption in data centers integrated with renewable energy systems. Furthermore, the study investigates how the phenomenon of curtailment affects operational efficiency, sustainability, and energy supply stability within these infrastructures. The specific objectives include: (i) investigating the technical and operational factors associated with the occurrence of curtailment in renewable energy systems used to supply data centers; (ii) analyzing the application of intelligent technologies capable of mitigating the effects of this phenomenon on electricity consumption; and (iii) evaluating the impacts of sustainable and technologically integrated strategies on both energy efficiency and the operational resilience of essential digital infrastructures. The establishment of these objectives enables a comprehensive analysis of the technical, operational, and environmental dimensions associated with the topic under investigation.

In order to achieve the proposed objectives, a qualitative methodological approach was adopted, considering that the research seeks to interpret and understand the phenomena associated with energy curtailment and the technological strategies employed in energy management within data centers. Qualitative research is particularly relevant in scientific investigations involving complex phenomena situated within dynamic and interdisciplinary contexts. In this perspective, knowledge related to technology, the energy sector, and sustainability becomes essential for understanding the interactions and consequences arising from these dimensions in contemporary society. Methodologically, the study employed a bibliographic review as its primary research strategy, enabling the systematic organization and critical analysis of scientific productions addressing the investigated theme.

Regarding the structural organization of the manuscript, the article was divided into four main sections, developed in an articulated and coherent manner according to the objectives established for the research. The first section corresponds to the introduction, in which the theme is contextualized, the research objectives are clearly presented, and the methodological strategy adopted in the study is described. This section establishes the theoretical and conceptual foundations necessary for understanding the relevance of the topic and the direction of the investigation. The second section presents the methodological procedures employed throughout the development of the research, detailing the scientific methods and techniques adopted. The third section is dedicated to the theoretical framework, addressing the phenomenon of energy curtailment, intelligent technologies for efficient energy management, and the relevance of sustainability in data centers powered by renewable energy sources. Finally, the fourth section presents the final considerations, synthesizing the principal findings of the study and proposing future research perspectives directly related to the optimization of energy consumption in computational environments dependent on renewable energy sources.

II. Material And Methods

The growing demand for electricity has been accelerated by the continuous expansion of data centers worldwide, largely driven by the exponential increase in data processing, the widespread adoption of cloud computing, and the advancement of applications associated with artificial intelligence. This trend reflects a significant transformation in the contemporary technological landscape, in which energy efficiency has become increasingly relevant. Within this context, the integration of renewable energy sources into computational systems has emerged as one of the most extensively discussed subjects in both scientific research and technological innovation, particularly regarding energy efficiency and sustainability in operational processes. This growing emphasis demonstrates the relevance of the topic in the search for alternatives capable of reducing environmental impacts while promoting a more conscious and responsible use of available resources. Nevertheless, the intermittency inherent to both solar and wind energy constitutes one of the principal factors associated with energy curtailment. This term refers to the practice of partially restricting or interrupting energy generation from renewable sources due to operational, technical, or structural limitations within the electrical system. Therefore, it becomes essential to investigate technological solutions capable of increasing energy consumption efficiency in data centers powered by renewable energy sources. Such a necessity arises from the urgent need to balance computational performance, stability in energy supply, and the reduction of energy waste. This evaluation is particularly relevant because it seeks to identify effective mechanisms for reconciling the growing dependence on technology with the contemporary demands of sustainability. As emphasized by Antonio Carlos Gil (2022), scientific investigation must be conducted systematically and directed toward solving practical societal and technological problems, thereby enabling the production of robust knowledge grounded in effective and consolidated methodologies.

The present research adopts a qualitative approach, as it seeks to interpret and understand the phenomena associated with energy curtailment while also examining the technologies employed in the management of energy consumption in data centers operating with renewable energy sources. Qualitative research holds substantial relevance in contemporary science because it enables broader interpretations of phenomena characterized by complexity, multidimensionality, and contextualization within dynamic and constantly evolving scenarios. This perspective becomes especially pertinent in interdisciplinary fields involving energy, technology, and sustainability. Consequently, qualitative research constitutes an indispensable methodological instrument for understanding the complexities and interconnections that characterize such interdisciplinary domains. According to Silva et al. (2022), qualitative research enables a deeper investigation into relationships, meanings, perceptions, and structures embedded within a given context. These dimensions are highly intricate and cannot be fully interpreted solely through quantitative metrics or numerical indicators. As a result, scientific research becomes more closely integrated with the social, technical, and operational dimensions associated with the investigated objects of study, thereby favoring more consistent and coherent interpretations aligned with the demands of contemporary global scientific production.

From a methodological perspective, the study employed bibliographic review as its primary research method. This approach is widely recognized within the international academic community because it enables the organization, critical analysis, and synthesis of existing knowledge regarding a specific subject, thereby contributing to the identification of theoretical convergences, research gaps, and methodological trends. According to Gil (2022), bibliographic review allows researchers to access previously published scientific contributions, thus establishing a robust analytical foundation for the development of new investigations. In the present study, the bibliographic review was based on 26 research sources, predominantly composed of scientific articles and specialized books addressing energy curtailment, energy efficiency, data centers, and renewable energy systems. The selection of sources considered thematic relevance, scientific consistency, and academic pertinence in relation to the objectives of the research.

