



Developing Environmental Sustainability Frameworks for Managing Energy, Water, and Emissions Impacts of Expanding Data Centres

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ABSTRACT :

The accelerating expansion of digital infrastructure, driven by cloud computing, artificial intelligence, high-performance computing, and increasingly data-intensive services, has intensified the environmental pressures associated with data centre development. Rising electricity demand, substantial cooling-water requirements, and greenhouse gas emissions increasingly require sustainability approaches that consider interconnected resource impacts rather than isolated efficiency measures. This study develops an integrated environmental sustainability framework for managing the energy, water, and emissions impacts of expanding data centres. The framework evaluates energy efficiency, renewable electricity integration, water usage effectiveness, advanced cooling technologies, carbon intensity, resource availability, and operational performance across data centre systems. It further examines renewable procurement, energy storage, workload optimization, water recycling, liquid cooling, waste-heat recovery, and carbon-aware computing as complementary intervention strategies. Particular emphasis is placed on identifying trade-offs between energy consumption, water conservation, emissions reduction, reliability, and computational growth. By integrating measurable environmental indicators with operational and infrastructure strategies, the proposed framework supports systematic sustainability assessment, informed resource-management decisions, and environmentally responsible expansion of data centre infrastructure.

Keywords: Data Centres; Environmental Sustainability; Energy Efficiency; Water Management; Carbon Emissions; Sustainable Digital Infrastructure

1. INTRODUCTION

1.1 Expansion of Data Centres and Growing Environmental Pressures

Rapid digitalization is accelerating data centre development as artificial intelligence, cloud computing, high-performance computing, streaming services, Internet-of-Things applications, and enterprise digitalization increase requirements for computational capacity [1]. Supporting these activities requires expanding servers, storage, networking systems, specialized processors, and associated physical infrastructure [2]. Increasing computing density consequently raises electricity consumption both directly through IT equipment and indirectly through cooling, power conversion, and auxiliary systems [3]. Greater server heat generation simultaneously increases cooling requirements, which can create substantial water demand where evaporative or water-dependent heat-rejection technologies are employed [4]. Electricity consumption and infrastructure expansion also contribute to greenhouse gas emissions through grid electricity, backup generation, construction, equipment manufacturing, and associated supply chains [5]. These environmental pressures are interconnected rather than independent: computing demand affects electricity use, electricity use generates heat, heat drives cooling requirements, cooling influences water and energy consumption, and both operational and infrastructure requirements influence emissions [6]. Data centre sustainability therefore represents an interconnected energy–water–carbon challenge [2].

1.2 Limitations of Fragmented Data Centre Sustainability Approaches

Assessing energy efficiency, water conservation, and carbon reduction independently can produce incomplete or potentially counterproductive sustainability decisions [7]. A cooling technology may reduce electricity consumption by exploiting evaporative heat rejection while simultaneously increasing freshwater consumption and local water-stress exposure [8]. Conversely, replacing water-intensive cooling with dry cooling can reduce direct water requirements while increasing electricity consumption under certain climatic and operating conditions [6]. If that additional electricity is supplied by carbon-intensive generation, a water-conservation measure can consequently increase greenhouse gas emissions [9]. Similar interactions arise when renewable generation, energy storage, cooling systems, and computational efficiency are assessed without considering lifecycle impacts and infrastructure requirements [4]. Improvements in relative efficiency indicators can also obscure increasing absolute resource consumption when rapid facility expansion outpaces efficiency gains [5]. Fragmented assessment therefore risks shifting environmental burdens between energy, water, and carbon dimensions rather than reducing overall impact [7]. Effective sustainability management requires identifying these interactions, quantifying trade-offs, and evaluating mitigation strategies within a unified environmental framework [3].

1.3 Aim, Scope, and Analytical Direction

This article develops an integrated environmental sustainability framework for simultaneously evaluating and managing the energy, water, and emissions impacts associated with expanding data centre infrastructure [1]. The framework begins with resource consumption by examining electricity requirements, direct and indirect water use, and carbon-generating activities across facility operations and infrastructure lifecycles [4]. Environmental intensity provides a second analytical dimension by relating resource consumption to computational activity, grid conditions, water scarcity, and emissions characteristics [7]. Operational efficiency incorporates computing performance, cooling effectiveness, power management, and opportunities for reducing unnecessary resource demand [6]. Infrastructure constraints include grid capacity, renewable availability, climate, water resources, facility scale, and reliability requirements [8]. Mitigation strategies encompass efficiency improvements, renewable electricity, alternative water sources, advanced cooling, storage, workload flexibility, and resource recovery [5]. Performance indicators are then required to measure absolute consumption, efficiency, environmental exposure, and lifecycle impacts [9]. Integrated decision-making ultimately connects these dimensions so that improvements in one environmental domain are evaluated against their consequences for energy, water, emissions, reliability, and infrastructure sustainability [3].

