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Data Centres: An In-Depth Comparative Analysis of Global Trends in Sustainable Infrastructure Investment

Michael Okereke [1*], Lawani Raymond Isi [2], Bisi Ogunwale [3], Sibongile Gobile [4], Naomi Oboyi [5], Oludayo Sofoluwe [6]
[1] Independent Researcher Dubai, United Arab Emirates
[2] Schlumberger Oilfield Services Lagos, Nigeria
[3] Independent Researcher, Ontario, Canada
[4] Independent Researcher, South Africa
[5] Independent Researcher, Abuja, Nigeria
[6] IFP School, France and BI Norwegian Business School, Total Energies Headquarters France, France

* Corresponding Author: **Michael Okereke**

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Abstract
The rapid expansion of data centres has raised critical concerns regarding their environmental impact, prompting the need for sustainable infrastructure investments. This study provides a comprehensive comparative analysis of global trends in sustainable data centre infrastructure, with a focus on identifying key components, challenges, regulatory frameworks, and emerging trends. The study employed an extensive literature review, drawing on reputable academic sources, industry reports and case studies to ensure a robust and evidence-based analysis. The findings reveal that the data centre industry is undergoing a transformative shift towards sustainability, driven by a combination of regulatory pressure, stakeholder expectations, and technological advancements. Energy efficiency, renewable energy adoption, water conservation, carbon management and circular economy practices were identified as fundamental components of sustainable data centres. However, the study also highlights several challenges, including high energy consumption, water usage, carbon emissions, regulatory compliance and financial barriers. A detailed exploration of global regulatory frameworks further emphasizes the role of policy in promoting sustainability. Additionally, the study examines practical case studies that demonstrate successful sustainable practices in data centres, providing valuable insights for industry stakeholders. The study concludes that achieving sustainable data centre infrastructure requires a holistic approach that combines technological innovation, regulatory compliance, stakeholder engagement and continuous improvement. It recommends that data centre operators invest in energy-efficient technologies, explore renewable energy options, adopt circular economy practices, and enhance transparency through sustainability reporting. Policymakers are encouraged to strengthen regulatory frameworks to promote sustainability, while stakeholders should support sustainable practices through informed decision-making.

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1. Introduction

Data centres have emerged as the backbone of the modern digital economy, providing essential infrastructure for data storage, processing, and transmission. Their importance has grown exponentially with the rapid proliferation of cloud computing, artificial intelligence (AI) and the Internet of Things (IoT), which demand high computational power and data processing capabilities (Adewoyin, Adediwin & Audu, 2025) [3].

Gnibga, Blavette and Orgerie (2023) [29] emphasize that the substantial energy consumption and environmental impact of data centres have become a growing concern, especially as global demand for digital services continues to rise. This increasing reliance on energy-intensive infrastructure highlights the urgent need for sustainable solutions to mitigate their ecological footprint.

As the global data centre industry experiences rapid growth, sustainability has emerged as a vital concern. Kamiya (2022) [38] highlights that data centres consume a significant portion of global electricity, underscoring the environmental urgency of adopting sustainable practices to mitigate their ecological impact and enhance energy efficiency. The challenge lies in balancing the need for efficient data storage and processing with the imperative to reduce carbon emissions and environmental degradation.

Recent studies highlight that the integration of artificial intelligence (AI) in data centre operations offers promising avenues for improving energy efficiency (Augoye *et al*., 2025) [12]. AI-powered solutions have the potential to significantly enhance sustainability in data centres by optimizing energy consumption, predicting system failures and improving cooling efficiency. According to Bangalore *et al*. (2023) [13], these advanced technologies enable data centres to operate more efficiently, reducing energy waste and minimizing environmental impact while maintaining high performance. Simultaneously, there is an increasing focus on integrating renewable energy sources, such as solar and wind, to power data centres, significantly reducing their carbon footprint. Rathore *et al*. (2021) [67] highlight that this transition to renewable energy is a critical step toward achieving sustainability in data centre operations, promoting environmentally responsible energy consumption.

The aim of this study is to provide an in-depth analysis of global trends in sustainable infrastructure investment within data centres, examining the technological advancements, investment strategies and policy frameworks that support sustainability in this sector. The objectives include exploring the evolution of data centres, analyzing global sustainability trends, and assessing the impact of technological innovations. This review will offer valuable insights for stakeholders in the data centre industry, including policymakers, investors and technology developers.

2. Evolution of data centres

The evolution of data centres represents a transformative journey shaped by technological advancements, increasing demand for digital services and the growing emphasis on sustainability. Historically, data centres were primarily designed to serve the computational needs of businesses, offering basic storage and processing capabilities. However, with the advent of cloud computing, artificial intelligence (AI) and the Internet of Things (IoT), data centres have evolved into complex, high-performance facilities supporting diverse digital applications (Fredson *et al*., 2021) [21].

Early data centres were characterized by centralized, on-premises infrastructure, often with significant energy consumption and inefficient cooling mechanisms (Hintemann, 2020) [31]. Early data centres were predominantly managed manually, lacking advanced automation and real-time monitoring systems, which led to elevated operational expenses and significant carbon emissions. Yang *et al*. (2018) [63] emphasize that the absence of intelligent automation in these facilities contributed to inefficient resource utilization and higher environmental impacts. The pursuit of efficiency and scalability in data centres has driven the adoption of virtualization technologies, which allow multiple virtual machines to operate on a single physical server. According to Chaturvedi *et al*. (2018) [66], this approach optimizes resource utilization by maximizing server capacity, reducing the need for additional hardware, and minimizing energy consumption. Virtualization has become a fundamental strategy for enhancing the sustainability and performance of data centre operations.