The combination of the qualitative approach with bibliographic review proved to be appropriate for achieving the objectives of the investigation, as it enabled an integrated analysis of the technological, energetic, and operational factors involved in optimizing energy consumption in data centers powered by renewable sources. This methodological integration facilitated a more contextualized interpretation of energy curtailment mitigation strategies while promoting the articulation of distinct theoretical perspectives present in contemporary scientific literature. According to Silva et al. (2022), qualitative research, when combined with bibliographic analysis, contributes to the development of interpretations that are theoretically grounded and aligned with the complexity of the investigated phenomena. Thus, the adopted methodology provided a theoretical and analytical foundation consistent with the objectives of the study, strengthening both the scientific rigor of the research and the critical understanding of the investigated theme.

III. Theoretical Framework

The theoretical framework of the present study was structured around three interdependent thematic axes, organized with the objective of providing a systematic understanding of the relationships between energy curtailment, technological management, and operational efficiency in data centers powered by renewable energy sources. The first topic, entitled "Curtailment in Renewable Energy Systems: Causes, Operational Challenges, and Impacts on Energy Supply for Data Centers," addresses the technical and structural factors associated with the limitation of renewable energy generation, as well as their implications for the stability and reliability of energy supply directed toward computational infrastructures. The second topic, entitled "Intelligent Technologies for Energy Management in Data Centers: Artificial Intelligence, Automation, and Energy Storage," focuses on the analysis of technological solutions applied to the optimization of energy consumption, emphasizing the use of automated systems, artificial intelligence algorithms, and energy storage mechanisms designed to enhance operational efficiency. Finally, the third topic, "Sustainability and Energy Efficiency in Data Centers Based on Renewable Energy Sources," discusses strategies related to the reduction of environmental impacts, the rationalization of energy consumption, and the strengthening of sustainable practices in computational environments characterized by high energy demand. The organization of these thematic axes enabled the establishment of an analytical sequence coherent with the objectives of the research, thereby facilitating the articulation between the theoretical foundations and the central issues investigated throughout the study.

Curtailment in Renewable Energy Systems: Causes, Operational Challenges, and Impacts on Energy Supply for Data Centers

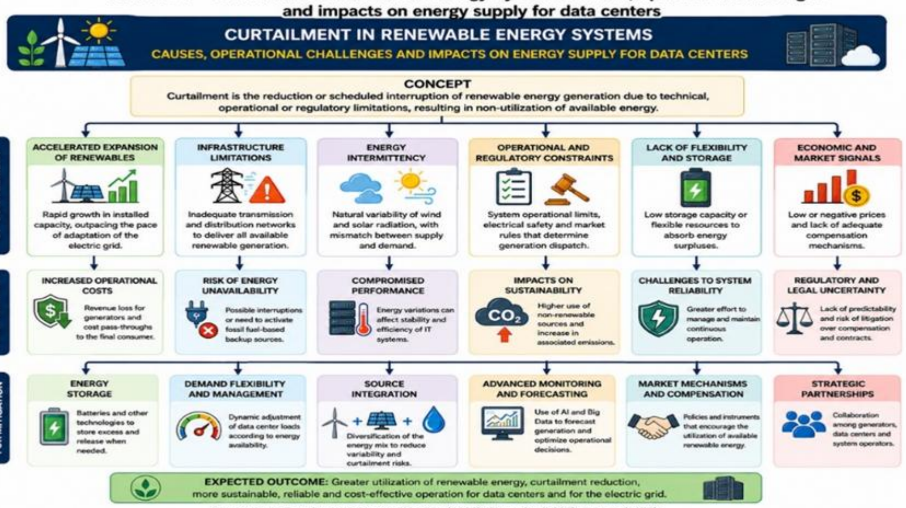
The growing contribution of renewable energy sources to the global electricity matrix has generated significant transformations in the operation of modern energy systems. These changes have profoundly influenced the way energy operations are currently conducted, introducing new methods and challenges in the management and utilization of sustainable energy sources. The rapid and continuous expansion of solar and wind energy, although associated with carbon emission reduction and the strengthening of sustainability policies, has also exposed a series of structural limitations directly related to the capacity of electrical grids to transmit, store, and balance the generated energy. This issue has become increasingly evident as renewable sources assume a more prominent role within the contemporary energy landscape. In this context, the phenomenon known as *curtailment* emerges as a circumstance involving the total or partial restriction of renewable energy generation. This phenomenon occurs primarily when there is an excess of energy generation or when electrical infrastructure is unable to accommodate the produced energy. According to Caracas Neto, Gomes et al. (2025), greater participation of renewable sources in the energy sector requires the implementation of new governance strategies and technical mechanisms capable of ensuring the operational stability of energy systems.