2. ENVIRONMENTAL FOOTPRINT OF EXPANDING DATA CENTRE INFRASTRUCTURE

2.1 Energy-Intensive Nature of Data Centre Operations

Data centres are inherently energy-intensive because electricity is required continuously across computing and supporting infrastructure [6]. Servers consume power through processors, memory, accelerators, and internal components, while storage systems and networking equipment sustain data processing, transfer, and availability [11]. Computational intensity strongly influences these requirements because artificial intelligence and high-performance workloads can increase processor utilization and rack-level power density [9]. Utilization is equally important: poorly utilized servers may continue consuming substantial electricity despite delivering limited computational output [14]. Beyond IT equipment, cooling systems require electricity for chillers, pumps, fans, cooling towers, and air-handling equipment that remove server-generated heat [8]. Power-conversion and distribution systems, including uninterruptible power supplies and transformers, create additional consumption and conversion losses [12]. Backup infrastructure maintains operational continuity during grid interruptions, while lighting, security, monitoring, and other auxiliary systems contribute further facility loads [10]. Because data centres frequently operate continuously and require high availability, these interconnected systems create persistent electricity demand [13]. Increasing computational capacity therefore expands both direct IT electricity consumption and the supporting infrastructure required to maintain reliable operating conditions [7].

2.2 Water Dependence and Cooling Requirements

Water consumption is closely connected to data centre thermal management because electricity consumed by computing equipment is ultimately converted largely into heat that must be removed [8]. Cooling towers reject heat through evaporation and therefore require continuous makeup water to replace evaporative losses, drift, and blowdown [11]. Direct evaporative and adiabatic cooling can similarly consume water while reducing dependence on mechanical refrigeration under suitable environmental conditions [6]. Data centres also create indirect water demand because electricity generation can require water for cooling, steam-cycle processes, and other power-plant operations [14]. Consequently, cooling technologies that reduce direct facility water consumption may still carry an upstream water footprint through increased electricity requirements [12]. Climate substantially influences these relationships because temperature and humidity determine opportunities for economization, evaporative cooling, and other heat-rejection approaches [13]. Facility location is therefore critical: identical cooling architectures can produce different environmental consequences under different climatic and hydrological conditions [9]. Sustainable cooling decisions should consider local water availability, seasonal scarcity, watershed stress, facility scale, cooling architecture, and electricity-system characteristics simultaneously [10].

2.3 Carbon and Wider Environmental Consequences

Data centre carbon emissions are strongly influenced by electricity consumption and the generation sources supplying that electricity [7]. Operational emissions can therefore vary considerably between facilities with similar energy requirements but different grid carbon intensities or renewable-energy access [11]. Direct emissions arise from sources controlled at the facility, including combustion of diesel or other fuels in backup generators [13]. Indirect operational emissions primarily arise from purchased electricity used by servers, cooling systems, networking equipment, power distribution, and auxiliary infrastructure [8]. Environmental assessment should additionally consider embodied impacts associated with constructing data centre buildings and manufacturing servers, batteries, cooling systems, electrical equipment, and renewable-energy infrastructure [12]. Extraction and processing of materials, transportation, equipment replacement, and eventual disposal or recycling further extend environmental consequences across supply chains [10]. Focusing exclusively on operational electricity can therefore underestimate the total footprint of expanding digital infrastructure [14]. Carbon assessment should instead connect direct emissions, electricity-related emissions, embodied impacts, infrastructure expansion, and equipment lifecycles while recognizing their interaction with energy efficiency, water consumption, cooling technology, and broader resource pressures [9].

