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PAPER

A Multidisciplinary Review of Sustainable Cloud Data Centers: Practices, Adoption Challenges, and Emerging Research Directions toward Alignment with the Sustainable Development Goals (SDGs)

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ABSTRACT

Cloud data centres are the backbone of the digital economy; however, their rapid expansion has raised concerns regarding vast energy consumption, carbon emissions, and environmental impact, posing challenges to sustainability. This multidisciplinary review investigates how cloud data centre operations can be strategically aligned with the United Nations' sustainable development goals (SDGs). The paper aims to synthesize current sustainable practices, assess adoption challenges, and propose a framework for advancing socio-technical alignment within the industry. Through a structured literature review spanning computer science, environmental engineering, and organizational governance, this study identifies several emerging green practices such as renewable energy integration, AI-driven workload scheduling, advanced cooling systems, waste heat reuse, and circular hardware lifecycle management. Despite these advancements, the review identifies persistent obstacles, including the intermittency of renewable energy, escalating workload demands from AI and IoT, economic and regulatory constraints, and insufficient cross-sector coordination. To address these gaps, the paper proposes a Socio-Technical Sustainability Alignment Framework encompassing four interrelated layers: technical infrastructure, organizational governance, behavioural engagement, and external policy. This framework offers a practical roadmap for guiding the transition toward greener and more resilient digital infrastructure. Finally, the findings highlight that aligning cloud data centre development with the SDGs is not only viable but essential for reducing carbon emissions and ensuring the digital infrastructure contributes meaningfully to global sustainability goals.

KEYWORDS

cloud data centres, sustainable development goals (SDGs), green IT, energy efficiency, renewable energy, carbon footprint, sustainable cloud computing

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1 INTRODUCTION

The growth number and size of cloud data centres globally have increased in parallel with the exponential expansion of cloud computing. These facilities provide the computational backbone for modern digital services, including artificial intelligence, streaming platforms, enterprise applications, and e-commerce. However, because these data centres consume a lot of electricity and water and produce a lot of greenhouse gas emissions, their environmental impact has caused serious sustainability issues [1], [2]. Data centres use between 1% and 2% of the world's electricity, according to current estimates, and this number could rise as demand rises [1]. This environmental impact positions cloud infrastructure at the intersection of global sustainability and climate mitigation efforts [3].

The need to align cloud data centre operations with the Sustainable Development Goals (SDGs) of the UN is becoming more widely acknowledged. This is especially true for SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action) [4], [5]. In response, operators have made investments in solar and wind energy [4], increased water and energy efficiency, and repurposed waste heat for community use [6], [7]. Additionally, circular practices connect to SDG 11 (Sustainable Cities and Communities), which calls for redistributing server waste heat into urban district heating systems [4].

While many studies address isolated aspects of efficiency or energy usage, comprehensive frameworks that integrate infrastructure design, operational strategy, and environmental metrics remain limited [8]. Despite considerable research efforts, gaps remain in the integration of technical solutions with policy frameworks and organizational readiness. Previous studies have either emphasized engineering approaches (e.g., virtualization, energy-aware scheduling, advanced cooling systems) [3], [6] or environmental policy recommendations in isolation [3], [9], with limited interdisciplinary synthesis. Consequently, it remains difficult to fully assess the maturity of cloud data centres in advancing SDG alignment across technical, organizational, and regulatory dimensions.

There are still gaps in the integration of technology solutions with organizational readiness and policy frameworks, despite significant research efforts. With little interdisciplinary synthesis, previous studies have either focused on engineering approaches (such as virtualization, energy-aware scheduling, and advanced cooling systems) [3], [6] or environmental policy recommendations in isolation [3], [9], with limited interdisciplinary synthesis. As a result, it remains challenging to fully assess the maturity of cloud data centres in advancing SDG alignment across technical, organizational, and regulatory dimensions.

Although there is increasing awareness of the environmental impacts of cloud data centres, the literature lacks a thorough, socio-technical synthesis connecting sustainable operational practices to SDG targets. Most studies explore technological interventions or sustainability frameworks separately, with minimal exploration of how these strategies can be coordinated across disciplines and stakeholders [10], [11]. This fragmented approach limits the ability to map out actionable pathways toward sustainable transformation of cloud infrastructure.