The manifestation of curtailment is closely associated with a series of technical, regulatory, and operational factors commonly observed in both distributed and centralized generation systems. These factors are fundamental to the functioning and efficiency of energy generation infrastructures. Among the elements most directly related to this process are the intermittency of renewable energy sources, characterized by variability in power generation; limitations in transmission line capacity, which restrict the transportation of large amounts of electricity; regional energy congestion, resulting from excessive demand in specific areas; and the absence of large-scale energy storage systems, which remain insufficiently robust and efficient, thereby hindering the management and stability of energy supply. According to Faveret (2025), the increase in renewable energy generation in Brazil has substantially intensified pressure on the national electrical infrastructure. These increasingly frequent operational interruptions are considered necessary to maintain the stability of the interconnected electrical system. This phenomenon is not an isolated case. On a global scale, the reduction of renewable energy production has continuously increased in markets with high penetration of renewable sources. In 2025 alone, several significant cases were reported: Spain intentionally curtailed nearly 20% of its wind energy generation in May; France reached a peak in August, with more than 11% reduction in wind production; and, in the United Kingdom, the curtailed electricity would have been sufficient to supply all Scottish households during the first half of that year. In China, some provinces recorded curtailment rates exceeding 30% for both wind and solar energy during the first six months of the year (Willige, 2025).

In data centers, the repercussions of curtailment become even more critical due to the intense dependence of these facilities on continuity and predictability in energy supply. Data centers operate under heavy computational workloads and require high electrical availability to maintain processing systems, data storage, cooling infrastructure, and digital connectivity. According to Chiappini (2025), the rapid proliferation of data centers has intensified pressure on electrical grids, especially in regions where energy infrastructure already exhibits signs of overload. In addition to structural issues, the climatic variability associated with solar and wind sources further aggravates energy management challenges in high-demand computational environments. Abrupt fluctuations in wind speed or solar irradiance may compromise the predictability of renewable energy generation and require rapid energy compensation solutions. According to Fagundes (2025), the synergy among energy storage systems, intelligent management, and technological integration emerges as a significant alternative for mitigating the operational effects of curtailment in renewable energy systems.

In this context, large-scale battery storage solutions, smart electrical grids, and flexible energy distribution models have gained increasing prominence within the energy sector. According to Feitosa Neto and Gomes et al. (2025), *smart curtailment management* is capable of balancing energy supply and demand, minimizing energy waste, and optimizing operational efficiency in systems with high participation of renewable sources. The authors also emphasize that data centers may function as flexible consumption units, reducing part of their computational loads during periods of critical energy instability. Figure 1 below summarizes the main factors associated with curtailment in renewable energy systems and illustrates how these factors affect data centers, considering electrical infrastructure, energy intermittency, intelligent management, and computational stability.

FIGURE 1 – Curtailment in Renewable Energy Systems: causes, operational challenges and impacts on energy supply for data centers



Source: Based on Caracas Neto and Gomes (2025); Fagundes (2025); Faveret (2025); Feitosa Neto and Gomes (2025); Rodrigues (2024); Rolim (2025); Simple Energy (2026); Chiappini (2025).

The economic effects resulting from curtailment, defined as the practice of reducing or restricting electricity generation from renewable energy sources, have also become the subject of intense debate and discussion. This occurs largely because significant financial losses are associated with renewable energy that is not effectively utilized. Consequently, increasing attention has been directed toward the broader economic impacts of this practice, particularly as dependence on sustainable energy sources becomes progressively more essential. According to Rodrigues (2024), several companies operating within the Brazilian renewable energy sector have begun reporting substantial financial losses. These losses have resulted from generation cuts implemented by the national electrical system operator, causing severe operational and economic damage to these companies. This scenario clearly demonstrates that curtailment is not merely a technical issue, but rather an economic matter of considerable relevance, directly linked to the feasibility and profitability of investments in energy infrastructure and digital transformation.

In addition to the economic consequences associated with the mandatory reduction of renewable generation, curtailment also reveals technical limitations related to the operational efficiency of electrical distribution networks. In this regard, Silva, Moura, and Barroso (2022) argue that the assessment of technical losses in medium-voltage feeders represents an important factor for both energy planning and the improvement of electrical systems operating under high load conditions. The authors propose a model for evaluating technical losses based on both single-phase and three-phase load flow data, enabling more precise identification of electrical inefficiencies within distribution networks. Therefore, this discussion is directly intertwined with the context of curtailment in renewable generation systems, where structural limitations and energy losses in electrical infrastructure may intensify operational restrictions, leading to the inability to fully utilize generated energy and, consequently, causing instability in energy supply for high-performance computational environments such as data centers.

According to sectoral regulations and guidelines, Rolim (2025) suggests that renewable energy producers have been seeking compensation mechanisms in response to the negative financial impacts caused by operational reductions. These initiatives aim to offset the damages resulting from imposed limitations by identifying effective strategies to mitigate the adverse economic effects associated with this condition. At the core of this debate are several aspects directly related to the necessity of adequately expanding electrical infrastructure. This discussion also encompasses the limitations imposed by regulations governing electricity transmission, as well as the compensation models applied to agents affected by curtailment, that is, the reduction or interruption of energy generation due to operational constraints. Consequently, the interconnection among these different dimensions illustrates the complexity of the debate, which is essential for understanding and addressing the challenges involving the electrical sector. In the context of the rapid expansion of data centers, facilities dedicated to the storage and processing of large volumes of data, these discussions become even more relevant and necessary. In this sense, the energy demand required to sustain the operation of these centers is expected to increase substantially over the coming years, representing a trend that requires careful planning and strategic attention.