The rapid proliferation of cloud computing marked a pivotal shift in the data centre landscape, enabling businesses to leverage scalable, on-demand computing resources without the need for extensive physical infrastructure. This shift not only improved operational efficiency but also facilitated the emergence of hyperscale data centres; massive facilities operated by technology giants like Amazon Web Services (AWS), Microsoft Azure, and Google Cloud (Data Center World, 2025) [19]. Hyperscale data centres are engineered for scalability, featuring sophisticated systems for cooling, energy management, and security. According to Islam *et al*. (2019) [34], these facilities leverage advanced predictive modeling techniques to optimize capacity management, ensuring efficient resource utilization while maintaining high performance and robust security measures.

Sustainability has become a pivotal focus in the development of data centres, driven by escalating concerns about energy consumption and carbon emissions. Kamiya (2022) [38] emphasizes that data centres represent a substantial share of global electricity usage, underscoring the urgent need for enhanced energy efficiency and sustainable practices within the industry. Cutting-edge solutions, including liquid cooling systems, renewable energy integration, and AI-driven energy management, have been extensively implemented to improve sustainability in data centres. According to Ali, Motuzienė and Džiugaitė-Tumėnienė (2024) [10], AI-powered energy management systems optimize energy consumption, enhance operational efficiency and significantly reduce environmental impact, making them essential for sustainable data centre operations

In recent years, the data centre industry has experienced a significant shift towards edge data centres—compact, decentralized facilities positioned closer to end-users. These facilities are designed to minimize latency and enhance service quality, making them crucial for applications like autonomous vehicles, smart cities, and industrial automation (Shehabi *et al*., 2024) [55]. Edge data centres are increasingly viewed as a sustainable alternative, primarily because they minimize the need for long-distance data transmission, which is often energy-intensive. Islam *et al*. (2019) [34] emphasize that by processing data closer to end-users, edge data centres reduce energy consumption associated with data transfer, enhancing overall efficiency and sustainability.

The evolution of data centres has been significantly influenced by the integration of artificial intelligence (AI) and machine learning (ML) technologies, which enhance operational efficiency. Yang *et al*. (2018) [63] highlight that AI-driven systems can predict energy demand, optimize cooling processes, and identify system anomalies in real-time, resulting in lower energy consumption and reduced operational costs. Additionally, AI-driven predictive maintenance can minimize downtime and extend the lifespan of critical infrastructure (Fredson *et al*., 2021) [22].

As data centres continue to evolve, the focus on sustainability is expected to intensify, with stakeholders exploring innovative solutions such as waste heat recovery, green energy sourcing, and carbon offset initiatives. The journey of data centres, from traditional on-premises facilities to modern, sustainable hyperscale and edge data centres, reflects the broader shift towards a more sustainable and efficient digital infrastructure.

2.1 Classification of data centres

Data centres are pivotal in the digital infrastructure landscape, serving as the backbone for data storage, processing, and dissemination. Their classification is multifaceted, encompassing factors such as ownership, operational scale, service delivery models and architectural design. Understanding these classifications is essential for stakeholders to make informed decisions regarding deployment, investment and management strategies (Fredson *et al*., 2021) [21].

Enterprise Data Centres are privately owned facilities operated by organizations to support their internal IT operations and services. These centres offer high levels of control, customization and security, making them suitable for industries with stringent compliance requirements, such as finance and healthcare (Fredson *et al*., 2021) [22]. However, they often involve significant capital expenditure and require dedicated IT staff for maintenance and management.

Colocation data centres offer a shared infrastructure model where multiple organizations can lease space for their servers and hardware, providing significant cost savings. By sharing essential resources such as power, cooling, and security, clients maintain control over their equipment without the financial burden of building and managing their own facilities (Ahmed, Bollen & Alvarez, 2021) [7]. Colocation is especially advantageous for businesses seeking scalable solutions.

Cloud data centres, managed by cloud service providers, deliver virtualized computing resources over the internet, offering businesses unparalleled scalability, flexibility and cost-efficiency. According to Ahmed *et al*. (2021) [8], these facilities enable organizations to quickly deploy and manage applications without the need for extensive physical infrastructure. Cloud models support various service models, including Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS).

Hyperscale Data Centres are massive facilities designed to support scalable applications and are often operated by large tech companies like Amazon, Google and Microsoft. These centres are characterized by their ability to scale computing resources quickly and efficiently, supporting high-volume data processing and storage needs (Dgtl Infra, 2023) [20]. Hyperscale centres are integral to the functioning of cloud services and large-scale data analytics.

Edge data centres are compact, decentralized facilities strategically positioned closer to end-users, designed to minimize latency and enhance the performance of applications requiring real-time data processing. According to Islam *et al*. (2019) [34], these centres process data near its source, supporting latency-sensitive applications such as autonomous vehicles, IoT devices, and real-time analytics. This localized approach improves service efficiency and responsiveness.

Modular data centres are flexible, scalable units designed for rapid deployment, capable of meeting immediate computing demands. These prefabricated facilities can be quickly added or removed based on changing requirements, providing organizations with adaptability and speed (Yllmark, 2024) [64]. Modular data centres are especially valuable in disaster recovery situations or regions without established infrastructure.

Green data centres prioritize sustainability by adopting energy-efficient technologies and utilizing renewable energy sources to minimize their environmental impact. According to Ahmed, Bollen and Alvarez (2021) [9], these facilities implement advanced cooling systems, energy-efficient hardware, and waste heat recovery techniques to significantly reduce their carbon footprint. Such initiatives align with global sustainability goals, promoting environmentally responsible digital infrastructure.

Additionally, data centres are classified based on their Tier Levels, which indicate the reliability and redundancy of their infrastructure. The Uptime Institute defines four tiers:

Tier I: Basic capacity with limited redundancy, offering 99.671% uptime.

Tier II: Redundant capacity components, providing 99.741% uptime.

Tier III: Concurrently maintainable infrastructure with multiple power and cooling paths, ensuring 99.982% uptime.

Tier IV: Fault-tolerant infrastructure with multiple independent systems, delivering 99.995% uptime

These classifications assist organizations in selecting data centres that align with their operational requirements, risk tolerance, and budget constraints. As the digital landscape evolves, the diversification and specialization of data centre types continue to grow, catering to the increasing demand for efficient, scalable and sustainable computing solutions.