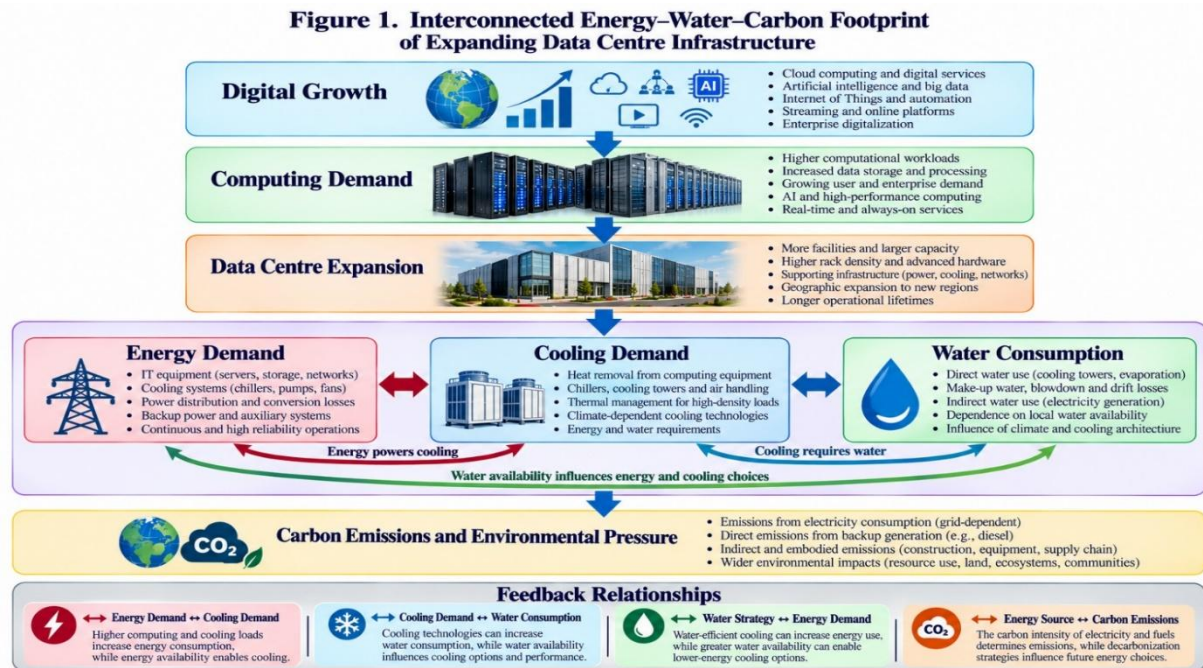


Figure 1. Interconnected Energy–Water–Carbon Footprint of Expanding Data Centre Infrastructure

3. ENERGY SUSTAINABILITY AND ELECTRICITY DEMAND MANAGEMENT

3.1 Data Centre Energy Demand and Operational Efficiency

Data centre energy sustainability begins with reducing unnecessary electricity consumption while maintaining computational performance and reliability [13]. Server utilization is particularly important because underutilized equipment can consume substantial electricity despite delivering limited useful computing output [15]. Virtualization, workload consolidation, efficient processors, and dynamic power management can increase computational output relative to energy consumption [18]. Workload characteristics also influence demand because artificial intelligence, high-performance computing, storage, and network-intensive applications impose different utilization and power-density profiles [14]. Beyond computing equipment, cooling systems create significant additional loads, while uninterruptible power supplies, transformers, and distribution equipment introduce conversion losses [17]. Redundancy requirements further increase installed infrastructure because data centres maintain reserve electrical and cooling capacity to satisfy reliability objectives [20]. PUE provides a facility-level measure comparing total data centre energy with energy consumed by IT equipment [16]. However, improving PUE does not necessarily mean that total electricity consumption decreases. A rapidly expanding facility can achieve lower PUE while consuming more electricity overall [19]. Sustainability assessment should therefore distinguish relative infrastructure efficiency from absolute electricity demand and evaluate both alongside computational productivity and facility growth [13].

3.2 Renewable Energy Integration and Grid Interaction

Renewable-energy integration can reduce the carbon intensity associated with data centre electricity consumption while changing how facilities interact with power systems [14]. On-site solar or wind generation can directly supply facility loads where sufficient land, renewable resources, and infrastructure are available [17]. However, large data centres frequently require substantially more continuous electricity than on-site resources can reliably provide, making off-site procurement important [20]. Power purchase agreements and other renewable-electricity procurement mechanisms can support larger renewable projects and associate facility demand with low-carbon generation [15]. Battery storage can improve integration by storing electricity during periods of renewable surplus and discharging during periods of lower generation or higher grid demand [18]. Microgrids can coordinate on-site generation, storage, backup resources, and controllable loads while strengthening local resilience [13]. Grid-interactive data centres can additionally participate in demand response and other flexibility services [19]. Nevertheless, solar and wind output varies temporally, whereas computing loads can remain continuous [16]. Annual renewable procurement therefore does not necessarily ensure that renewable electricity is available when consumption occurs. Effective integration requires attention to hourly generation profiles, storage capability, grid conditions, reliability requirements, and temporal matching between renewable supply and electricity demand [20].

