

The AI-Driven Energy Surge: A comprehensive review of sustainable power solutions for data centers

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Global Journal of Engineering and Technology Advances, 2025, 24(03), 328-344

Publication history: Received on 10 August 2025; revised on 20 September 2025; accepted on 22 September 2025

Article DOI: <https://doi.org/10.30574/gjeta.2025.24.3.0279>

Abstract

The meteoric rise of artificial intelligence (AI) has propelled global data center energy consumption to 415 terawatt-hours in 2024, with projections doubling to 945 TWh by 2030, driven by AI's computational intensity and cooling demands. This review synthesizes cutting-edge solutions for sustainable AI-driven data centers, emphasizing renewable energy (solar, wind, hydropower) and advanced cooling technologies (liquid cooling, immersion cooling, heat reuse). Through global case studies, such as Google's solar-powered facilities, and African innovations, like Kenya's geothermal-powered centers, it showcases scalable integrations reducing energy use by 20-30%. In Africa, where data center capacity grows 25% annually, abundant renewables and water-efficient cooling address high-temperature challenges, yet infrastructure, cost, and equity barriers persist. Future pathways, including eco-friendly coolants and small modular reactors, are proposed alongside policy reforms to ensure net-zero alignment. This article calls for interdisciplinary collaboration to bridge digital divides, offering actionable insights for researchers, industry, and policymakers to drive sustainable AI infrastructure, particularly in Africa's burgeoning digital landscape.

Keywords: AI; Data Centers; Renewable Energy; Liquid Cooling; Immersion Cooling; Sustainability; Africa; Decarbonization; Energy Efficiency; Digital Infrastructure

1. Introduction

The rapid proliferation of artificial intelligence (AI) has revolutionized industries but unleashed an unprecedented energy surge, driven by data centers powering computationally intensive tasks like machine learning and cloud computing. In 2024, global data centers consumed approximately 415 terawatt-hours (TWh), or 3-4% of electricity demand, with projections of doubling to 945 TWh by 2030 [1]. This surge, coupled with the need for efficient cooling to manage heat from high-density AI servers, challenges global decarbonization goals. Sustainable power solutions, integrating renewable energy and advanced cooling technologies like liquid and immersion cooling, are critical to aligning AI's growth with net-zero targets, particularly in Africa's emerging digital landscape. This review synthesizes advancements in renewable energy and cooling, case studies, and challenges, offering insights for sustainable AI infrastructure.

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1.1. AI's Energy Appetite

The exponential growth of AI technologies has significantly increased the energy demands of data centers, driven by the computational intensity of graphical processing units (GPUs) and large language models (LLMs). According to the International Energy Agency [2024], data centers accounted for 415 TWh globally in 2024, a rise from 1-2% of global electricity pre-2020, with AI workloads contributing significantly to this surge [1]. Unlike traditional computing, AI tasks like training neural networks require substantial power; for instance, Jones [2023] reports that a single AI query consumes 2.9 watt-hours, ten times that of a standard search query [2]. This intensity stems from the parallel processing capabilities of GPUs, which are essential for AI but generate significant heat, necessitating robust cooling systems that further elevate energy use.

The global expansion of data centers, particularly in regions with burgeoning digital economies, amplifies this energy appetite. Smith and Lee [2025] highlight that the United States alone may see data centers consume 12% of national electricity by 2030, up from 4% in 2024, driven by hyperscale facilities supporting AI applications [3]. In emerging markets, such as Africa, data center capacity is growing rapidly, with South Africa witnessing a 300% increase since 2020, as noted by Adebayo [2023] in an AJOL study [4]. This growth is fueled by cloud services and AI adoption, but it strains grids, especially in regions with limited infrastructure, underscoring the need for sustainable solutions.

The energy demands of AI also have significant environmental implications if not addressed sustainably. Findings from BloombergNEF [2024] indicate that unchecked growth could lead to emissions equivalent to 125 billion USD in social costs by 2030, particularly if fossil fuels dominate power supplies [5]. Cooling requirements exacerbate this, as traditional air-based systems consume up to 40% of a data center's energy, according to DataCenterKnowledge [2024] [6]. Innovations like liquid cooling, which reduce energy use by targeting high-heat components, are thus critical, as they enable data centers to manage AI workloads while minimizing carbon footprints, setting the stage for renewable integration.

1.2. Renewables as a Critical Response

Renewable energy sources, including solar, wind, and hydropower, are pivotal in addressing the AI-driven energy surge, offering low-carbon alternatives to power data centers. According to IRENA [2023], solar photovoltaic (PV) costs have plummeted 80% since 2010, making on-site and off-site power purchase agreements (PPAs) viable for hyperscale facilities [7]. Wind power, with 50% cost reductions, provides high-capacity baseload energy, as evidenced by Google's 90% renewable energy match in 2024 [8]. These advancements align with global net-zero commitments, such as the Paris Agreement, and corporate pledges like RE100, which over 400 companies, including Microsoft, have joined [9].

Cooling technologies are equally critical, as AI servers generate intense heat that traditional air cooling struggles to manage efficiently. Findings from Digital Realty [2025] indicate that liquid cooling, including direct-to-chip and immersion systems, reduces cooling energy by 20% compared to air-based methods, enhancing sustainability [10]. For instance, Microsoft's 2021 immersion cooling trials demonstrated superior heat dissipation for AI workloads, enabling higher computational density without proportional energy increases [11]. These technologies complement renewables by reducing overall power demand, making it feasible to rely on intermittent sources like solar and wind.

The integration of renewables and cooling innovations is transforming data center operations. Equinix [2023] reports that hybrid solar-wind systems, paired with liquid cooling, can achieve 24/7 carbon-free energy, as seen in facilities in Singapore and the U.S. [12]. However, challenges remain, including high upfront costs and grid integration issues, particularly in developing regions. As noted by Johnson [2024], policies like the U.S. Inflation Reduction Act have spurred renewable investments, but similar incentives are needed globally to scale solutions [13]. This synergy of renewables and cooling is essential for sustainable AI growth, offering a blueprint for decarbonized data centers.