The primary objective of this review is to provide a comprehensive multidisciplinary synthesis of sustainability efforts within the cloud data centre industry. Specifically, the study aims to (1) identify and categorize the sustainable practices currently implemented by cloud data centre operators, (2) analyse the key technical, organizational, and regulatory barriers that inhibit alignment with global sustainability targets such as the Sustainable Development Goals (SDGs), and (3) propose future research directions alongside an integrated socio-technical framework to guide ongoing advancements in environmentally responsible and efficient cloud data centre operations worldwide.

Previous study has provided rich technical insights. Virtualization, server consolidation, energy-conscious workload scheduling, and AI-driven cooling optimization are examples of green IT methods that have demonstrated the potential to save energy [12], [13]. Environmental engineering studies have explored renewable energy integration, power purchase agreements, and battery storage systems to reduce fossil fuel dependence [5], [7]. In parallel, studies in corporate governance and public policy have examined reporting standards, carbon benchmarking, and sustainability governance frameworks [9], [13], [14].

However, there remains a lack of synthesis across these disciplines to evaluate the collective contribution of such initiatives toward SDG achievement. This review addresses that gap by providing a holistic, multidisciplinary analysis of sustainable cloud data center practices, challenges, and opportunities. The structure of this paper is as follows: it outlines the methodology, presents the review findings structured around key thematic areas, propose of future research directions, offers a discussion of the results in relation to the SDGs and socio-technical alignment, and provides recommendations and conclusions for researchers, policymakers, and industry stakeholders.

2 METHODOLOGY

This study applied a structured systematic literature review methodology to identify and analyse recent research on sustainable practices for cloud data centres. The review followed best practices for multidisciplinary research synthesis as outlined by previous ICT and sustainability reviews [15], [16]. Literature was retrieved from established academic databases, including IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar, focusing on peer-reviewed journal articles, conference papers, and high-impact industry reports published between 2018 and 2025. Priority was given to recent works from 2022 onward to capture emerging trends in SDG-aligned sustainability practices.

A search strategy was applied using keywords including “cloud data centers,” “green IT,” “sustainable computing,” “energy-efficient data centers,” “renewable energy integration,” “carbon footprint reduction,” and “socio-technical frameworks.” Inclusion criteria required that articles explicitly address sustainability or environmental optimization within cloud data centre operations. In this writing, researchers initially screened 98 articles, but after applying inclusion criteria, only 75 were retained for synthesis. The searches were limited to articles published between 2021 and 2025, and titles and abstracts were screened to ensure relevance.

The initial search yielded a broad set of sources, including journal articles, conference papers, industry white papers, and relevant case studies. We then refined the selection by relevance and quality. Priority was given to peer-reviewed research and high-impact industry reports that explicitly discussed sustainable data centre practices or their relation to SDGs. To ensure comprehensive multidisciplinary coverage, the review includes: (1) computer science and engineering studies that propose technical innovations for enhancing data centre efficiency and integrating renewable energy sources [2], [3], [5], [6], [12], [17]; (2) environmental and energy engineering research focused on power systems, renewable energy deployment, and the climate-related impacts of data centre operations [5], [7], [16]; (3) Management and Policy literature addressing sustainability frameworks, standards, or case studies of data centre operators' initiatives [1], [9], [14]; and (4) Socio-Technical and Cross-domain analyses linking data centres to broader sustainability or development issues [10], [14].

A literature matrix was created to systematically extract key findings, including: (a) sustainable strategies and technologies, (b) related SDGs or sustainability metrics, (c) challenges reported, and (d) recommendations for further research. The data were analysed thematically to enable cross-comparison and to highlight where gaps or conflicting evidence existed (e.g., differing views on full renewable energy viability).

A structured literature matrix was developed to systematically extract and organize key information from the selected studies. This included: (a) sustainable practices implemented in cloud data centres, (b) reported implementation challenges, and (c) proposed recommendations or future research directions. A thematic synthesis approach was used to group the findings by practice area, highlight recurring challenges, and map contributions to relevant SDGs. This process also allowed the identification of research gaps and areas of conflicting evidence—for instance, differing perspectives on the long-term viability of exclusive reliance on renewable energy sources in large-scale data centre operations.