Furthermore, the 2026 analysis conducted by Simple Energy indicates that curtailment has ceased to be perceived solely as an operational problem and has increasingly been understood as a structural risk of significant concern for the Brazilian electrical sector. This interpretation becomes even more evident in regions of the country where renewable generation sources are highly concentrated, while the electrical transmission infrastructure responsible for distributing generated energy remains insufficient. The interaction among digital technologies, intelligent energy monitoring systems, and flexible energy consumption approaches appears to be increasingly essential for reducing operational impacts on data processing centers, namely data centers. This integration is progressively viewed as a necessity for addressing the challenges faced by these facilities, particularly in scenarios where maximizing resource utilization and ensuring efficiency are fundamental requirements. Therefore, the efficient use of electricity consumption in these environments depends not only on the expansion of renewable energy sources, but also on the ability to manage, in an agile manner, the variabilities and constraints of the current electrical system. Real-time management is essential to ensure that the fluctuations and operational standards characterizing modern electrical grids are properly handled, thereby enabling more efficient and sustainable utilization of available energy resources.

Thus, there is an imperative need to consolidate intelligent electrical grid management capable of encouraging energy consumption among industrial and residential users, thereby helping absorb excess energy and reduce peak demand. In this regard, smart grid technologies capable of monitoring and controlling electricity flows in real time would be crucial for achieving this objective, in addition to improving overall grid management (Willige, 2025).

Intelligent Technologies for Energy Management in Data Centers: Artificial Intelligence, Automation, and Energy Storage

The increasing digitalization of the economy and society has resulted in progressively higher energy consumption by data centers. This becomes particularly evident in data centers that provide cloud computing services, big data processing, and artificial intelligence applications. This trend demonstrates the growing dependence on digital technologies, which require increasing amounts of energy resources to operate efficiently. Consequently, electricity consumption management has evolved from a purely reactive activity, focused exclusively on monitoring and controlling electricity usage, into a broader set of initiatives aimed at promoting energy efficiency, sustainability, and the resilience of computational infrastructure. This transformation highlights the growing necessity for an integrated approach to energy resource management. According to Brito, Matai, and Santos (2023), modern data centers undoubtedly require sophisticated and advanced energy monitoring systems. Such systems are essential for minimizing energy waste while simultaneously maximizing both thermal performance and processing capacity. This strategy not only optimizes the use of energy resources but also enhances the operational efficiency of data centers.

To illustrate the magnitude of this issue, according to the International Energy Agency (IEA), half of the global growth in electricity demand generated by data centers is expected to be supplied by renewable energy sources, supported by energy storage systems and electrical grids. Consequently, renewable energy generation is projected to increase by more than 450 TWh to meet data center demand by 2035 (IEA, 2025).

Artificial intelligence applied to energy management systems has promoted remarkable advances in electricity demand forecasting and in the real-time adaptation of computationally managed workloads. These developments are essential for optimizing energy utilization and increasing the efficiency of operational processes within this highly strategic sector. Machine learning models are capable of analyzing, in real time, data related to historical energy consumption patterns, climate conditions, and the availability of renewable generation. As a result, these systems can automatically and accurately adjust equipment performance, maximizing efficiency while adapting to changes in operational conditions. According to Ferreira et al. (2024), the application of Artificial Intelligence within data center infrastructures enables operational decisions to be made with a substantially higher degree of precision. Furthermore, it significantly reduces energy overloads and contributes to greater stability in environments affected by the typical fluctuations of renewable energy sources. The relationship between technological innovation and operational efficiency is therefore fundamental to the modernization of data center operations.

Amid the ongoing energy and digital transition, the technology and energy sectors have become more interconnected than ever before. Supplying the energy required for artificial intelligence applications and simultaneously leveraging the benefits of AI for the energy sector will demand deeper dialogue and stronger collaboration between technology and energy industries. In this regard, the IEA will continue to provide robust data and analyses to support decision-making processes and assist both sectors in becoming better prepared as AI adoption continues to expand (IEA, 2025).

Beyond intelligent automation, energy storage systems have assumed a strategic role in reducing the effects of curtailment within electrical grids characterized by high penetration of renewable sources. Through large-capacity battery systems, excess energy generated during periods of low demand can be stored and redistributed during moments of higher computational consumption. According to Feitosa Neto and Gomes et al. (2025), the integration of data centers, battery storage systems, and flexible energy compensation policies contributes to balancing electrical grids and minimizing losses resulting from interruptions in renewable energy generation.

The adoption of smart grids has also improved energy consumption management in highly demanding digital infrastructures. These intelligent networks operate through the integration of sensors, analytical platforms, automation systems, and real-time communication technologies, thereby enabling greater predictability of renewable generation and more efficient distribution of electrical loads. According to Silva (2018), infrastructures aligned with the principles of green information technology must integrate energy efficiency, operational automation, and sustainable planning of computational facilities, particularly in environments that depend on the continuous availability of electrical energy.

The remarkable advancement of generative artificial intelligence, combined with the development of computational clusters designed for training highly complex models, has led to a significant increase in energy consumption by data centers worldwide. This phenomenon highlights the growing demand for energy resources driven by the efficiency and sophistication of emerging technologies that are continuously implemented and enhanced. In their 2023 analysis, Chatterjee and Venugopal emphasize that facilities dedicated to Artificial Intelligence processing require substantially more robust and efficient energy architectures. These architectures must be capable of managing elevated computational density, which implies the ability to perform a large volume of simultaneous operations without compromising thermal stability or operational efficiency. Simultaneously, Stacciarini and Gonçalves (2025) argue that the expansion of digital infrastructure associated with artificial intelligence has intensified debates surrounding fundamental issues such as energy security, the extraction of strategic resources, and the reconfiguration of geopolitical dynamics involving the global technological supply chain.