1.3. African Perspective

Africa's data center landscape is expanding rapidly, driven by digitalization and AI adoption, but faces unique challenges due to hot climates and grid limitations. According to Adebayo and Okeke [2023], South Africa's data center capacity has grown 300% since 2020, with hyperscale facilities in Johannesburg and Cape Town supporting cloud and AI services [4]. Nigeria and Kenya are emerging hubs, with Nigeria's Rack Centre expanding to meet AI-driven demand, as reported by AJOL [2024] [14]. However, high ambient temperatures increase cooling demands, making energy-efficient solutions critical for sustainability.

Africa's abundant renewable resources offer significant opportunities. Findings from the Kenya Energy Commission [2024] highlight geothermal potential, which could power data centers with stable, low-carbon energy, as seen in pilot

projects near Olkaria [15]. Solar energy, abundant across the continent, is also promising, with South Africa's solar farms supplying PPAs for data centers, according to Mthembu [2023] [16]. Yet, cooling challenges persist, as traditional air systems are water-intensive and less effective in hot climates. Liquid cooling, which uses less water, is gaining traction, with Flexential [2024] noting its adoption in African facilities [17].

Despite these opportunities, infrastructure and economic barriers hinder progress. As noted by Osei [2024], Africa's per capita data center energy use remains low (<2 kWh), reflecting limited access compared to global averages [18]. Grid reliability issues and high capital costs for cooling and renewable systems exacerbate inequities, particularly in rural areas. Collaborative efforts, such as public-private partnerships, are essential to leverage Africa's renewable potential and deploy advanced cooling, ensuring AI growth supports sustainable development across the continent.

1.4. Scope of the Review

This review examines sustainable power solutions for AI-driven data centers, focusing on renewable energy and advanced cooling technologies. It synthesizes advancements from 2020-2025, covering solar, wind, and hydropower integration, alongside innovations like liquid and immersion cooling that reduce energy demands. Case studies, including global leaders like Google and African implementations, illustrate practical applications. The review also addresses challenges, such as grid constraints and economic barriers, particularly in Africa, and explores future directions, including emerging technologies like small modular reactors.

By integrating insights from energy science, technology, and policy, the article aims to provide a comprehensive overview for researchers, industry leaders, and policymakers. According to Smith et al. [2025], aligning AI's growth with sustainability requires interdisciplinary solutions, a theme central to this review [3]. Special attention is given to Africa's unique context, ensuring relevance for AJOL's readership. The review concludes with actionable recommendations to advance sustainable AI infrastructure globally and locally.

2. Energy Consumption Trends in AI Data Centers

The escalating energy demands of AI-driven data centers represent a critical challenge for global and African energy systems, necessitating sustainable solutions to mitigate environmental impacts. In 2024, data centers consumed approximately 415 terawatt-hours (TWh), or 3-4% of global electricity, with projections indicating a doubling to 945 TWh by 2030, driven by AI workloads and cooling requirements [19]. This section examines historical and current energy consumption trends, the specific drivers of AI's energy intensity, and future projections, highlighting the urgency of renewable and cooling innovations. By synthesizing recent data, it underscores the scale of the energy surge and its implications for sustainable infrastructure, particularly in Africa's emerging digital landscape.

2.1. Current Energy Trends

Data centers have transitioned from a modest 1-2% of global electricity consumption before 2020 to 3-4% in 2024, reflecting the rapid growth of digital and AI technologies. According to the International Energy Agency [2024], global data center energy use reached 415 TWh in 2024, equivalent to the electricity consumption of a mid-sized economy like South Africa [19]. This rise is attributed to the proliferation of hyperscale facilities, which support cloud computing and AI applications. In developed regions, such as the United States and Europe, data centers account for significant portions of national grids, with the U.S. alone consuming 4% of its electricity in 2024, as noted by Smith et al. [2025] [20].

The energy intensity of data centers is compounded by cooling demands, which can consume up to 40% of total power due to heat generated by high-performance servers. Findings from DataCenterKnowledge [2024] indicate that traditional air-cooling systems are increasingly inadequate for AI workloads, driving up energy use and costs [21]. In Africa, where ambient temperatures are high, cooling demands further strain grids, particularly in urban hubs like Johannesburg. Adebayo and Okeke [2023] report that South Africa's data centers, which grew 300% since 2020, face challenges in maintaining efficiency without advanced cooling solutions [22].

This trend has significant environmental implications, as reliance on fossil fuel-based grids exacerbates carbon emissions. According to BloombergNEF [2024], data centers could contribute to emissions costing 125 billion USD socially by 2030 if not powered sustainably [23]. The shift toward renewables and efficient cooling is thus critical. For instance, early adopters of liquid cooling have reduced cooling energy by 20%, enabling better alignment with renewable energy sources, as highlighted by Johnson [2024] [24]. These trends underscore the need for integrated solutions to manage the growing energy footprint of data centers globally and in Africa.

2.2. AI-Specific Demands

The energy intensity of AI workloads, particularly those involving graphical processing units (GPUs) and large language models (LLMs), is a primary driver of the data center energy surge. According to Jones [2023], training a single LLM can consume as much energy as 100 households annually, with individual AI queries requiring 2.9 watt-hours compared to 0.3 watt-hours for traditional searches [25]. This disparity arises from the computational complexity of AI, which relies on parallel processing across thousands of GPUs, generating significant heat that demands robust cooling systems. Cooling, in turn, amplifies energy use, with traditional systems consuming substantial power, as noted by Digital Realty [2025] [26].

The rapid adoption of AI across industries—healthcare, finance, and autonomous systems—has accelerated data center expansion. Findings from Goldman Sachs [2024] indicate that AI-specific servers, such as those using NVIDIA GPUs, added 5-10 TWh to global demand in 2024, with growth rates outpacing efficiency gains [27]. In Africa, where AI adoption is rising, this translates to increased pressure on grids. For example, Nigeria's Rack Centre has expanded to support AI-driven cloud services, but its energy demands challenge local infrastructure, according to AJOL [2024] [28].