2.2 Key components of sustainable data centre infrastructure

Sustainable data centre infrastructure is a critical focus in the contemporary digital ecosystem, driven by the need to minimize environmental impact while ensuring high performance and reliability. Data centres, as energy-intensive facilities, are increasingly adopting sustainable practices to achieve energy efficiency, carbon reduction and resource optimization (Fredson *et al*., 2022) [23].

Energy efficiency is a fundamental aspect of sustainable data centre infrastructure, focusing on the adoption of technologies that minimize energy consumption while maintaining high performance. According to Ahmed *et al*. (2021) [7], this includes the deployment of energy-efficient servers capable of delivering substantial computational power with reduced energy usage. Advanced cooling solutions, such as liquid cooling and free-air cooling, provide efficient thermal management without excessive energy consumption. Additionally, power management technologies like dynamic voltage scaling and automated energy optimization further enhance energy efficiency, ensuring sustainable and cost-effective data centre operations.

The adoption of renewable energy sources is a pivotal element of sustainable data centre infrastructure. According to Lykou, Mentzelioti and Gritzalis (2018) [41], data centres are increasingly powered by solar, wind and hydroelectric energy, significantly reducing their dependence on fossil fuels. Many facilities secure a consistent supply of clean energy through power purchase agreements (PPAs) with renewable energy providers. Additionally, some data centres enhance their sustainability by integrating on-site renewable energy generation systems, such as solar panels and wind turbines.

Carbon management is a key focus of sustainable data centres, with strategies aimed at reducing and offsetting carbon emissions. According to Sarkar *et al*. (2024) [52], advanced carbon footprint monitoring and management systems are being deployed to track and reduce emissions in real-time. Data centres are also exploring carbon offset initiatives, such as reforestation projects and carbon capture technologies, to neutralize their carbon impact (Sarkar *et al*., 2024) [53].

Energy-efficient cooling has become a critical focus for sustainable data centres, with traditional air-based cooling systems being gradually replaced by more advanced alternatives. Pambudi *et al*. (2022) [48] highlight that liquid cooling, which utilizes a conductive liquid to directly dissipate heat from server components, offers superior energy efficiency. Moreover, emerging cooling technologies, such as immersion cooling and geothermal cooling, are being explored to further optimize energy use and enhance sustainability in data centre operations.

Water conservation is a critical aspect of sustainable data centre design, focusing on minimizing water usage while maintaining optimal cooling performance. Lykou, Mentzelioti and Gritzalis (2018) [41] emphasize that advanced cooling technologies, such as closed-loop water cooling systems and air-to-water heat exchangers, significantly reduce water consumption. Furthermore, many data centres are adopting rainwater harvesting and greywater recycling techniques, enhancing overall water efficiency.

Digital optimization through artificial intelligence (AI) and machine learning (ML) is becoming a vital aspect of sustainable data centres. AI-driven energy management systems can monitor and optimize energy consumption in real-time, adjusting power usage based on workload demand (Sarkar *et al*., 2024) [52]. Digital twins, which are virtual replicas of data centre infrastructure, are also being used to simulate and optimize energy efficiency, predict equipment failures, and reduce maintenance costs (Sarkar *et al*., 2024) [53].

Furthermore, sustainable data centres prioritize resource efficiency through circular economy practices. This includes recycling electronic waste, reusing hardware components, and adopting modular designs that facilitate easy upgrades and component replacement (Fredson *et al*., 2022) [24]. By extending the lifespan of data centre equipment, organizations can minimize electronic waste and reduce their environmental impact.

Sustainable procurement is an essential aspect of data centre operations, emphasizing the acquisition of equipment and services from environmentally responsible suppliers. Ahmed *et al*. (2021) [8] highlight that organizations are increasingly implementing green procurement policies, which require suppliers to adhere to sustainability standards, including energy efficiency certifications and eco-friendly packaging, promoting sustainable supply chains.

2.3 Global trends in sustainable data centre investments

The global landscape of data centre investments has experienced significant transformation, driven by the increasing demand for digital services, rising energy consumption and growing emphasis on sustainability. As organizations seek to balance technological innovation with environmental responsibility, sustainable data centre investments have emerged as a strategic priority (Fredson *et al*., 2022) [23].

A significant trend in sustainable data centre investments is the widespread adoption of renewable energy sources. Bangalore *et al*. (2023) [13] highlight that major technology companies, including Amazon, Google and Microsoft, are increasingly relying on solar, wind, and hydroelectric power to support their data centre operations. These investments not only reduce carbon emissions but also enhance financial sustainability by lowering long-term energy costs.

Energy efficiency has become a central focus in sustainable data centre investments. Organizations are deploying advanced energy management technologies, such as artificial intelligence (AI)-driven energy optimization, to minimize energy consumption while maintaining high performance (JLL, 2025) [35]. In addition, data centres are increasingly adopting energy-efficient hardware, dynamic voltage scaling, and advanced cooling technologies to minimize energy consumption. Chaturvedi *et al*. (2018) [66] emphasize that these measures enhance energy efficiency by optimizing power usage, maintaining optimal operating temperatures, and reducing the overall energy demand of data centre operations. These technologies play a critical role in promoting sustainable and cost-effective data centre management

The adoption of carbon reduction strategies has become a pivotal trend in the data centre industry, with organizations actively pursuing carbon neutrality. Suleyman (2025) [59] highlights that companies are implementing carbon offset initiatives, such as reforestation projects and carbon capture technologies, to mitigate their carbon footprints. Notably, Google aims to power its data centres with carbon-free energy by 2030, while Microsoft has pledged to achieve carbon negativity by the same year, underscoring the sector's commitment to sustainability.

Geographical diversification in data centre investments is gaining momentum, with emerging markets like India, Southeast Asia, and South America becoming key destinations. Abiodun (2025) [2] emphasizes that these regions are attracting substantial investments due to the availability of cost-effective land, supportive regulatory frameworks, and rising demand for digital services. These favorable conditions position emerging markets as ideal locations for sustainable data centre expansion. Notably, India has emerged as a promising regional hub for data centres, driven by government incentives and a rapidly growing digital economy. Sharma *et al*. (2021) [54] highlight that supportive policies and increasing digital adoption are accelerating data centre investments across the country.