During the manuscript preparation, the authors utilized an AI language model to assist in refining the clarity and coherence of human-authored text. The tool was used for improving sentence structure, enhancing readability, and rephrasing for academic tone. No generative content or conceptual contributions were produced by the AI. The content and structure were developed by the authors, and AI assistance was limited to stylistic editing. All final content decisions and validations were made by the authors.

The methodology ensured rigorous multidisciplinary coverage and provided the foundation for a coherent synthesis of current knowledge, emerging trends, and research needs in advancing the sustainability of cloud data centres.

3 LITERATURE REVIEW

3.1 Sustainable practices

To address environmental concerns and meet global sustainability goals, cloud data centres are adopting innovative strategies across energy, operational efficiency, resource reuse, and reporting. The practices identified are structured as follows:

Renewable energy integration. The shift to renewables, including solar and wind energy, is fundamental for decarbonizing data centre operations [18]. Cloud service providers are increasingly investing in on-site renewable installations or securing long-term Power Purchase Agreements (PPAs) to ensure access to clean energy [19]. To address the intermittency and variability of renewable supply, AI-driven workload scheduling is employed to optimize task distribution in alignment with energy availability [5], [20]. In addition, routing tasks to regions with low-carbon energy further enhances efficiency and emission reduction [21]. These efforts are often complemented by energy storage systems and carbon strategies, which collectively strengthen the reliability and sustainability of renewable energy integration in cloud data centre operations [2].

AI-Driven workload scheduling. Artificial intelligence (AI) plays a critical role in minimizing emissions by aligning data centre tasks with periods and locations of low-carbon energy supply [5]. [6] demonstrated the effectiveness of carbon-intensity-aware scheduling models that dynamically adjust computing tasks based on real-time emission data. Similarly, [22] introduce holistic energy management frameworks that integrate AI with sustainability metrics to improve operation decision-making. [13] and [23] proposed steering frameworks that integrate AI with sustainability to optimize hybrid cloud workloads; [24] added virtual machine (VM) migration based on renewable energy forecasting.

Advanced cooling technologies. Cooling accounts for up to 40% of data centre energy use [1], [4]. Liquid cooling systems reduced cooling energy by 50% [12]. Free-air and ambient cooling are also used [18], [25], [26]. AI optimization of cooling [3] and integrated predictive cooling models [27] further enhance energy efficiency.

Virtualization & server consolidation. Virtual machine (VM) consolidation and server right-sizing effectively reduce energy use [22], [28]. [29] reported energy savings of up to 30%. [13] introduced cache-based VM relocation. [30] highlighted thermal-aware load balancing to reduce energy waste.

Waste heat reuse. Data centre heat is increasingly reused in district heating systems in Europe [4], [31]. Such reuse has been shown to offset fossil fuel use and improve community acceptance [15]. However, broader deployment depends on urban infrastructure and regulatory frameworks [30], [32].

Water-efficient cooling. Operators are adopting water-saving systems such as dry coolers, closed-loop cooling, and greywater recycling [33]. Large firms such as Google aim for water positivity [19]. Google's 2024 environmental report details the company's progress toward achieving net water-positive operations by focusing on water recycling and responsible water management across its global data centre facilities [2] & [8]. In addition, [25] emphasized the role of integrated water-energy optimization. Recent industry efforts have also highlighted the importance of Water Usage Effectiveness (WUE) as a key metric to evaluate water conservation strategies in data centres, complementing energy metrics like PUE [31].

Sustainability reporting. Cloud service providers are increasingly disclosing key sustainability metrics such as energy mix, Power Usage Effectiveness (PUE), and Water Usage Effectiveness (WUE) to enhance transparency and accountability [2]. Transparent reporting has been shown to play a critical role in driving sustainability performance, as it enables stakeholders to monitor progress and identify areas for improvement [34]. Similarly, [35] also highlights that comprehensive disclosure supports strategic sustainability benchmarking, allowing providers to align operations with industry standards and global environmental goals.

Circular hardware lifecycle. Circularity initiatives in cloud data centres increasingly focus on modular server design, equipment reuse, and responsible recycling practices [20], [36]. [20] describe how organizations extend the operational lifespan of hardware components to minimize electronic waste and enhance sustainability. Additionally, [20] and [36] highlight design strategies that facilitate easier component replacement and upgradeability.