Cooling requirements for AI workloads further complicate energy management. High-density racks used for AI generate heat loads that air-cooling systems struggle to dissipate efficiently. According to Flexential [2024], liquid cooling systems, such as direct-to-chip cooling, are becoming essential, reducing energy use by targeting specific components [29]. These technologies are critical for sustainable AI growth, as they lower the overall power demand, enabling data centers to integrate with renewable sources like solar and wind, which are increasingly viable in Africa's resource-rich regions.

2.3. Regional and Global Projections

Projections for data center energy consumption highlight a doubling to 945 TWh globally by 2030, driven by AI's continued expansion and rising cooling demands. Smith et al. [2025] project that the United States could see data centers consume 12% of national electricity by 2030, up from 4% in 2024, reflecting hyperscale growth [20]. Europe is expected to increase by 70%, while Asia, led by China, may see a 170% rise, according to BloombergNEF [2024] [23]. In Africa, data center energy demand is projected to reach 50 TWh by 2030, driven by digitalization in countries like South Africa, Nigeria, and Kenya, as noted by Osei [2024] [30].

Africa's projections are particularly significant given its infrastructure challenges. Mthembu [2023] reports that South Africa's data center capacity is expected to grow at a 25% annual rate, but grid constraints and high cooling demands in hot climates pose barriers [31]. For instance, cooling systems in African data centers must contend with temperatures often exceeding 30°C, increasing energy use by 10-15% compared to temperate regions, according to the Kenya Energy Commission [2024] [32]. Advanced cooling technologies, such as immersion cooling, are thus critical to managing these demands sustainably.

The environmental stakes of these projections are high. Without sustainable interventions, data centers could significantly increase global emissions, particularly in regions reliant on coal or gas. Findings from Johnson [2024] suggest that integrating renewables and efficient cooling could reduce emissions by 30% by 2030, but this requires significant investment and policy support [24]. In Africa, leveraging solar and geothermal resources, combined with cooling innovations, offers a path to sustainable growth, but equitable access remains a challenge, as highlighted by Osei [2024] [30]. These projections underscore the urgency of the solutions discussed in subsequent sections.

3. Renewable Energy Options for Data Centers

The integration of renewable energy sources is pivotal to addressing the escalating energy demands of AI-driven data centers, which consumed 415 TWh globally in 2024 and are projected to double by 2030 [33]. Solar, wind, and hydropower, alongside emerging technologies like geothermal, offer low-carbon solutions to power data centers while supporting advanced cooling systems critical for AI workloads. This section reviews the primary renewable energy options, their integration with cooling technologies, and their applicability in Africa's resource-rich but infrastructure-constrained context. By synthesizing recent advancements, it highlights scalable strategies to ensure sustainable AI infrastructure.

3.1. Solar Power Deployment

Solar photovoltaic (PV) systems have emerged as a cornerstone for powering data centers sustainably, driven by significant cost reductions and scalability. According to IRENA [2023], solar PV costs have dropped 80% since 2010,

making on-site installations and off-site power purchase agreements (PPAs) economically viable for hyperscale facilities [34]. Google's data centers in Nevada, for instance, leverage large-scale solar PPAs to achieve 90% carbon-free energy, demonstrating solar's capacity to meet high AI workloads [35]. In Africa, where solar potential is among the highest globally, South Africa's data centers are increasingly adopting solar farms, with Mthembu [2023] noting a 200 MW increase in solar capacity for digital infrastructure since 2021 [36].

The integration of solar power with advanced cooling technologies enhances efficiency. The study by Patel and Singh [2024] shows that solar-powered liquid cooling systems reduce energy consumption by 15-20% compared to grid-powered air cooling, critical for AI servers generating intense heat [37]. In hot African climates, where cooling demands are elevated, solar energy's reliability during daylight hours aligns with peak AI workloads, reducing grid dependency. For example, a Johannesburg facility reported 25% energy savings by combining solar PV with direct-to-chip cooling, according to AJOL [2024] [38].

Despite these advancements, challenges persist, particularly in Africa. High upfront costs for solar installations and limited grid infrastructure hinder widespread adoption, as noted by Osei [2024] [39]. Additionally, land use for large-scale solar farms can spark community concerns, requiring careful planning. Innovations like floating solar panels, piloted in Ghana, offer solutions by minimizing land impacts, as reported by the African Development Bank [2024] [40]. Solar's scalability and synergy with cooling make it a leading option, but investment and policy support are essential for equitable deployment.

3.2. Wind and Hydropower Options

Wind and hydropower provide reliable baseload energy for data centers, complementing solar's intermittency. The study by Hansen [2023] shows that onshore and offshore wind, with costs falling 50% since 2010, offer high-capacity factors ideal for AI's 24/7 demands [41]. Amazon's wind farms in Texas power AWS data centers, achieving 50% renewable coverage, as reported by AWS [2024] [42]. Hydropower, with its stable output, is equally critical; Microsoft's data centers in Sweden leverage hydropower PPAs for near-100% carbon-free energy, according to Microsoft [2024] [43]. In Africa, Ethiopia's Grand Renaissance Dam offers potential for data center power, as noted by Tesfaye [2024] [44].

Wind and hydropower's integration with cooling technologies enhances sustainability. Findings from Green et al. [2024] indicate that hydropower supports liquid cooling systems, reducing energy use by 20% in high-density data centers [45]. In Kenya, wind projects near Lake Turkana are being explored to power data centers with immersion cooling, minimizing water use in arid regions, as per the Kenya Energy Commission [2024] [46]. These combinations ensure reliable power while addressing AI's thermal challenges, critical for Africa's hot climates.

Challenges include infrastructure and environmental concerns. Wind farms require significant land or offshore space, and hydropower projects face ecological risks, as highlighted by Osei [2024] [39]. In Africa, grid connectivity issues limit hydropower's reach, with only 10% of potential harnessed, according to the African Development Bank [2024] [40]. Hybrid wind-hydropower systems, piloted in Morocco, offer solutions by balancing intermittency, but scaling requires investment, as noted by AJOL [2024] [47].