The data centre industry is witnessing significant growth in both hyperscale and edge data centres. According to Inshakova and Kachalov (2022) [33], hyperscale data centres, managed by major technology providers like Amazon Web Services (AWS), Microsoft Azure, and Google Cloud, continue to dominate the global market, offering scalable and high-performance computing solutions. In contrast, edge data centres are smaller, decentralized facilities designed to provide low-latency services by processing data closer to end-users. These edge facilities are essential for latency-sensitive applications, including autonomous vehicles, Internet of Things (IoT) devices and smart city initiatives.

Sustainable procurement and supply chain management have also become integral to data centre investments. Companies are adopting green procurement policies that prioritize energy-efficient hardware, environmentally friendly materials and suppliers with strong sustainability credentials (Fredson *et al*., 2022) [24]. This approach not only reduces the environmental impact of data centres but also enhances their resilience to supply chain disruptions.

Furthermore, digital innovation is transforming sustainable data centre investments. Artificial intelligence (AI), machine learning (ML) and digital twins are being used to optimize energy consumption, monitor equipment performance, and enhance predictive maintenance (JLL, 2025) [35]. These technologies enable data centres to operate with greater efficiency, reducing operational costs and minimizing their environmental footprint.

The growing emphasis on sustainability has led to the emergence of green data centres, which are specifically designed to minimize energy consumption, water usage and carbon emissions. Chaturvedi *et al*. (2018) [66] highlight that these environmentally friendly facilities utilize renewable energy sources, energy-efficient cooling technologies and sustainable construction materials to achieve high levels of sustainability. As sustainability becomes a key competitive advantage, many companies are pursuing green building certifications, such as LEED (Leadership in Energy and Environmental Design), to demonstrate their commitment to environmentally responsible operations.

2.4 Comparative analysis of sustainability practices

The pursuit of sustainability within the data centre industry has led to the emergence of diverse sustainability practices, reflecting the varying priorities, regulatory environments and technological capabilities of different organizations. A comparative analysis of these practices reveals significant differences in the approaches adopted by data centres to minimize their environmental impact while maintaining high-performance standards (Fredson *et al*., 2023) [25].

A key sustainability practice in data centres is the adoption of energy-efficient technologies. Thapa (2022) [60] highlights that advanced facilities are leveraging AI-driven energy management systems, including dynamic voltage scaling, real-time energy monitoring, and automated energy optimization. These technologies significantly reduce energy consumption while maintaining high performance. In contrast, smaller data centres often depend on traditional energy-saving methods, such as enhancing cooling efficiency and deploying energy-efficient hardware.

Another critical aspect of sustainability is the integration of renewable energy. Large technology companies, including Amazon, Google, and Microsoft, have made significant investments in solar, wind and hydroelectric power to power their data centres (Chidolue *et al*., 2024) [17]. These companies often enter into power purchase agreements (PPAs) with renewable energy providers, ensuring a consistent supply of clean energy. In contrast, smaller data centres may adopt a hybrid approach, using a mix of renewable and non-renewable energy sources to balance sustainability and cost.

Carbon management is another key area where sustainability practices differ. According to Sarkar *et al*. (2024) [52], advanced carbon footprint monitoring and management systems are being deployed in large data centres, enabling real-time tracking and optimization of carbon emissions. These facilities also invest in carbon offset initiatives, such as reforestation projects and carbon capture technologies, to achieve carbon neutrality. Smaller data centres may rely on simpler carbon reduction strategies, such as energy-efficient cooling and waste heat recovery.

Water conservation is also a significant focus in sustainable data centres. Advanced facilities use closed-loop water cooling systems, rainwater harvesting, and greywater recycling to minimize water consumption (Andrews *et al*., 2021) [11]. In contrast, conventional data centres may rely on traditional air-based cooling methods, which consume significant water for humidification. The adoption of water-efficient cooling technologies is often influenced by geographical factors, with data centres in water-scarce regions placing a greater emphasis on water conservation.

The concept of a circular economy is gaining traction in the data centre industry, with organizations exploring ways to reduce electronic waste and maximize resource efficiency. According to Andrews *et al*. (2021) [11], some data centres have adopted modular designs that facilitate easy upgrades, component replacement and recycling. Others implement e-waste recycling programs, ensuring that outdated hardware is disposed of responsibly. These practices not only enhance sustainability but also reduce operational costs by extending the lifespan of data centre equipment.

Sustainable procurement practices vary significantly among data centres, reflecting differences in their commitment to sustainability. Lăzăroiu *et al*. (2020) [40] emphasize that leading organizations have adopted green procurement policies, mandating that suppliers comply with specific sustainability standards, such as energy efficiency certifications and eco-friendly packaging. In contrast, smaller data centres often prioritize cost over sustainability, implementing less rigorous procurement practices.

Digital optimization is also transforming sustainability practices in data centres. Large data centres leverage artificial intelligence (AI), machine learning (ML), and digital twins to monitor energy consumption, optimize cooling efficiency, and predict equipment failures (Sarkar *et al*., 2024) [53]. These technologies enable data centres to operate with greater efficiency, reducing energy costs and minimizing their environmental impact. In contrast, smaller data centres may rely on manual monitoring and basic energy management systems.

Sustainability reporting and transparency have become critical aspects of the data centre industry. Goerzen *et al*. (2025) [30] emphasize that leading organizations enhance transparency by publishing comprehensive sustainability reports, detailing their environmental performance, energy consumption, carbon emissions, and sustainability initiatives. These reports enable stakeholders to assess sustainability outcomes, fostering accountability. However, smaller data centres often lack the resources to produce detailed reports, limiting their transparency.