Beyond internal reuse, [14] highlight the value of repurposing older hardware for educational and secondary computing purposes, contributing to both resource efficiency and digital inclusion.

Sustainable data center practices, including advanced cooling systems, modular architecture, and intelligent energy monitoring, have been emphasized in recent holistic frameworks [8]. The diverse sustainable practices identified across the literature illustrate a comprehensive and evolving approach by cloud data centres to address environmental, energy, and resource-related challenges. These practices not only contribute to operational efficiency but also directly support key global sustainability objectives. To synthesize the findings of this review and provide a clear reference for researchers and practitioners, Table 1 summarizes the key categories of sustainable strategies, their specific focus areas, and representative studies from recent literature.

Table 1. Summary of sustainable practices adopted by cloud data centres

Practice	Description	References
Renewable Energy Integration	Use of solar, wind, and hydropower to power data centers, complement with storage and carbon offsets	[2], [5], [18], [19], [20], [21]
AI-Driven Workload Scheduling	Align workloads with periods or locations of low-carbon energy availability	[5], [6], [13], [22], [24], [28]
Advanced Cooling Technologies	Adoption of liquid immersion, free-air cooling, and AI-driven cooling to reduce energy and water use	[1], [3], [4], [12], [18], [25], [26], [27]
Virtualization & Server Consolidation	Maximizing server utilization to reduce energy waste through virtualization and intelligent placement	[13], [22], [28], [29], [30]
Waste Heat Reuse	Using data centre waste heat for district heating and other reuse applications	[4], [15], [30], [31], [32]
Water-Efficient Cooling	Reducing water consumption through closed-loop, dry cooling, and greywater recycling systems	[2], [8], [19], [25], [31], [33]
Sustainability Reporting	Public disclosure of energy, emissions, water use, and sustainability metrics	[2], [34], [35]
Circular Hardware Lifecycle	Modular server design, reuse of equipment, recycling, and repurposing for education or secondary workloads	[14], [20], [36]

This review highlights that leading cloud data centres are already adopting a variety of sustainable practices. These include integrating renewable energy sources, deploying AI-driven workload scheduling to reduce energy and carbon intensity, optimizing cooling systems to improve energy and water efficiency, repurposing waste heat, and embracing circular hardware lifecycle management. Collectively, these strategies demonstrate that the sector holds significant potential to transition from energy-intensive operations to sustainability leadership within the global ICT ecosystem.

3.2 Key challenges identified

While the above practices show an optimistic picture of progress, the literature also straightforwardly identifies several challenges and barriers to fully sustainable cloud data centres. Intermittency of renewable energy is a persistent technical and economic challenge. As noted, without affordable large-scale energy storage, data centres cannot rely on renewables alone 24/7 [37]. Overprovisioning capacity (installing more solar panels or wind turbines than needed on average) can mitigate this, but at a high financial cost. Thus, many data centres still must use grid power at night or when renewable output lags, meaning their carbon footprint is not completely eliminated. [5] points out that optimizing a multisite cloud for low carbon use may sometimes conflict with minimizing cost or latency; there are trade-offs between sustainability and performance that must be carefully balanced.

Despite notable progress, the literature highlights persistent challenges preventing full sustainability in cloud data centres. These barriers can be categorized into five main areas:

Intermittency of renewable energy. Despite significant progress, renewable energy remains highly variable and difficult to depend on exclusively without the support of scalable energy storage systems [5], [38]. During periods of low renewable output, data centres often revert to conventional grid electricity, which can partially undermine carbon reduction targets. Overprovisioning renewable capacity to ensure reliability is a potential solution but often incurs substantial costs, leading to a complex trade-off between environmental sustainability, economic feasibility, and performance efficiency [2], [37], [39].

Economic and regulatory constraints. High capital costs required to retrofit existing data centres with green technologies such as advanced cooling systems or on-site renewable energy installations remain a significant barrier, particularly for smaller providers and operators in developing regions [40], [41]. Regulatory inconsistency further complicates sustainability adoption, as global carbon reporting standards and data centre efficiency mandates are largely voluntary in most jurisdictions [42]. [31] emphasize that regional progress is heavily influenced by the presence of governmental incentives, such as tax credits and renewable energy subsidies, which can offset the financial burden and encourage broader adoption of sustainable practices.