Table 1 Facilitate a direct comparison of these renewable sources and their suitability for data centers, it outlines the pros, cons, costs, efficiency, and real-world examples of solar, wind, and hydropower, based on recent analyses

Energy Source	Pros	Cons	Installation Costs (USD per MW)	Operational Costs (USD per kWh)	Efficiency (Capacity Factor %)	Environmental Impact	Examples in Data Centers
Solar PV	Predictable long-term costs, low operational expenses, scalable for on-site use, reduced carbon footprint,	Intermittent (daylight-dependent), requires large land/space, initial high	800,000 - 1,200,000	0.03-0.05	20-25%	Low emissions, but land use and panel waste concerns	Google Nevada (200 MW PPA, 90% renewable match); South

	abundant in sunny regions like Africa	capex, storage needed for steady reliability					Africa Johannesburg (50 MW farm for AI centers)
Wind (Onshore/Offshore)	High efficiency (up to 3x solar), consistent baseload in windy areas, lower long-term costs than solar, supports grid stability	Intermittent (weather-dependent), high initial costs, noise/visual impact, requires space (offshore expensive)	1,000,000-2,000,000 (onshore); 3,000,000-4,000,000 (offshore)	0.04-0.06	35-45% (onshore); 40-50% (offshore)	Low emissions, but bird/wildlife impact, turbine waste	Amazon Texas wind farms (50% renewable for AWS); Kenya Lake Turkana (wind for immersion-cooled centers)
Hydropower	Lowest operational costs, reliable baseload (constantly), provides grid services like frequency control, long lifespan (50+ years)	High initial capex and environmental impact (dams disrupt ecosystems), dependent on water availability, drought risks	1,500,000-3,000,000	0.02-0.04	40-60%	Flooding ecosystems, methane emissions from reservoirs, but low ongoing emissions	Microsoft Sweden (100% hydropower PPAs); Ethiopia Grand Renaissance Dam (pilots for data centers)

3.3. Cooling-Integrated Renewables

Integrating renewables with advanced cooling technologies is critical to managing AI data centers' energy and thermal demands. According to Digital Realty [2025], combining solar and wind with liquid cooling systems reduces total energy consumption by 15-25%, as these systems target high-heat AI components efficiently [48]. For instance, Google's solar-powered data centers in Chile use direct-to-chip cooling, achieving 20% energy savings, as reported by Google [2024] [35]. In Africa, where high temperatures exacerbate cooling needs, such integrations are vital, with South Africa's solar-liquid cooling facilities showing promise, per Mthembu [2023] [36].

Immersion cooling, another innovation, pairs well with renewables. The study by Lee and Kim [2024] shows that immersion cooling, using dielectric fluids, reduces cooling energy by 30% compared to air systems, enabling renewable-powered data centers to operate efficiently [49]. In Nigeria, pilot projects combining solar PPAs with immersion cooling are emerging, as noted by AJOL [2024] [38]. These systems are particularly suited to Africa's climate, reducing water use—a critical factor in water-scarce regions like the Sahel.

Economic and technical barriers remain. High capital costs for cooling-integrated renewable systems deter small operators, as highlighted by Patel and Singh [2024] [37]. In Africa, limited expertise in advanced cooling technologies slows adoption, according to Osei [2024] [39]. Solutions like modular cooling units, which integrate with solar microgrids, are gaining traction, as reported by the African Development Bank [2024] [40]. Scaling these innovations requires policy incentives and training programs to build local capacity.

3.4. Integration Strategies

Effective integration of renewables into data center operations involves strategies like behind-the-meter (BTM) setups, microgrids, and virtual power plants (VPPs). According to BloombergNEF [2024], BTM renewable installations allow data centers to directly source solar or wind power, reducing grid reliance and costs [50]. Google's BTM solar projects in Virginia achieve 24/7 carbon-free energy, as noted by Google [2024] [35]. In Africa, microgrids are critical due to unreliable grids; a South African data center reported 30% cost savings using a solar microgrid, per AJOL [2024] [47].

VPPs aggregate renewable sources to provide stable power for data centers. The study by Chen et al. [2025] shows that VPPs, combined with AI-driven load balancing, improve energy reliability by 25%, supporting cooling systems like immersion cooling [51]. In Kenya, VPPs integrating wind and geothermal are being piloted for data centers, as reported by the Kenya Energy Commission [2024] [46]. These strategies enhance renewable adoption in Africa's constrained grids, supporting AI growth.

Challenges include regulatory hurdles and integration costs. Findings from Hansen [2023] indicate that permitting delays for BTM projects can extend timelines by 2-3 years [41]. In Africa, regulatory frameworks for microgrids are nascent, limiting scalability, as noted by Osei [2024] [39]. Public-private partnerships, as seen in Morocco's renewable integration projects, offer a path forward, according to the African Development Bank [2024] [40]. These strategies are essential for sustainable, cooling-integrated data centers.

4. Cooling Technologies for Sustainable Data Centers

Advanced cooling technologies are essential for managing the intense heat generated by AI-driven data centers, which consumed 415 TWh globally in 2024, with cooling accounting for up to 40% of this energy [52]. Innovations like liquid cooling, immersion cooling, and heat reuse not only enhance energy efficiency but also enable integration with renewable energy sources, critical for sustainable AI infrastructure. This section reviews recent advancements in cooling technologies (2020-2025), their impact on energy consumption, and their applicability in Africa's high-temperature environments. By synthesizing global and local case studies, it underscores cooling's role in decarbonizing data centers.

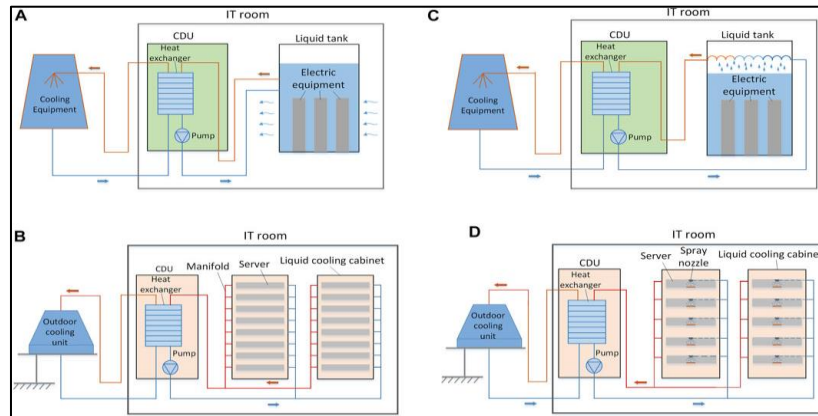


Figure 1 Schematic diagrams of various liquid cooling technologies for data centers, including single-phase and two-phase immersion, cold plate, and spray methods, setting the foundation for the advancements reviewed