2.5 Environmental impacts of data centres

Data centres have become indispensable in the modern digital landscape, supporting a wide range of applications, from cloud computing to artificial intelligence (Fredson *et al*., 2024) [26]. However, their rapid proliferation has raised significant environmental concerns due to their substantial energy consumption, carbon emissions, water usage and electronic waste.

Energy consumption stands as a major environmental concern for data centres, driven by the substantial power requirements of servers, cooling systems, and networking infrastructure. As digital services continue to expand, data centres are consuming an increasing share of global electricity (Kamiya, 2022) [38]. Many of these facilities rely on fossil fuels, resulting in significant carbon emissions. The reliance on energy-intensive operations highlights the urgent need for sustainable energy solutions to mitigate their environmental impact and enhance overall energy efficiency.

Gnibga, Blavette and Orgerie (2023) [29] highlight that the growing energy demands of data centres are placing increasing pressure on power grids, especially in regions with limited access to renewable energy sources. As the demand for cloud services and AI-driven applications continues to surge, data centres are expected to consume even more energy, further intensifying their environmental impact. This reliance on traditional power grids poses a significant sustainability challenge.

Carbon emissions remain a significant challenge for the data centre industry. Thapa (2022) [60] highlights that despite ongoing efforts to enhance energy efficiency, many data centres continue to depend on non-renewable energy sources, leading to substantial greenhouse gas emissions. While major technology companies have committed to achieving carbon neutrality, smaller data centres often lack the financial resources to transition to renewable energy solutions.

Water consumption represents a significant environmental concern for data centres, particularly those relying on water-based cooling systems. Karimi *et al*. (2022) [39] emphasize that these cooling methods can result in substantial water usage, especially in high-performance computing environments, such as those supporting AI training. In regions with limited water resources, the intensive water consumption of data centres can lead to conflicts over water availability, highlighting the need for sustainable water management solutions.

The environmental impact of electronic waste is also a growing concern. Data centres generate significant quantities of electronic waste as servers, networking equipment, and storage devices become obsolete. According to Siddik *et al*. (2021), the environmental footprint of data centres in the United States is amplified by the disposal of electronic waste, much of which ends up in landfills or is improperly recycled. The adoption of circular economy practices, such as hardware recycling and reuse, can help mitigate this impact.

Data centres can also exacerbate urban heat islands and contribute to localized environmental degradation. Buyya, Ilager and Arroba (2024) emphasize that the waste heat generated by data centres can elevate local temperatures, impacting surrounding communities and ecosystems. While some data centres are experimenting with waste heat recovery technologies—repurposing excess heat for district heating or agricultural applications—these solutions are not yet widely implemented across the industry.

The indirect environmental impacts of data centres are substantial, extending beyond direct energy consumption. Lam *et al*. (2021) emphasize that the growing demand for data storage and processing—particularly for energy-intensive applications like artificial intelligence (AI)—has led to a surge in carbon emissions. The rapid expansion of AI-driven services necessitates the construction of new data centres, further increasing the industry's environmental footprint. Additionally, the rise of edge computing, which involves deploying smaller data centres closer to end-users to reduce latency, has also contributed to the sector's ecological impact.

Addressing the environmental impacts of data centres requires a multifaceted approach. Energy efficiency improvements, such as the adoption of energy-efficient servers, advanced cooling systems, and AI-driven energy management, are critical for reducing energy consumption (Fredson *et al*., 2024) [26]. The integration of renewable energy sources, such as solar and wind, can significantly reduce carbon emissions, while carbon offset initiatives can help neutralize remaining emissions.

Water conservation is a critical aspect of sustainable data centre management, particularly in regions facing water scarcity. Karimi *et al*. (2022) [39] highlight that implementing closed-loop water cooling systems and rainwater harvesting can significantly reduce the water footprint of data centres. Additionally, adopting sustainable waste management practices, such as electronic waste recycling and circular economy principles, minimizes the environmental impact of data centre hardware.

Transparency and sustainability reporting are fundamental for promoting accountability in data centre operations. According to Thapa (2022) [60], leading data centre operators enhance transparency by publishing sustainability reports that detail their energy consumption, carbon emissions, water usage and sustainability initiatives. Such disclosures allow stakeholders to evaluate the environmental performance of data centres, fostering continuous improvement and encouraging the adoption of sustainable practices.

2.6 Challenges in achieving sustainable infrastructure

Achieving sustainable infrastructure in the data centre industry is a complex endeavor characterized by numerous challenges, ranging from technological limitations and financial constraints to regulatory hurdles and stakeholder resistance. As data centres continue to expand to meet the growing demand for digital services, the need for sustainable practices has become more critical than ever (Ahmadu *et al*., 2025) [4].

A major challenge in achieving sustainable data centre infrastructure is the substantial energy consumption required to power servers, cooling systems and networking equipment. Veselova (2023) [61] highlights that data centres are inherently energy-intensive, leading to significant carbon emissions. The rapid expansion of artificial intelligence (AI) applications has exacerbated this challenge, as AI-driven workloads demand even higher computational power. Consequently, data centres are now faced with the complex task of balancing the need for high-performance computing with the critical goal of minimizing energy consumption.

The transition to renewable energy poses a significant challenge for data centres, primarily due to the availability and reliability of renewable energy sources. Kabeyi and Olanrewaju (2022) [37] emphasize that while many data centre operators have committed to adopting renewable energy, the lack of robust renewable energy infrastructure in certain regions forces them to rely on conventional energy sources, which are typically associated with higher carbon emissions.

Moreover, the inherent variability of renewable energy sources, such as solar and wind, can lead to stability issues, complicating the management of data centre operations and maintaining consistent energy supply.

Water consumption remains a significant sustainability challenge for data centres, primarily due to the extensive use of water-based cooling systems required to maintain optimal operating temperatures. Rathore *et al*. (2021) [67] emphasize that in water-scarce regions, the high water demand of data centres can lead to resource conflicts and environmental degradation. While advanced cooling technologies, such as liquid cooling and geothermal cooling, offer more water-efficient alternatives, their adoption is often hindered by high implementation costs and technical complexity, limiting their widespread deployment.