Rising workload demands (rebound effect). Another challenge is rapidly growing demand for cloud services. According to [1], [43], efficiency improvements per server can be offset by the sheer increase in the number of servers needed globally to meet rising digital needs. The proliferation of AI, big data, and IoT applications means data centre workloads are expected to grow exponentially. [2] warns that without breakthrough innovations, even significant efficiency gains might not prevent an overall rise in total energy use and emissions, a phenomenon sometimes called the rebound effect. Thus, solutions must scale faster than demand growth, a non-trivial task. Even as individual servers become more energy efficient, the exponential rising demand from AI, big data, and IoT risks negating gains, a phenomenon known as the rebound effect [6]. [6] warns that without breakthrough innovations, total energy and emissions may still grow significantly.

Technical and operational barriers. Balancing energy optimization with quality of service (QoS) continues to be a persistent challenge in sustainable data centre operations. [28] introduced a secure load management approach designed to navigate the trade-offs between performance and cybersecurity. Similarly, [11] and [8] proposed expert-guided virtual machine (VM) migration to enhance energy efficiency; however, their findings also revealed potential risks of QoS degradation during optimization processes. Building on these concerns, [10] emphasized ongoing gaps in architectural standardization and the need for better alignment between infrastructure design and long-term sustainability goals.

Socio-technical coordination and human capital. One major challenge is the absence of standardized frameworks to integrate energy metrics with infrastructure and governance decisions, a gap highlighted in previous sustainability models [8]. Multidisciplinary coordination between IT engineers, utilities, policymakers, and communities remains insufficient [14], [44]. [4] provides a case where waste heat reuse was hindered by absent district heating infrastructure. Human capital development is also needed, as stressed by [14], which is the role of education and training in bridging skill gaps and enabling successful implementation of sustainable technologies.

The key challenges identified in achieving sustainability within cloud data centers are summarized in Table 2. These include issues related to energy variability, economic and regulatory barriers, rising workload demands, technical and operational limitations, and socio-technical coordination.

Table 2. Summary of key challenges in achieving sustainable cloud data centres

Challenge Area	Description	Example References
Intermittency of Renewable Energy	Variability in solar/wind output and lack of scalable storage solutions	[2], [5], [37], [38]
Economic and Regulatory Constraints	High capital costs, inconsistent or absent regulatory standards, and varying government incentives	[31], [40], [41], [42]
Rising Workload Demands (Rebound Effect)	Growth of AI, big data, and IoT increases energy demands despite efficiency gains	[1], [2], [6], [43]
Technical and Operational Barriers	Difficulty balancing QoS with energy optimization; lack of standard design models	[10], [11], [28]
Socio-Technical Coordination and Human Capital	Lack of collaboration across stakeholders; skill shortages; absence of infrastructure	[4], [8], [14]

Overall, while the industry has made measurable progress in adopting sustainable practices, these challenges highlight the need for continued innovation, clearer regulatory frameworks, and stronger collaboration among stakeholders to fully realize the potential of sustainable cloud data centres.

4 RECOMMENDATIONS AND FUTURE RESEARCH DIRECTIONS

Addressing the complex sustainability challenges of cloud data centres requires the development of holistic, multidisciplinary strategies. A key priority is investment in large-scale energy storage systems and smart grids to mitigate the intermittency of renewable energy sources [7]. Additionally, the integration of AI-driven tools that dynamically optimize task scheduling for carbon efficiency without compromising quality of service (QoS) is a promising area of innovation [31]. To meet growing environmental and regulatory demands, advancements in zero-water cooling technologies and climate-resilient infrastructure are also essential [45].

Emerging approaches include the adoption of distributed edge computing and server right-sizing to balance workload demands and reduce energy intensity [31], as well as the expansion of district heating networks to recover and reuse waste heat from data centers [4]. Water sustainability can be further enhanced through closed-loop cooling systems and on-site greywater recycling [1]. [46] introduced the concept of virtualizing energy systems to expose carbon intensity metrics in real-time, enabling adaptive, carbon-aware workload management and challenging conventional energy efficiency measures.