Subsequently, Table 1 presents and synthesizes the most significant and innovative technologies applied to energy management in data centers operating within renewable energy-based systems. This overview comprehensively addresses the practical application of these technologies and their significant role in mitigating the adverse effects of energy curtailment, defined as the restriction of electricity generation from renewable sources under specific operational conditions.

Table 1. Intelligent Technologies Applied to Energy Management in Data Centers Operating in Renewable Energy-Based Systems

Technology	Operational Application in Data Centers	Contribution to Curtailment Mitigation
Artificial Intelligence	Energy demand forecasting and automated workload management	Dynamic adjustment of energy consumption according to energy availability
Machine Learning	Predictive analysis of energy consumption and operational behavior	Reduction of energy waste and greater operational stability
Battery Storage Systems	Storage of surplus renewable energy	Subsequent utilization of non-consumed energy
Smart Grids	Intelligent monitoring and distribution of energy	Greater balance between electricity supply and demand
Sustainable Cloud Computing	Virtualization and optimization of computational resources	Reduction of energy consumption and improved operational efficiency
Energy Automation	Real-time control of cooling and processing systems	Minimization of energy fluctuations and operational costs
Flexible Load Management	Redistribution of computational tasks	Operational adaptation during periods of energy restriction

Source: Prepared based on Feitosa Neto and Gomes et al. (2025), Brito, Matai and Santos (2023), Ferreira et al. (2024), Silva (2018), Chatterjee and Venugopal (2023), and Welsch (2022).

The implementation of sustainable cloud computing has emerged as another widely discussed strategy in recent literature concerning energy efficiency in data centers. Welsch (2022) emphasizes that major technology companies have expanded investments in renewable energy sources and energetically optimized digital platforms as a means of reducing emissions associated with the continuous operation of computational infrastructures. This movement encompasses initiatives ranging from renewable energy supply agreements to automated load-balancing processes among operational centers located across different regions.

Additionally, the intersection of artificial intelligence, energy automation, battery storage systems, and smart grids is expected to transform the manner in which data centers operate within renewable energy systems. The synergy among these technologies enables greater adaptability to fluctuations in electricity generation, mitigating operational risks associated with curtailment while simultaneously increasing the efficiency of computational energy consumption. Consequently, the sustainability of modern data centers no longer depends exclusively on the expansion of renewable generation capacity, but also on the implementation of intelligent systems capable of balancing, in real time, energy demand, operational stability, and energy efficiency.

Finally, based on the aforementioned considerations, it is important and timely to highlight that Artificial Intelligence is already being employed by energy companies to optimize energy generation, transmission, and consumption, with the objectives of reducing costs, increasing energy supply, and extending the lifespan of digital infrastructure (IEA, 2025).

Sustainability and Energy Efficiency in Renewable Energy-Based Data Centers

The expansion of digital infrastructure worldwide has intensified debates concerning the energy sustainability of data centers, particularly in light of the continuous growth in electricity consumption associated with cloud computing, artificial intelligence, and massive data processing. In this context, the incorporation of renewable energy sources has assumed a central role in corporate policies aimed at reducing emissions and increasing operational efficiency. According to Aslan et al. (2025), the pathway toward climate neutrality in data centers lies in the integration of greenhouse gas inventories, advanced energy management systems, and operational models aligned with international decarbonization goals.

In response to this emerging reality, Green Data Centers have gained prominence by employing energy-efficient technologies to optimize energy consumption, minimize environmental impacts, and reduce operational costs. Green data centers also frequently rely on renewable energy sources, such as solar and wind power. Consequently, these infrastructures prioritize efficiency and environmental sustainability through the adoption of intelligent energy management approaches (Khan; Goodwin, 2026).

Energy efficiency in data centers is generally measured through technical indicators capable of quantifying the operational performance of information technology infrastructure. Parameters such as PUE (*Power Usage Effectiveness*), thermal efficiency, energy reuse, and carbon intensity are currently employed by companies and operators to evaluate electricity consumption. Brito, Matai, and Santos (2023) emphasize that, for these metrics to become increasingly effective, it is essential to integrate technological modernization, automation of operational processes, and intelligent control over energy distribution in high-performance computational environments.

Cooling systems are among the components with the highest energy consumption in data centers, accounting for a substantial portion of the electrical load within these facilities. Thermal management represents one of the principal operational challenges of modern digital infrastructure, particularly in regions characterized by high temperatures and increasing computational density, as highlighted by Huang et al. (2024). The authors state that the use of liquid cooling systems, automated airflow control, and real-time thermal monitoring has contributed significantly to reducing energy waste and improving the operational efficiency of computational systems.