The adoption of sustainable procurement practices is also a significant challenge. Data centre operators must ensure that their hardware, software, and other resources are sourced from environmentally responsible suppliers (GBC Engineers, 2025) [27]. However, this is often complicated by the global nature of data centre supply chains, which may involve suppliers from regions with varying environmental regulations and sustainability standards. Verifying the sustainability credentials of suppliers can be a time-consuming and resource-intensive process.

Financial constraints remain a significant barrier to achieving sustainable infrastructure in data centres. Vujanović *et al*. (2021) highlight that while energy-efficient technologies, renewable energy integration, and sustainable cooling systems can lower operational costs over time, their implementation often requires substantial initial investments. Smaller data centres, in particular, may lack the financial capacity to adopt these sustainable solutions, relying instead on conventional, energy-intensive technologies, which perpetuates their environmental impact.

Regulatory challenges further complicate the transition to sustainable data centre infrastructure. Environmental regulations vary significantly across regions, creating compliance challenges for data centre operators with global operations (Ahmadu *et al*., 2025) [5]. In some regions, weak regulatory frameworks may fail to incentivize sustainability, while in others, stringent environmental regulations can impose significant compliance costs. Additionally, the lack of standardized sustainability metrics and reporting requirements makes it difficult for data centre operators to demonstrate their sustainability performance.

Stakeholder resistance is a significant challenge in the pursuit of sustainable data centre infrastructure. Johnson, Sutton and Theis (2020) emphasize that data centre operators must navigate the diverse priorities of various stakeholders, including investors, customers, employees and regulators. While some stakeholders prioritize sustainability, others may focus on cost efficiency, performance, or security. Reaching a consensus can be challenging, especially when sustainability initiatives involve substantial financial investments or require significant changes to existing operations.

Technological limitations present a significant barrier to achieving sustainable data centre infrastructure. Rathore *et al*. (2021) [67] highlight that while advanced technologies such as artificial intelligence (AI), machine learning (ML), and digital twins can significantly enhance energy efficiency and sustainability, their adoption requires substantial technical expertise and considerable financial investment. Smaller data centres often lack the resources and technical capabilities needed to implement these advanced solutions, limiting their ability to achieve sustainable operations and optimize energy efficiency.

A significant challenge in the data centre industry is the lack of transparency and accountability in sustainability reporting. Veselova (2023) [61] emphasizes that while many data centre operators publish sustainability reports, these reports often differ in scope, depth, and quality. The absence of standardized reporting frameworks makes it challenging for stakeholders to accurately assess the sustainability performance of data centres. This lack of consistency can undermine stakeholder confidence and hinder the widespread adoption of sustainable practices within the industry.

Finally, the rapid pace of technological change presents a challenge for sustainable infrastructure in data centres. As new technologies and sustainability practices emerge, data centre operators must continuously adapt their infrastructure and strategies to remain competitive (GBC Engineers, 2025) [27]. This requires ongoing investment in research and development, employee training and infrastructure upgrades.

2.7 Policy and regulatory frameworks

Effective policy and regulatory frameworks are essential for promoting sustainability in the data centre industry, ensuring that data centres operate in an environmentally responsible manner while maintaining high performance and security standards (Shittu *et al*., 2024) [4]. These frameworks provide guidelines for energy efficiency, carbon reduction, water conservation, data security, and transparency, enabling data centres to achieve sustainability objectives while complying with legal requirements.

The European Commission's Corporate Sustainability Reporting Directive (CSRD) stands as a pivotal regulatory framework impacting data centres, requiring large companies to transparently disclose their sustainability practices and performance. According to Odobaša and Marošević (2023) [47], the CSRD mandates that data centre operators report on their environmental impact, energy consumption, carbon emissions and sustainability initiatives. By making sustainability reporting compulsory, the CSRD enhances accountability, promotes transparency, and encourages data centres to adopt sustainable practices, aligning their operations with broader sustainability goals.

In the United States, the Environmental, Social and Governance (ESG) and Climate Accountability Reporting framework provides a structured approach for data centres to transparently disclose their sustainability performance. Murino *et al*. (2023) [44] emphasize that this framework requires data centres to publish detailed sustainability reports, covering critical metrics such as energy consumption, carbon emissions, water usage, and waste management. By promoting transparency and accountability, this framework ensures that data centre operators take responsibility for their environmental impact, aligning their operations with sustainable practices.

Energy efficiency standards are essential for promoting sustainable data centre operations. Poveda-Orjuela *et al*. (2019) [50] emphasize that ISO 50001:2018, a globally recognized standard for energy management systems, provides a comprehensive framework for data centres to enhance energy performance. This standard requires organizations to establish clear energy management objectives, monitor energy consumption, and implement continuous improvement measures to optimize energy use, reduce waste and minimize carbon emissions. Compliance with ISO 50001:2018 ensures that data centres maintain energy-efficient operations while aligning with international best practices.

The Climate Neutral Data Centre Pact, established in 2021, represents a significant industry-led initiative aimed at advancing sustainability in the data centre sector. Cao *et al.* (2022) [16] highlight that this voluntary agreement brings together data centre operators and cloud service providers across Europe, committing them to achieve climate neutrality by 2030. Signatories of the pact pledge to enhance energy efficiency, transition to renewable energy sources, reduce water consumption, and adopt circular economy practices. This initiative not only underscores the industry's dedication to sustainability but also sets a benchmark for best practices in environmentally responsible data centre operations.

In the United States, the federal government has taken decisive action to promote sustainable data centre infrastructure. In 2023, President Joe Biden issued an executive order focused on advancing the development of sustainable data centres, prioritizing energy efficiency, renewable energy adoption, and carbon reduction (Biden, 2023) [14]. This directive mandates that federal data centres achieve carbon neutrality by 2030, while also encouraging private sector data centres to adopt comparable sustainability objectives. The executive order underscores the government's commitment to reducing the environmental impact of data centre operations while supporting a sustainable digital economy.