Strengthening accountability and transparency across the industry will require the wider adoption of standardized green certifications and independent third-party audits [14]. The application of comprehensive sustainability metrics such as Carbon Usage Effectiveness (CUE) in conjunction with Power Usage Effectiveness (PUE) can offer a more accurate and actionable assessment of environmental impacts [31], [42]. To consolidate these emerging solutions and guide future implementation, this paper proposes a Socio-Technical Sustainability Alignment Framework for cloud data centres.

To consolidate these emerging solutions and guide future implementation, this paper proposes a Socio-Technical Sustainability Alignment Framework for cloud data centres. The framework draws from the layered sustainability taxonomies and classification models outlined by [8], promoting a structured approach across four interrelated layers:

- Technical Layer: Infrastructure-focused solutions including renewable energy integration, energy-efficient computing, advanced cooling technologies, and carbon-aware workload scheduling.
- Organizational Layer: Address governance structure, environmental, social, and governance (ESG) alignment, and sustainability performance reporting as critical components for ensuring transparency, compliance, and internal accountability.
- Human/Behavioural Layer: Initiatives to build internal capacity, promote stakeholder engagement, and foster a strong culture of sustainability.
- External/Policy Layer: Policy development, regulatory compliance, benchmarking, and cross-sector collaboration to drive industry-wide improvements.

Collectively, these layers provide a comprehensive roadmap to help advance the sustainability maturity of cloud data centres, enabling them to deliver environmentally responsible and resilient digital infrastructure.

To illustrate how these multidimensional strategies can be systematically applied, Figure 1 presents the proposed Socio-Technical Sustainability Alignment Framework. The framework integrates technical, organizational, behavioural, and policy-level interventions to address the sustainability challenges identified in this review. It serves as a practical guide for researchers, industry practitioners, and policymakers working toward greener and more responsible cloud data centre operations. One valuable global framework that cloud data centres can adopt to systematically improve energy performance and support structured energy reduction is the ISO 50001 Energy Management Standard [47].