In addition to cooling techniques, waste heat recovery and dynamic computational load management are increasingly being incorporated into energy efficiency initiatives in data centers operating with renewable energy. According to Lin et al. (2023), *green-aware* models enable a more efficient trade-off among computational performance, energy consumption, and thermal stability, thereby facilitating the reuse of heat generated by equipment for industrial, urban, and commercial applications. This strategy enhances the overall efficiency of digital infrastructure while reducing energy losses associated with traditional heat dissipation processes.

From an environmental perspective, the adoption of sustainable information technology practices has become an integral component of strategies related to environmental governance, social responsibility, and the reduction of organizational carbon footprints. Pinto, Campos, and Azevedo (2016) argue that achieving sustainability in data centers requires more than simply replacing conventional energy sources. It also demands appropriate architectural planning, server virtualization, reduction in the number of physical devices, and the implementation of permanent environmental management policies. Within this context, Environmental, Social, and Governance (ESG) principles have begun to directly influence investments in sustainable digital infrastructure and corporate energy transparency systems.

The intersection among artificial intelligence, sustainable energy, and digital infrastructure has become even more significant due to the rapid proliferation of large computational centers dedicated to training advanced AI models. According to Prieto et al. (2025), studies conducted on Google Data Centers between 2024 and 2025 indicate that the increasing computational demands associated with artificial intelligence have made the efficient integration of renewable energy sources, intelligent cooling systems, and automated energy management platforms indispensable. According to the authors, the environmental sustainability of these environments will only be viable if computational performance, energy security, and reductions in operational emissions can be effectively balanced.

Energy resilience has also become a widely discussed concept within contemporary literature concerning sustainable data centers. The recurrent treatment of this subject highlights its importance for understanding the challenges and opportunities involved in implementing sustainability-oriented practices within this sector. According to Silva et al. (2026), maintaining the operational continuity of these infrastructures depends on the implementation of integrated strategies capable of mitigating risks associated with variability in renewable energy generation, fluctuations in energy demand, and constraints within electrical systems. Among the most relevant measures adopted are battery energy storage systems, automated management of critical workloads, integration with smart grids, and predictive monitoring systems focused on ensuring the operational stability of computational environments. These initiatives are therefore fundamental for enhancing both operational efficiency and reliability.

Complementing these considerations, Vasconcelos (2025) emphasizes that the sustainability of contemporary data centers has increasingly been recognized as a strategic element within the digital green economy. This perspective has become even more relevant due to the rapid growth in data storage demands and the continuous expansion of cloud-based services. According to the author, companies operating within the technology sector have significantly increased investments in renewable energy agreements, water reuse initiatives, thermal efficiency improvements, and energy automation systems. These measures are implemented as part of a broader strategy aimed at mitigating the environmental impacts generated by digital infrastructure, which, despite being essential to modern societal development, also creates substantial demand for natural resources and may contribute to environmental degradation. Consequently, the integration of energy efficiency, operational resilience, and environmental sustainability tends to promote and consolidate the development of new management models directed toward data centers operating within renewable and digitally interconnected energy systems. This approach is expected to significantly improve management processes, fostering advancements in efficiency, responsiveness, and sustainability within increasingly modern computational infrastructures.

IV. Final Considerations

Discussions and studies concerning energy curtailment and energy consumption in data centers have become increasingly essential within the contemporary scientific and technological context. This relevance becomes even more pronounced considering the rapid expansion of digital infrastructures and the continuously growing demand for large-scale data processing worldwide. Such a scenario reflects increasing concern regarding energy efficiency and the environmental impacts associated with these operations, since the expansion of storage capacity and data volume requires careful management of available energy resources. In this context, the integration of renewable energy sources into large-scale computational systems emerges as an alternative aligned with the demands for environmental sustainability and operational efficiency. Nevertheless, the variability inherent to renewable energy generation, combined with the structural limitations of electrical systems, continues to create challenges related to maintaining energy stability. Furthermore, these issues directly affect the proper and efficient utilization of energy generated from renewable sources. Given this context, the present study proved highly relevant by investigating several technological approaches aimed at maximizing electricity consumption efficiency in data centers connected to renewable energy systems. The study also considered the operational effects and environmental impacts associated with energy curtailment, defined as the reduction of electricity generation during periods of overproduction.

The results obtained from the conducted research demonstrated that the general objective proposed for the investigation was fully achieved. Consequently, it was possible to evaluate several technological approaches dedicated to minimizing the negative impacts of curtailment on the operation of data centers powered by renewable energy sources. In addition to the general objective, the specific objectives established for the study were also successfully accomplished, since the investigation effectively identified various technical and operational factors associated with the occurrence of the phenomenon known as curtailment. Furthermore, the study provided a detailed analysis of the adoption of several intelligent technologies designed for efficient energy management. The investigation also examined the effects of implementing sustainable strategies on the operational efficiency and resilience of the aforementioned computational infrastructures. Energy management in data centers, according to all aspects discussed throughout this study, requires the implementation of integrated solutions capable of promoting effective synergy among computational system performance, energy supply security, and energy consumption optimization. This perspective is fundamental for the efficient and sustainable operation of these technological ecosystems.