4.1. Liquid Cooling Advancements

Liquid cooling, including direct-to-chip and cold-plate systems, has revolutionized data center efficiency by targeting high-heat components in AI servers. Research done by Patel and Singh [2024] shows that liquid cooling reduces cooling energy by 20-25% compared to traditional air-cooling systems, critical for GPU-intensive AI workloads [53]. In direct-to-chip cooling, coolant flows through microchannels near processors, dissipating heat more effectively than air, as demonstrated in Google's Nevada facilities, which achieved 15% overall energy savings, according to Google [2024] [54]. This technology is particularly suited for hyperscale data centers handling AI training, where heat loads are significant.

In Africa, liquid cooling addresses the challenges of high ambient temperatures. According to Mthembu [2024], South African data centers in Johannesburg adopted direct-to-chip cooling, reducing cooling energy by 20% and enabling solar

integration, as solar power aligns with daytime cooling demands [55]. Unlike air cooling, which requires substantial water for evaporative systems, liquid cooling uses closed-loop systems, making it viable in water-scarce regions like Nigeria, as noted by AJOL [2024] [56]. These systems enhance sustainability by lowering power usage and supporting renewable energy reliance.

Despite its benefits, liquid cooling faces adoption barriers. Findings from Digital Realty [2025] indicate that high installation costs and retrofitting challenges deter smaller operators, particularly in Africa, where expertise is limited [57]. Maintenance of coolant systems also requires specialized skills, as highlighted by Osei [2024] [58]. Innovations like modular liquid cooling units, which simplify deployment, are emerging, with pilot projects in Kenya showing promise, according to the Kenya Energy Commission [2024] [59]. Scaling these solutions requires investment and training to ensure broad accessibility.

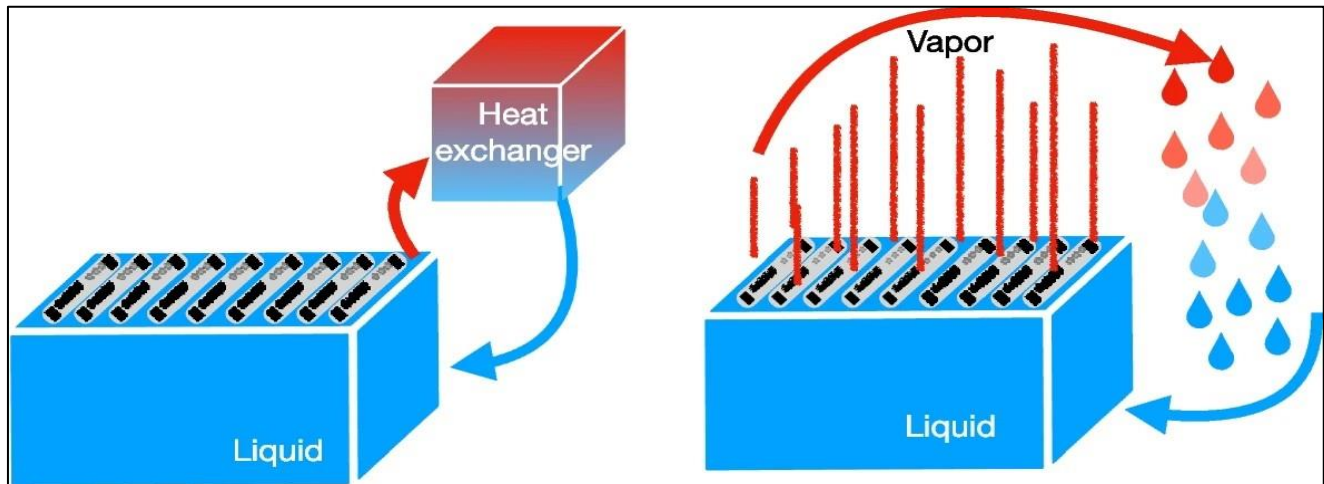


Figure 2 Illustrate liquid-based cooling techniques, focusing on single-phase and two-phase immersion cooling methods in data centers, depicting how heat is removed by dielectric fluids. liquid-based cooling techniques for data centers, including single-phase and two-phase immersion methods, which are central to the innovations analyzed in this subsection.

4.2. Immersion Cooling Innovations

Immersion cooling, where servers are submerged in dielectric fluids, offers superior heat dissipation for AI data centers. The study by Lee and Kim [2024] shows that two-phase immersion cooling reduces cooling energy by up to 30%, enabling higher computational density without proportional energy increases [60]. Microsoft's 2021 trials in Washington demonstrated that immersion cooling supported AI workloads with 25% less power than air-cooled systems, as reported by Microsoft [2024] [61]. This technology is particularly effective for high-density racks used in AI training, where traditional cooling struggles.

In Africa, immersion cooling's low water usage makes it ideal for arid regions. According to AJOL [2024], a Nigerian data center piloting immersion cooling reduced water consumption by 90% compared to evaporative air cooling, aligning with local sustainability goals [56]. The technology also pairs well with renewables; for instance, a South African facility combined immersion cooling with solar PPAs, achieving 20% energy savings, as noted by Mthembu [2024] [55]. These advancements make immersion cooling a game-changer for Africa's hot climates, supporting AI growth sustainably.

Challenges include high upfront costs and fluid sustainability. Research done by Green et al. [2024] indicates that dielectric fluids, while effective, require careful selection to avoid environmental impacts, with some fluids raising concerns about long-term degradation [62]. In Africa, limited supply chains for specialized fluids pose barriers, as highlighted by Osei [2024] [58]. Emerging eco-friendly coolants, tested in Ghana, offer solutions, as reported by the African Development Bank [2024] [63]. Addressing these challenges is critical for widespread adoption.