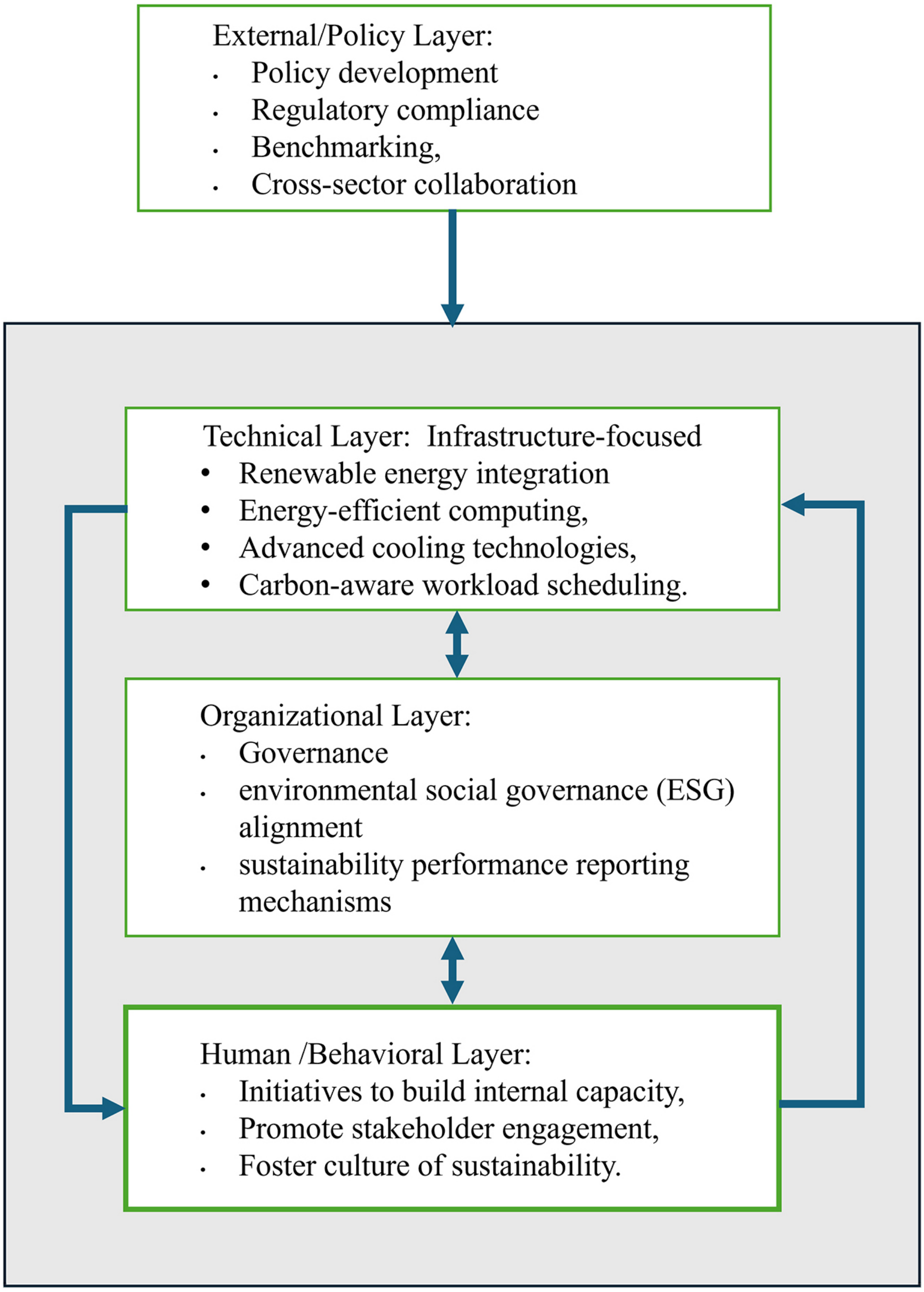

Fig. 1. Socio-technical sustainability alignment framework for cloud data centre

Our review reveals that substantial progress has been made in greening cloud data centres, yet it also illustrates the gap between current practices and the ambitious targets of the SDGs. In this discussion, we interpret how the findings align with specific SDGs and what interdisciplinary efforts are needed to overcome the identified challenges.

These recommendations reflect both practical implementation priorities and emerging research opportunities. Future studies should continue to explore the multidisciplinary interplay between technology, governance, and environmental systems to advance the sustainable transformation of cloud data centres.

5 DISCUSSION

This review highlights both the substantial advancements and remaining gaps in aligning cloud data centre operations with the SDGs. Sustainable practices such as renewable energy integration, AI-driven workload optimization, advanced cooling technologies, and circular hardware lifecycle approaches show measurable potential to reduce carbon footprints and resource [2], [5], [6], [17]. As shown in Table 1, several sustainable practices, such as renewable energy integration and AI-driven optimization, are increasingly adopted, yet their alignment with SDG targets remains partial and inconsistent.

To provide a clearer synthesis of the reviewed sustainability practices, a summary table has been constructed (refer to Table 3). This table outlines [2], [5], [6], [17] the core practices adopted by cloud data centres, alongside their associated benefits, inherent limitations, and alignment with relevant SDGs. The inclusion of both technical and organizational dimensions emphasizes the complexity of achieving true sustainability in this sector. For example, while renewable energy integration directly supports SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), its implementation is often hindered by supply variability and geographic disparities. Similarly, AI-driven workload scheduling can significantly optimize energy efficiency but requires complex predictive systems and real-time data access. This integrated view not only highlights the multifaceted nature of sustainable cloud operations but also reinforces the need for coordinated socio-technical strategies to overcome existing barriers and accelerate progress toward global sustainability targets.

Table 3. Summary of sustainable practices, benefits, limitations, and SDG alignment

Practice	Benefit	Limitation	SDG Alignment
Renewable Energy Integration	Reduces carbon emissions and dependence on fossil fuels.	Intermittent supply and high regional variance in renewables.	SDG 7, SDG 13
AI-Driven Workload Scheduling	Optimizes energy use by aligning processing with green power availability.	Requires real-time data and complex prediction models.	SDG 9, SDG 12
Advanced Cooling Technologies	Minimizes energy and water consumption through efficient cooling.	High cost and infrastructure requirements for implementation.	SDG 6, SDG 13
Virtualization & Server Consolidation	Maximizes server performance while minimizing energy waste.	May introduce performance bottlenecks or compatibility issues.	SDG 9, SDG 12
Waste Heat Reuse	Transforms waste into usable heat for external applications.	Requires proximity to facilities that can reuse heat effectively.	SDG 7, SDG 12
Water-Efficient Cooling	Reduces strain on water resources and improves efficiency.	Effectiveness depends on local climate and system design.	SDG 6, SDG 12
Sustainability Reporting	Promotes transparency and benchmarking of sustainability performance.	Lack of standard metrics and consistent reporting practices.	SDG 12, SDG 13
Circular Hardware Lifecycle	Extends hardware lifespan and reduces e-waste generation.	Limited frameworks for lifecycle tracking and reuse incentives.	SDG 12