Throughout the development of the theoretical framework, it became evident that the phenomenon known as curtailment, characterized by the reduction of energy generation in renewable energy systems, occurs due to a series of complex and interrelated factors. Among these elements are limitations in electricity transmission systems, fluctuations in electricity generation, and incompatibilities between energy supply and demand during specific operational periods. It was also significantly observed that the consequences of this phenomenon may directly compromise the stability of electricity supply to data centers. Such impacts exert immediate effects on the operational efficiency of these facilities, potentially jeopardizing the adequate and uninterrupted functioning of services that depend on reliable and stable energy availability. Regarding intelligent and advanced technologies for energy management, the use of tools based on artificial intelligence, automated systems, and energy storage solutions proved to be highly relevant. These innovations contribute to more efficient forecasting of energy consumption, optimization of electrical load distribution, and reduction of energy waste, thereby promoting more efficient and sustainable energy management. Furthermore, the analysis of sustainable strategies demonstrated that technological practices not only improve energy consumption efficiency but also enhance the operational resilience of organizations. Consequently, these measures contribute to reducing the environmental impacts commonly associated with the continuous operation of digital infrastructures dependent on advanced technologies.

In conclusion, future studies are recommended to explore the practical application of predictive models based on artificial intelligence technologies for real-time energy management, particularly in computational environments characterized by high uncertainty in renewable energy generation. Such investigations may provide valuable insights into the efficient utilization of energy resources while considering the inherent instability typically associated with renewable generation systems. Likewise, it would be relevant to conduct empirical studies focused on comparative analyses among different energy storage technologies employed in renewable energy-powered data centers. This perspective may offer a more comprehensive understanding of the available alternatives and their effectiveness in promoting sustainability. Another highly relevant aspect to be considered involves the analysis of economic impacts and regulatory frameworks associated with the implementation of hybrid energy systems within large-scale digital infrastructures. Such investigations may clarify not only the financial costs but also the legal and regulatory requirements related to the implementation of these technologies, both in terms of funding mechanisms and regulatory compliance. These perspectives may contribute significantly to the advancement of scientific research related to energy efficiency, operational sustainability, and technological modernization of computational systems integrated with renewable energy sources. Exploring these issues may foster the development of innovative and efficient solutions capable of addressing the growing demands of an increasingly sustainability-oriented world.

References

[1]. Aslan, T., Et Al. (2025). Toward Climate Neutral Data Centers: Greenhouse Gas Inventory, Scenarios, And Strategies. Iscience, 28(1), 111637. Https://Doi.Org/10.1016/J.Isci.2024.111637

[2]. Brito, J. L. R. De, Matai, P. H. L. Dos S., & Santos, M. R. Dos. (2023). Data Centers And Energy Efficiency. Brazilian Journal Of Business, 5(2), 786–795. Https://Doi.Org/10.34140/Bjbv5n2-002

[3]. Caracas Neto, R. A., Gomes, R. L. R., Et Al. (2025). Curtailment, Sustainability, And Governance: The Strategic Role Of Renewable Energy Sources Within The ESG Framework. IOSR Journal Of Business And Management (IOSR-JBM), 27(5), 17–26. E-ISSN 2278-487X, P-ISSN 2319-7668. Https://Doi.Org/10.9790/487X-2705111726

[4]. Chatterjee, A., & Venugopal, V. (2023). Designing Data Centers For AI Clusters. JDCN. Retrieved March 21, 2026, From Https://Www.Juniper.Net/Documentation/Us/En/Software/Nce/Ai-Clusters-Data-Center-Design/Aiclusters-Data-Center-Design.Pdf

[5]. Chiappini, G. (2025). The Surge In Data Centers Strains The Electric Grid And Challenges Energy Planning. Agência Eixos. Retrieved July 10, 2025, From Https://Eixos.Com.Br/Newsletters/Dialogos-Da-Transicao/Disparada-Dos-Data-Centers-Pressiona-Rede-Eletrica-E-Desafia-Planejamento/

[6]. Fagundes, E. M. (2025). Mitigating Energy Curtailment: Opportunities And Challenges For Investing In Renewables And Storage Solutions In Brazil. Tech & Energy Insights. Retrieved July 11, 2025, From Https://Efagundes.Com/Blog/Mitigando-Curtailment-Energia-Brasil/

[7]. Faveret, J. V. (2025). Curtailment In Brazil: Impacts, Regulation, And Challenges For The Energy Sector. Tyr Energia S.A.

[8]. Feitosa Neto, A., Gomes, R. L. R., Et Al. (2025). Smart Curtailment Management In Power Grids With High Renewable Penetration: The Role Of Batteries, Data Centers, And Flexibility Compensation Policies. IOSR Journal Of Business And Management (IOSR-JBM), 27(7), 41–48. E-ISSN 2278-487X, P-ISSN 2319-7668. Https://Doi.Org/10.9790/487X-2707074148

[9]. Ferreira, R. B., Et Al. (2024). The Impact Of Artificial Intelligence (AI) On Data Center Infrastructures. Revista Brasil Pós: Engenharia, Tecnologia E Gestão, 1(1). Https://Doi.Org/10.5281/Zenodo.13831119

[10]. Gil, A. C. (2022). How To Develop Research Projects (7th Ed.). Atlas.