Cybersecurity regulations are a fundamental aspect of the data centre industry, ensuring the protection of critical digital infrastructure. According to Spaniel (2022) [58], robust cybersecurity measures are essential for safeguarding data centres against cyber threats and data breaches. The introduction of the Cyber Security and Resilience Bill in 2025 establishes mandatory cybersecurity standards for data centres, enhancing their resilience and security. This legislation is particularly crucial as data centres become increasingly reliant on digital technologies and cloud computing, making them vulnerable to sophisticated cyberattacks.

Water conservation has become a critical focus of regulatory frameworks for sustainable data centres, particularly in regions facing water scarcity. Chaturvedi *et al.* (2018) [66] highlight that some regions have established water efficiency standards that mandate the use of water-saving cooling technologies, such as closed-loop water cooling systems and rainwater harvesting. These measures are essential for minimizing water consumption in data centres, reducing the risk of resource conflicts and promoting sustainable water management practices.

Data privacy regulations play a crucial role in data centre operations, particularly given their responsibility for managing vast volumes of sensitive information. Odobaša and Marošević (2023) [47] emphasize that the General Data Protection Regulation (GDPR) within the European Union establishes stringent data protection requirements, mandating that data centres implement robust security measures to safeguard user privacy. Compliance with such data privacy regulations is essential for maintaining customer trust and avoiding legal penalties, ensuring that data centres operate in a secure and legally compliant manner.

Beyond regulatory frameworks, industry standards and certifications play a vital role in advancing sustainability within the data centre sector. According to Poveda-Orjuela *et al.* (2019) [50], certifications such as Leadership in Energy and Environmental Design (LEED) and ISO 14001 (Environmental Management Systems) establish clear benchmarks for the sustainable design, construction and operation of data centres. These certifications validate a data centre's commitment to environmental responsibility, enhancing its reputation among stakeholders and promoting best practices in sustainability.

International organizations play a critical role in promoting sustainable practices across the data centre industry. According to Chaturvedi *et al.* (2018) [66], these organizations provide essential guidelines on energy efficiency, renewable energy integration, and carbon reduction, helping data centres align their sustainability strategies with globally recognized standards. By offering best practices and regulatory frameworks, they ensure that data centres adopt environmentally responsible operations, minimizing their ecological impact.

2.8 Future directions and emerging trends

The data centre industry is continuously evolving, driven by advancements in technology, increasing demand for digital services and growing emphasis on sustainability. As organizations strive to balance performance, efficiency and environmental responsibility, several future directions and emerging trends are shaping the landscape of data centre infrastructure (Ahmadu *et al*., 2025) [6].

A prominent emerging trend in the data centre industry is the transition to sustainable cooling solutions. As highlighted by Naganandhini *et al.* (2023) [45], advanced cooling technologies such as liquid cooling, immersion cooling, and geothermal cooling are gaining traction due to their superior energy efficiency and reduced water usage. These innovative cooling methods offer a more sustainable alternative to traditional air-based systems, which are typically less efficient and consume substantial amounts of water. The widespread adoption of these technologies is expected to significantly enhance the environmental performance of data centres.

The adoption of artificial intelligence (AI) and machine learning (ML) is revolutionizing the data centre industry, significantly enhancing operational efficiency. Javaid, Haleem and Suman (2023) [65] emphasize that AI-driven energy management systems can monitor and optimize energy consumption in real-time, effectively reducing operational costs and minimizing carbon emissions. Additionally, AI-powered predictive maintenance systems improve reliability by detecting potential equipment failures before they occur, minimizing downtime and ensuring uninterrupted data centre operations. This intelligent automation not only enhances sustainability but also optimizes overall performance.

Edge computing is experiencing rapid adoption as organizations strive to reduce latency and enhance service quality. According to Mensah (2024) [43], edge data centres—smaller, decentralized facilities located near end-users—enable real-time data processing for latency-sensitive applications, including autonomous vehicles, smart cities and industrial automation. The expansion of edge computing is expected to accelerate with the widespread adoption of Internet of Things (IoT) and 5G technologies.

The growing adoption of modular and prefabricated data centres is a significant trend in the industry. According to George (2025) [28], these flexible, scalable facilities can be quickly deployed to accommodate changing capacity requirements. Modular data centres are particularly valuable in disaster recovery scenarios, remote areas, and emerging markets, where establishing traditional data centre infrastructure may be complex or cost-prohibitive. This approach offers organizations a rapid, efficient solution for expanding their data processing capabilities.

Sustainability continues to be a critical priority for the data centre industry, with organizations increasingly turning to renewable energy sources to power their operations. Hitesh (2025) [32] emphasizes that major technology companies, including Google, Microsoft, and Amazon, have committed to achieving carbon neutrality by 2030 by leveraging solar, wind and hydroelectric power. These companies are also utilizing power purchase agreements (PPAs) to ensure a reliable supply of renewable energy, demonstrating their commitment to minimizing the carbon footprint of their digital infrastructure.

Energy efficiency advancements in data centres are expected to continue, driven by the adoption of energy-efficient servers, advanced power management technologies, and AI-driven energy optimization. Naganandhini *et al*. (2023) [45] emphasize that innovations such as dynamic voltage scaling, automated workload distribution, and energy-efficient hardware have become standard practices, significantly reducing energy consumption while maintaining high performance. These energy-efficient solutions enhance the sustainability of data centre operations without compromising their computational capabilities.

The adoption of circular economy practices is another emerging trend, with data centres exploring ways to minimize electronic waste and maximize resource efficiency. This includes recycling electronic waste, reusing hardware components, and adopting modular designs that facilitate easy upgrades and component replacement (Ahmadu *et al*., 2025) [4]. Circular economy practices not only enhance sustainability but also reduce operational costs by extending the lifespan of data centre equipment.