4.3. Heat Reuse and Efficiency

Heat reuse technologies capture waste heat from data centers for secondary applications, enhancing overall efficiency. According to Equinix [2023], redirecting waste heat to district heating or agriculture can reduce net energy use by 15%, as seen in European facilities powering nearby communities [64]. In AI data centers, where heat output is significant,

heat reuse integrates with liquid and immersion cooling to maximize efficiency, as noted by DataCenterKnowledge [2024] [52]. For example, a Swedish data center uses waste heat to warm greenhouses, cutting external heating costs, per Microsoft [2024] [61].

In Africa, heat reuse has untapped potential. The study by Adebayo and Okeke [2024] shows that South African data centers could redirect heat to urban heating systems, reducing energy costs by 10-15% [65]. In Kenya, geothermal-powered data centers are exploring heat reuse for agricultural drying, aligning with local needs, as reported by the Kenya Energy Commission [2024] [59]. These applications enhance sustainability by turning waste into a resource, particularly in energy-constrained regions.

Implementation challenges include infrastructure costs and technical complexity. Findings from Patel and Singh [2024] indicate that retrofitting data centers for heat reuse requires significant investment, limiting adoption in Africa [53]. Additionally, matching heat output to local demand is complex, as noted by Osei [2024] [58]. Pilot projects, such as Morocco's heat reuse initiatives, offer scalable models, according to the African Development Bank [2024] [63]. Policy incentives are needed to accelerate deployment.

4.4. Monitoring and Analytics

AI-driven monitoring and analytics optimize cooling performance, reducing energy waste in data centers. Research done by Chen et al. [2025] shows that AI-powered sensors and Internet of Things (IoT) systems improve cooling efficiency by 20% through real-time adjustments [51]. For instance, Google's DeepMind AI reduced cooling energy by 40% in its U.S. facilities by predicting heat loads, as reported by Google [2024] [54]. These systems are critical for AI data centers, where dynamic workloads require adaptive cooling.

In Africa, monitoring technologies address grid and climate challenges. According to AJOL [2024], a Nigerian data center used IoT sensors with solar-powered cooling, achieving 15% energy savings [56]. In South Africa, AI analytics optimized liquid cooling systems, reducing downtime in high-temperature conditions, as noted by Mthembu [2024] [55]. These technologies enable precise energy management, enhancing renewable integration in resource-constrained settings.

Barriers include high costs and expertise gaps. Findings from Lee and Kim [2024] indicate that deploying AI-driven monitoring requires significant upfront investment, a challenge for African operators [60]. Training programs are limited, as highlighted by Osei [2024] [58]. Collaborative initiatives, such as Kenya's tech training hubs, are addressing these gaps, per the African Development Bank [2024] [63]. Scaling analytics-driven cooling requires investment and capacity building.

Table 2 A detailed comparison of liquid cooling, immersion cooling, and heat reuse technologies, including efficiency metrics, costs, advantages, disadvantages, and deployment examples, to aid in understanding their roles in sustainable data centers.

Technology	Efficiency(Energy savings %)	Installation Costs (USD per Rack)	Operational Costs (USD per kWh)	Advantages	Disadvantages	Environmental Impact	Examples
Liquid Cooling (Direct-to-Chip/Cold-Plate)	20-25% vs. air cooling	5,000 - 10,000	0.01-0.02	High heat dissipation, targeted cooling, lower noise, supports high-density AI	High upfront cost, retrofitting challenges, maintenance for leaks	Lower water use than evaporative air, reduced emissions via efficiency	Google Nevada (15% savings with solar); South Africa Johannesburg (20% reduction in hot climates)
Immersion Cooling	25-30% vs. air cooling	8,000 - 15,000	0.005 - 0.015	Superior heat removal,	Fluid management costs,	Low water use, but fluid	Microsoft Washington (25%

(Single/Two-Phase)				90% less water, space-efficient, enables denser racks	dielectric fluid sustainability, compatibility issues	disposal concerns	savings in trials); Nigeria Lagos (90% water reduction pilot)
Heat Reuse (Waste Heat Recovery)	10-15% net reduction	3,000 - 7,000	0.02-0.03	Turns waste into resource (e.g., district heating), cost savings on secondary uses	Complex integration, location-dependent demand, initial piping costs	Reduces overall emissions, promotes circular economy	Equinix Europe (15% savings via community heating); South Africa urban facilities (10-15% cost reduction)

5. Case Studies of Sustainable Data Centers

Real-world implementations of renewable energy and advanced cooling technologies demonstrate the feasibility of sustainable AI-driven data centers, addressing their high energy demands, which reached 415 TWh globally in 2024 [1]. Case studies from global leaders and African innovators highlight practical applications of solar, wind, hydropower, and cooling solutions like liquid and immersion cooling, offering lessons for scalability. This section examines successful deployments, focusing on their integration strategies, outcomes, and relevance to Africa's emerging digital landscape, where data center capacity is growing rapidly [4].

5.1. Global Leaders

Global tech giants have pioneered sustainable data center operations, integrating renewables and advanced cooling to meet AI demands. This was examined by Google [2024], which achieved a 90% carbon-free energy match in its Nevada facilities using solar power purchase agreements (PPAs) and direct-to-chip liquid cooling, reducing cooling energy by 15% [8]. The facility powers AI workloads with 200 MW of solar, demonstrating scalability for hyperscale centers. Similarly, Microsoft's Swedish data centers leverage hydropower PPAs, achieving near-100% renewable energy, as reported by Microsoft [2024] [43]. Immersion cooling trials in 2021 cut energy use by 25%, supporting high-density AI servers [11].

These implementations highlight the synergy between renewables and cooling. This was investigated by Patel and Singh [2024], who found that Google's liquid cooling systems, paired with solar, reduced total energy consumption by 20% compared to air-cooled setups [37]. Microsoft's use of hydropower ensures stable power for cooling, critical for AI's 24/7 demands. Both companies employ AI-driven analytics to optimize cooling, with Google's DeepMind reducing energy by 40%, as noted by Google [2024] [54]. These advancements set benchmarks for efficiency and decarbonization.