[11]. Huang, J., Et Al. (2024). Data Centers Cooling: A Critical Review Of Techniques, Challenges, And Energy Saving Solutions. Sustainable Computing: Informatics And Systems, 42, 100989. Https://Doi.Org/10.1016/J.Suscom.2024.100989

[12]. IEA – International Energy Agency. (2025). Energy And AI: World Energy Outlook Special Report. Retrieved May 10, 2026, From Https://Iea.Blob.Core.Windows.Net/Assets/De9dea13-B07d-42c5-A398-D1b3ae17d866/Energyandai.Pdf

[13]. Khan, T., & Goodwin, M. (2026). What Is A Green Data Center? IBM. Retrieved May 11, 2026, From Https://Www.Ibm.Com/Think/Topics/Green-Data-Center

[14]. Lin, Y., Et Al. (2023). Green-Aware Data Centers: Workload Management, Thermal Management, And Waste Heat Recovery. Renewable And Sustainable Energy Reviews, 187, 113761. Https://Doi.Org/10.1016/J.Rser.2023.113761

[15]. Pinto, M. M. F., Campos, P. K. De, & Azevedo, V. R. De. (2016). Sustainability Of Data Centers Using Green IT. E-Locução / Revista Científica Da FAEX, 10(20). ISSN 2238-1899.

[16]. Prieto, R. B. P., Et Al. (2025). Energy And Environmental Sustainability In Artificial Intelligence Data Centers: A Case Study Of Google Data Centers (2024–2025). Revista DELOS, 18(75), 1–25. ISSN 1988-5245. Https://Doi.Org/10.55905/Rdelosv18.N75-008

[17]. Rodrigues, R. (2024, August 27). Renewable Energy Generation Cuts Cause Losses Of Nearly R$1 Billion To Companies In The Sector, Says Association. Valor Econômico. Retrieved May 10, 2026, From Https://Valor.Globo.Com/Empresas/Noticia/2024/08/27/Cortes-De-Gerao-De-Energiarenovvel-Causam-Prejuzos-De-Quase-R-1-Bi-A-Empresas-Do-Setor-Diz-Associao.Ghtml

[18]. Rolim, J. (2025). Curtailment Of Renewable Generation: 10 Reasons Justifying Compensation To Producers [Linkedin Post]. Linkedin. Retrieved May 10, 2026, From Https://Www.Linkedin.Com/Posts/Joaquimrolimjcro_Cortes-De-Gera%C3%A7%C3%A3o-Renov%C3%A1vel-Curtailment-Activity-7311478654943830016-Ajh7/

[19]. Silva, D. C. Da, Et Al. (2022). Characteristics Of Qualitative Research: A Study Of Dissertations In A Graduate Education Program. Educação Em Revista, 38, E26895. E-ISSN 2278-067X. Https://Doi.Org/10.1590/0102-469826895

[20]. Silva, F. B. Da. (2018). Criteria For Implementing Data Center Infrastructure Aligned With Green IT Principles: A Survey With Specialists (Master's Thesis). Instituto De Pesquisas Tecnológicas Do Estado De São Paulo, São Paulo, Brazil.

[21]. Silva, F. J. R. Da, Moura, A. P. De, & Barroso, G. C. (2022). Novel Proposal For The Analysis Of Technical Losses In Medium-Voltage Feeders From Single-Phase And Three-Phase Load Flow Data. Electric Power Systems Research, 211. Https://Doi.Org/10.1016/J.Epsr.2022.108239

[22]. Silva, L. A., Vasconcelos, E. S., Paiva, L. F. R. De, Goulart, C. S., Joaquim, W. M., Elias, M. E. P., & Collaço, M. H. Do V. R. (2026). Energy Consumption In Data Centers And Efficiency Strategies: A Literature Review. Revista De Engenharia, TI E Inovação, 3(1), 1–17. Https://Doi.Org/10.31496/Retii.V3i1.2038

[23]. Simple Energy. (2026). Curtailment: Structural Risk In The Brazilian Electrical Sector. Retrieved May 10, 2026, From Https://Simpleenergy.Com.Br/Curtailment-O-Novo-Risco-Estrutural-Do-Setor-Eletrico-No-Brasil/

[24]. Stacciarini, J. H. S., & Gonçalves, R. J. De A. F. (2025). Data Centers, Critical Minerals, Energy, And Geopolitics: The Foundations Of Artificial Intelligence. Sociedade & Natureza, 37, E77215. ISSN 1982-4513. Https://Doi.Org/10.14393/SN-V37-2025-77215

[25]. Vasconcelos, Y. (2025, March). Strategies To Make Data Centers More Sustainable. Revista Pesquisa FAPESP, 349. Retrieved May 10, 2026, From Https://Revistapesquisa.Fapesp.Br/As-Estrategias-Para-Tornar-Os-Data-Centers-Mais-Sustentaveis/

[26]. Welsch, C. (2022, November). As The World Goes Digital, Data Centers That Make The Cloud Work Look To Renewable Energy Sources. Microsoft. Retrieved March 21, 2026, From Https://News.Microsoft.Com/Source/Emea/Features/As-The-World-Goes-Digital-Datacenters-That-Make-The-Cloud-Work-Look-To-Renewable-Energy-Sources/

[27]. Willige, A. (2025, December 10). Energy Explained: What Is Curtailment And How Do We Address It? Mitsubishi Heavy Industries Group. Retrieved May 10, 2026, From Https://Spectra.Mhi.Com/Energy-Transition/Energy-Explained-What-Is-Curtailment-And-How-Do-We-Address-It