In addition to identifying best practices, this review highlights persistent challenges that hinder the full sustainability of cloud data centres. These include the intermittency of renewable energy sources, the rapid increase in computational workloads driven by AI and IoT technologies, a lack of consistent global regulations, and difficulties in coordinating across technical, organizational, and societal domains. These barriers are particularly significant when considering the sector's alignment with the SDGs. For example, achieving SDG 7 (Affordable and Clean Energy) is constrained by variability in renewable output and limited energy storage capacity, while SDG 13 (Climate Action) is challenged by the rebound effect associated with rising digital service demand. The discussion of these obstacles, summarized in Table 4, underscores the urgent need for integrated policy, innovation, and collaboration strategies to ensure meaningful progress toward sustainability goals.

Table 4. Key sustainability challenges in cloud data centres and SDG relevance

Challenge	Impact	Related SDGs
Intermittency of Renewable Energy	Unstable energy supply limits full reliance on renewables, especially in less sunny/windy regions.	SDG 7, SDG 13
Escalation of AI and IoT Workloads	Increased energy demand from smart technologies offsets efficiency gains.	SDG 9, SDG 12
Lack of Global Regulatory Consistency	Varying standards and policies make cross-border sustainability coordination difficult.	SDG 13, SDG 17
Limited Water Availability for Cooling	Water-scarce areas struggle to adopt conventional cooling methods.	SDG 6, SDG 12
Underdeveloped Circular Economy Standards	Few data centers implement systematic recycling or reuse of hardware.	SDG 12
Inconsistent Sustainability Reporting	Lack of standard metrics hinders transparency and benchmarking.	SDG 12, SDG 13
Regional Disparities in Infrastructure	Developing regions face significant barriers to adopting sustainable cloud technologies.	SDG 7, SDG 9, SDG 10

The necessity for coordinated technical, organizational, and regulatory strategies echoes the holistic approach advocated by Murino et al. (2023), which emphasizes integrated sustainability across data centre life cycles. The true alignment requires more integrated, multidisciplinary solutions. Adoption of the proposed Socio-Technical Sustainability Alignment Framework can bridge this gap by providing structured guidance for combining technical innovation with regulatory, organizational, and behavioural enablers [8], [48].

In synthesizing these findings, this review provides a distinctive contribution by offering a holistic socio-technical view, which has been underrepresented in prior literature. While substantial progress has been achieved in sustainable practices, the pathway toward full SDG alignment remains complex and requires harmonized efforts across technology, governance, and behavioural dimensions. Future implementations should also consider regional disparities, particularly in emerging markets, where infrastructural limitations and policy gaps may impede sustainability efforts. This study adds value to the literature by offering a consolidated socio-technical lens on sustainable cloud operations and proposing a clear roadmap for advancing sustainability maturity across the cloud data centre industry.

6 CONCLUSION

This multidisciplinary review synthesizes the current state of research and practice in sustainable cloud data centre operations. The evidence shows that cloud providers have made meaningful strides in adopting technologies and practices aimed at reducing environmental impact and improving energy efficiency. However, challenges related to renewable intermittency, regulatory variability, workload escalation, and socio-technical coordination remain.

To address these, the paper proposes a Socio-Technical Sustainability Alignment Framework, offering a holistic model integrating technical solutions, organizational strategies, behavioural interventions, and policy mechanisms. The framework serves as a roadmap for researchers, practitioners, and policymakers to collaboratively advance environmentally responsible cloud computing infrastructures.

In summary, this review not only consolidates current knowledge on sustainable data center practices but also contributes a structured framework to bridge the gap between operational efficiency and long-term SDG alignment. Its multidisciplinary insights are intended to guide both academic inquiry and industry innovation in the ongoing journey toward net-zero digital infrastructure.

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