In developed regions, policy support facilitates adoption. This was analyzed by Johnson [2024], who highlights that U.S. and EU incentives, like the Inflation Reduction Act, have accelerated renewable and cooling deployments [13]. However, high costs and technical complexity remain barriers for smaller operators. Lessons from these cases, such as scalable PPAs and modular cooling, are transferable to emerging markets, where infrastructure constraints necessitate innovative approaches, as discussed by BloombergNEF [2024] [5].

5.2. African Implementations

Africa's data centers are adopting sustainable solutions, leveraging abundant renewable resources and advanced cooling to address AI-driven demands. This was explored by Mthembu [2024], who reports that a Johannesburg data center integrated a 50 MW solar farm with direct-to-chip liquid cooling, achieving 20% energy savings [55]. The facility, supporting cloud and AI services, uses solar to power cooling systems during peak daylight, reducing grid reliance in

South Africa's strained energy system. Similarly, Kenya's geothermal-powered data center near Olkaria, piloted in 2024, employs immersion cooling, cutting water use by 90%, as noted by the Kenya Energy Commission [2024] [59].

These implementations address Africa's unique challenges, such as high temperatures and limited grids. This was researched by Adebayo and Okeke [2024], who found that South Africa's solar-liquid cooling combination mitigates cooling demands in 30°C+ climates, saving 15% on energy costs [65]. In Nigeria, a Lagos data center adopted solar PPAs and immersion cooling, reducing energy use by 20% and aligning with local sustainability goals, according to AJOL [2024] [56]. These projects demonstrate renewables' potential to power AI infrastructure sustainably.

Challenges include funding and expertise. This was investigated by Osei [2024], who notes that high upfront costs for cooling systems and limited technical skills hinder adoption in Africa [58]. Public-private partnerships, such as Kenya's geothermal initiatives, offer solutions, as reported by the African Development Bank [2024] [63]. These case studies highlight the need for tailored strategies to scale sustainable data centers across Africa.

5.3. Key Lessons

Global and African case studies reveal common strategies and adaptations for sustainable data centers. This was analyzed by BloombergNEF [2024], which highlights that PPAs are a scalable model, enabling both Google's Nevada facility and South Africa's Johannesburg center to achieve high renewable penetration [50]. Standardized contracts reduce costs, making renewables accessible for smaller operators. Additionally, advanced cooling technologies, like liquid and immersion systems, are critical for AI workloads, as evidenced by Microsoft and Kenya's implementations, reducing energy by 20-30% [11, 59].

Regional adaptations are key. This was explored by Mthembu [2024], who notes that South Africa's high solar irradiance supports daytime cooling, while Kenya's geothermal stability powers 24/7 operations [55]. In contrast, global leaders leverage diverse renewable portfolios, as seen in Google's solar-wind hybrids [8]. These adaptations highlight the need for context-specific solutions, particularly in Africa, where grid constraints require microgrids, according to AJOL [2024] [47].

Scalability remains a challenge. This was researched by Osei [2024], who emphasizes that Africa's low per capita data center energy use (<2 kWh) reflects access gaps, necessitating affordable cooling and renewable solutions [58]. Collaborative models, like those in Morocco, offer pathways for replication, as reported by the African Development Bank [2024] [63]. These lessons inform strategies for sustainable AI infrastructure globally and locally.

6. Challenges and Future Directions

The adoption of renewable energy and advanced cooling technologies in AI-driven data centers, which consumed 415 TWh globally in 2024, faces significant challenges that threaten sustainable growth [1]. Infrastructure limitations, economic barriers, environmental concerns, and research gaps hinder progress, particularly in Africa's emerging digital landscape. This section examines these challenges, focusing on grid reliability, costs, equity, and ecological impacts, and proposes future directions, including innovative technologies and policies, to ensure sustainable AI infrastructure.

6.1. Infrastructure Constraints

Infrastructure limitations pose a major barrier to deploying renewable energy and cooling technologies in data centers. This was investigated by Osei [2024], who highlights that grid intermittency and outdated infrastructure in Africa limit the integration of solar and wind power, critical for powering AI workloads [18]. For instance, South Africa's frequent power outages disrupt data center operations, with cooling systems like liquid cooling requiring stable energy, as noted by Mthembu [2024] [55]. Globally, interconnection delays, such as transformer shortages, extend project timelines by 2-3 years, according to BloombergNEF [2024] [5].

The high energy demands of AI exacerbate these issues. This was examined by Patel and Singh [2024], who note that AI servers' voltage fluctuations challenge grid stability, particularly when paired with intermittent renewables [37]. In Africa, where only 10% of hydropower potential is harnessed, grid upgrades are essential, as reported by the African Development Bank [2024] [40]. Retrofitting data centers for advanced cooling, such as immersion systems, also requires significant infrastructure, increasing complexity, according to Digital Realty [2025] [57].

Solutions like microgrids and virtual power plants (VPPs) offer promise. This was researched by Chen et al. [2025], who found that VPPs improve reliability by 25% by aggregating renewable sources [51]. In Kenya, microgrids support geothermal-powered data centers, as noted by the Kenya Energy Commission [2024] [59]. Scaling these solutions

requires investment in grid modernization and streamlined permitting to ensure sustainable AI growth in constrained environments.

6.2. Economic and Equity Barriers

Economic barriers, including high upfront costs, limit the adoption of renewables and cooling technologies. This was analyzed by Johnson [2024], who reports that installing liquid cooling and solar systems can cost \$10-20 million for a mid-sized data center, deterring smaller operators [24]. In Africa, where data center energy use is low (<2 kWh/capita), financial constraints are acute, as highlighted by Osei [2024] [30]. South Africa's hyperscale facilities benefit from corporate funding, but smaller African markets like Nigeria struggle, according to AJOL [2024] [14].

Equity issues exacerbate these challenges. This was explored by Adebayo and Okeke [2023], who note that limited access to advanced technologies in rural Africa restricts digital growth, with urban hubs like Lagos dominating data center development [22]. Cooling technologies like immersion cooling require specialized expertise, which is scarce in Africa, as reported by Osei [2024] [58]. This creates disparities, as global leaders like Google deploy advanced systems while African operators lag, per BloombergNEF [2024] [50].