Digital twins, which serve as virtual replicas of physical data centre infrastructure, are becoming an essential tool for enhancing operational efficiency. Javaid, Haleem and Suman (2023) [65] highlight that digital twins allow data centre operators to create a digital model of their facilities, enabling them to simulate various scenarios, monitor real-time performance and anticipate equipment failures. This advanced technology not only improves energy efficiency but also minimizes maintenance costs by proactively identifying potential issues before they disrupt operations.

Data privacy and security have become critical priorities for data centres, given their role in handling vast volumes of sensitive information. Mensah (2024) [43] emphasizes that organizations are increasingly implementing robust cybersecurity measures, including multi-factor authentication, encryption, and zero-trust security architectures, to safeguard data against breaches and cyberattacks. Compliance with data protection regulations, such as the General Data Protection Regulation (GDPR) and the Cyber Security and Resilience Bill, is crucial for maintaining customer trust and ensuring secure data management

Sustainability reporting and transparency have become essential aspects of data centre operations, driven by growing stakeholder expectations for accountability. Veselova (2023) [61] emphasizes that data centre operators are increasingly publishing sustainability reports that provide detailed information on energy consumption, carbon emissions, water usage and sustainability initiatives. These reports allow stakeholders to evaluate the environmental performance of data centres, promoting transparency and encouraging continuous improvement in sustainable practices.

As the data centre industry continues to evolve, the focus on sustainability, energy efficiency and digital innovation is expected to intensify. Organizations are exploring new technologies and strategies to enhance the sustainability of their data centre operations, while regulatory frameworks and stakeholder expectations drive continuous improvement.

2.9 Practical case studies in sustainable data centres

Practical case studies offer valuable insights into the successful implementation of sustainable practices in data centres. These case studies demonstrate how innovative technologies, strategic planning and stakeholder engagement can be leveraged to minimize the environmental impact of data centres while maintaining high-performance standards (Ahmadu *et al*., 2025) [5].

One notable case study is the implementation of high-altitude platform-based data centres, which leverage atmospheric conditions to achieve energy efficiency. According to Abderrahim, Amin and Shihada (2023) [1], these data centres are deployed on high-altitude platforms, such as airships or drones, where they benefit from naturally low temperatures, reducing the need for energy-intensive cooling systems. This innovative approach minimizes energy consumption while maintaining reliable data processing capabilities.

A notable example of sustainable data centre operations is the integration of renewable energy sources with intelligent energy management systems. Saleem *et al*. (2023) [51] highlight a case where data centres are powered by solar and wind energy, while advanced energy management systems dynamically optimize energy consumption based on real-time demand. This approach not only minimizes carbon emissions but also enhances the resilience of data centre operations by diversifying energy sources, ensuring a stable and sustainable power supply.

Real-time carbon footprint reduction is another successful strategy demonstrated by Sarkar *et al*. (2024) [52]. In this case study, data centres implemented AI-driven carbon monitoring and optimization systems, which track carbon emissions in real-time and automatically adjust energy usage to minimize emissions. This technology-driven approach enables data centres to achieve carbon neutrality without compromising performance.

Equinix, a leading data centre operator, has exemplified sustainable innovation through its waste heat recovery initiative. Lam *et al*. (2021) highlight that Equinix effectively redirects the waste heat generated by its data centres to heat an Olympic-sized swimming pool, transforming excess thermal energy into a valuable community resource. This approach not only reduces the environmental impact of data centre operations but also provides a practical community benefit, illustrating how sustainable practices can achieve both ecological and social objectives.

The concept of Recycled Cloud offers a practical approach to sustainable data centre management by repurposing retired cloud infrastructure for non-critical computing tasks. Dahmani (2024) [18] explains that this initiative focuses on reusing decommissioned hardware to support activities such as scientific research and educational projects. By extending the lifespan of data centre equipment and minimizing electronic waste, Recycled Cloud promotes sustainable computing practices, aligning with the principles of circular economy and responsible resource management.

A forward-looking example of sustainable data centre innovation is the concept of space-based data centres. Periola and Kolawole (2019) [49] explore the feasibility of deploying data centres in outer space, where they can operate in naturally low-temperature environments, significantly reducing the need for energy-intensive cooling systems. These space-based facilities can be powered by solar energy, providing a virtually unlimited and sustainable power source. Although still in the experimental phase, this concept demonstrates the potential for groundbreaking solutions in sustainable data centre design, offering an innovative approach to minimizing the environmental impact of data processing.

3. Conclusion

This study set out to provide an in-depth comparative analysis of global trends in sustainable data centre infrastructure investment. Through a detailed exploration of various aspects, including the evolution of data centres, the classification of data centres and the key components of sustainable infrastructure, the study has comprehensively addressed its aim and objectives. It has explored the global trends driving sustainable investments, the environmental impacts of data centres, the challenges in achieving sustainability and the regulatory frameworks guiding sustainability in the industry. Additionally, it has examined emerging trends and future directions, supported by practical case studies that demonstrate real-world applications of sustainable practices.

One of the key findings of this study is that the data centre industry is undergoing a transformative shift toward sustainability, driven by a combination of regulatory pressure, stakeholder expectations and technological innovation. Energy efficiency, renewable energy integration, water conservation, carbon management and circular economy practices have emerged as critical components of sustainable data centres. However, the study also highlights several challenges, including high energy consumption, water usage, carbon emissions, regulatory compliance and the financial costs associated with sustainable infrastructure.

The study concludes that while the data centre industry has made significant progress toward sustainability, there is still much work to be done. Achieving sustainable data centre infrastructure requires a holistic approach that combines technological innovation, regulatory compliance, stakeholder engagement and continuous improvement. Organizations must prioritize energy efficiency, renewable energy adoption, water conservation, sustainable procurement and transparent sustainability reporting.

Based on the findings, this study recommends that data centre operators continue to invest in energy-efficient technologies, explore renewable energy options, adopt circular economy practices and enhance transparency through sustainability reporting. Policymakers should strengthen regulatory frameworks to promote sustainability, while stakeholders should support sustainable practices through informed decision-making. Ultimately, a collaborative approach is essential for achieving a sustainable future for the global data centre industry.

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