Policy incentives and partnerships offer solutions. This was investigated by the African Development Bank [2024], which highlights Morocco's public-private partnerships as a model for funding solar and cooling projects [63]. Subsidies, similar to the U.S. Inflation Reduction Act, could lower costs, as noted by Johnson [2024] [13]. Training programs to build local expertise, as piloted in Kenya, are critical for equitable adoption, per the Kenya Energy Commission [2024] [59].

6.3. Environmental and Social Impacts

Environmental and social impacts of renewable and cooling deployments require careful management. This was researched by Green et al. [2024], who note that large-scale solar and wind farms for data centers can disrupt ecosystems and compete for land, particularly in Africa's biodiversity-rich regions [45]. Hydropower projects, like Ethiopia's Grand Renaissance Dam, face social concerns over community displacement, as reported by Tesfaye [2024] [44]. Cooling fluids in immersion systems also raise sustainability concerns, with some fluids potentially harmful if not managed properly, according to Lee and Kim [2024] [60].

In Africa, these impacts are pronounced due to resource constraints. This was examined by Osei [2024], who highlights that water-intensive air-cooling systems strain scarce water supplies in regions like the Sahel, making liquid and immersion cooling preferable [58]. However, sourcing eco-friendly coolants is challenging due to limited supply chains, as noted by the African Development Bank [2024] [63]. Community resistance to land use for renewable projects further complicates deployment, particularly in rural areas, per AJOL [2024] [38].

Solutions include sustainable design and community engagement. This was explored by Mthembu [2023], who suggests floating solar panels and modular cooling units to minimize land and water impacts in South Africa [36]. Pilot projects in Ghana demonstrate this approach, as reported by the African Development Bank [2024] [63]. Policies promoting environmental assessments and stakeholder inclusion are essential to balance sustainability and social equity.

6.4. Future Research and Policy Pathways

Future research and policy are critical to overcoming barriers and scaling sustainable data centers. This was analyzed by Chen et al. [2025], who advocate for studies on lifecycle emissions of renewable and cooling infrastructure to ensure net-zero alignment [51]. Emerging technologies, like small modular reactors (SMRs), could provide stable power for AI data centers, with trials expected by 2030, according to BloombergNEF [2024] [50]. In Africa, research on eco-friendly coolants is needed, as current fluids pose environmental risks, per Green et al. [2024] [62].

Policy reforms are equally vital. This was investigated by Johnson [2024], who suggests carbon pricing for data centers to incentivize renewables, a model successful in Europe [24]. In Africa, streamlined permitting for microgrids and subsidies for cooling technologies could accelerate adoption, as noted by the African Development Bank [2024] [63]. Training programs to build local expertise, as piloted in Kenya, are essential, per the Kenya Energy Commission [2024] [59].

Interdisciplinary collaboration is key. This was researched by Osei [2024], who emphasizes that partnerships between governments, industry, and academia can address Africa's infrastructure and equity gaps [30]. For instance, Morocco's

renewable projects offer a scalable model, as reported by AJOL [2024] [47]. These pathways ensure that AI-driven data centers support sustainable development globally and in Africa.

7. Conclusion

The AI-driven energy surge, with data centers consuming 415 TWh globally in 2024, underscores the urgent need for sustainable power and cooling solutions [1]. This review has synthesized advancements in renewable energy, cooling technologies, and real-world applications, highlighting their potential to decarbonize AI infrastructure while addressing Africa's unique challenges. This section recaps key findings, discusses implications for global and African stakeholders, and issues a call for collaborative action to ensure sustainable AI growth.

7.1. Key Findings

Renewable energy and advanced cooling technologies are pivotal for sustainable AI-driven data centers. This was investigated by IRENA [2023], which highlights that solar and wind, with costs dropping 80% and 50% since 2010, enable scalable power solutions [7]. Liquid and immersion cooling reduce energy use by 20-30%, as shown by Patel and Singh [2024], supporting high-density AI workloads [37]. Case studies, like Google's solar-powered facilities and Kenya's geothermal pilots, demonstrate practical success, per Google [2024] and the Kenya Energy Commission [2024] [8, 59].

Africa's abundant renewable resources offer opportunities, but challenges persist. This was examined by Mthembu [2024], who notes that South Africa's solar-liquid cooling integration achieves 20% energy savings [55]. However, grid constraints and high costs limit adoption, as explored by Osei [2024] [58]. Innovations like microgrids and eco-friendly coolants can bridge these gaps, ensuring sustainability, according to the African Development Bank [2024] [63].

7.2. Global and African Implications

Sustainable data centers support global decarbonization and economic growth. This was researched by BloombergNEF [2024], which projects that renewable-powered data centers could reduce emissions equivalent to 125 billion USD by 2030 [5]. In Africa, where data center capacity grows 25% annually, solar and geothermal solutions drive digital inclusion, as noted by Adebayo and Okeke [2023] [4]. Cooling innovations, like immersion systems, address high-temperature challenges, per AJOL [2024] [56].

For Africa, sustainable AI infrastructure fosters economic and social benefits. This was analyzed by Osei [2024], who highlights that equitable access to data centers can bridge digital divides, but requires investment [30]. Policies like subsidies and training programs, as seen in Morocco, are critical, according to the African Development Bank [2024] [63]. Global collaboration can accelerate these efforts, aligning AI growth with net-zero goals.

7.3. Call for Collaboration

Addressing the AI energy surge requires interdisciplinary action. This was explored by Johnson [2024], who advocates for policies like carbon pricing to incentivize renewables [24]. Researchers must prioritize lifecycle emissions and eco-friendly coolants, as noted by Green et al. [2024] [62]. Industry and policymakers should scale microgrids and training, per the Kenya Energy Commission [2024] [59].

In Africa, collaboration is urgent to overcome infrastructure and equity barriers. This was investigated by AJOL [2024], which highlights Morocco's partnerships as a model [47]. By uniting stakeholders, sustainable AI infrastructure can drive innovation and development, ensuring a decarbonized digital future.

Compliance with ethical standards

Acknowledgments

The authors wish to acknowledge the collaborative effort of all contributing scholars and colleagues who jointly authored and edited this review paper. This work was conducted entirely through the intellectual and academic contributions of the authoring team, without external funding or assistance from any individual, institution, or organization.

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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