3.3 Demand Flexibility and Carbon-Aware Computing

Demand flexibility provides an additional pathway for coordinating data centre electricity consumption with grid conditions and renewable availability [13]. Workload shifting can move delay-tolerant computational tasks toward periods when electricity demand is lower or renewable generation is more

abundant [18]. Demand-response programs can similarly reduce or reschedule selected facility loads during periods of grid stress, helping limit peak demand while supporting power-system reliability [15]. Dynamic scheduling can continuously allocate workloads according to computational capacity, electricity conditions, service requirements, and energy availability [20]. Where multiple facilities are available, geographical workload redistribution can transfer suitable computation toward locations experiencing lower-carbon electricity or greater renewable generation [17]. Energy storage complements these strategies by separating electricity consumption from immediate generation and supporting peak-load management [16]. Carbon-aware computing extends demand management by incorporating real-time or forecast grid carbon intensity into workload scheduling decisions [19]. However, not all workloads are flexible because latency, security, data sovereignty, reliability, and service-level requirements can restrict temporal or geographical shifting [14]. Coordinated demand flexibility should therefore identify suitable workloads while protecting essential services, enabling data centres to reduce emissions, improve renewable utilization, moderate peak demand, and contribute to grid stability [13].

Table 1. Energy Sustainability Strategies and Performance Implications for Data Centre Operations

Strategy	Primary Objective	Energy Impact	Grid Impact	Carbon Benefit	Key Limitation
Server optimization	Reduce computing waste	Lower demand	Reduced load	Moderate	Workload constraints
Renewable procurement	Decarbonize electricity	Neutral/indirect	Variable	High	Temporal matching
Battery storage	Load balancing	Efficiency dependent	High benefit	Context dependent	Cost/material footprint
Demand response	Increase flexibility	Shifts consumption	High	Moderate–high	Service requirements
Carbon-aware scheduling	Optimize timing	Redistributes demand	Positive	High	Workload flexibility

4. WATER SUSTAINABILITY AND COOLING-SYSTEM EFFICIENCY

4.1 Sources and Measurement of Data Centre Water Consumption

Data centre water consumption includes both water used directly within facility operations and indirect water associated with electricity generation [18]. Direct consumption primarily occurs through cooling towers, evaporative cooling, humidification, and other water-dependent thermal-management processes [20]. Indirect consumption occurs upstream where power plants require water for steam generation, cooling, and associated electricity-production processes [23]. Water Usage Effectiveness (WUE) provides a facility-level indicator relating annual water consumption to IT-equipment energy use and can support comparison of operational water efficiency [21]. However, WUE alone does not reveal absolute consumption or the environmental significance of withdrawing water from a particular location [24]. Freshwater dependency is therefore important for distinguishing potable or freshwater consumption from reclaimed, recycled, or alternative supplies [26]. Water-stress considerations further contextualize consumption according to local scarcity, drought exposure, ecological requirements, and competing municipal, agricultural, and industrial demands [22]. Comprehensive assessment should consequently combine WUE with absolute water consumption, freshwater dependency, indirect electricity-related water requirements, and location-specific water-stress indicators [25].

4.2 Cooling Technologies and Energy–Water Trade-offs

Cooling technology selection strongly influences the balance between data centre electricity consumption and water demand [18]. Conventional air cooling circulates conditioned air through data halls and can avoid substantial direct water consumption when paired with dry heat rejection, although mechanical refrigeration may increase electricity requirements [21]. Evaporative cooling exploits water evaporation to remove heat efficiently and can reduce compressor electricity demand under suitable climatic conditions, but it increases consumptive water use [23]. Chilled-water systems provide effective heat removal for large facilities, although their water and energy requirements depend on chiller efficiency and whether heat rejection uses cooling towers or dry systems [20]. Direct-to-chip liquid cooling transfers heat close to processors and is increasingly relevant for high-density computing because liquids provide effective heat transport [24]. Immersion cooling similarly places computing equipment in dielectric fluids, potentially reducing dependence on conventional air-handling infrastructure [26]. Closed-loop configurations can limit ongoing water losses by recirculating cooling fluids [22]. Nevertheless, liquid and immersion systems still require ultimate heat rejection. Technology selection should therefore consider climatic conditions, computing density, electricity consumption, direct water use, indirect water impacts, and heat-rejection architecture together [25].

4.3 Water Conservation and Circular Resource Strategies

Water conservation strategies should reduce dependence on freshwater while considering the wider hydrological consequences of data centre operations [19]. Reclaimed municipal wastewater can substitute for potable supplies in compatible cooling systems, while captured rainwater may provide supplementary resources where climate, storage capacity, treatment requirements, and regulations permit [22]. Closed-loop systems can reduce repeated withdrawals by recirculating cooling water or working fluids rather than continuously consuming new supplies [24]. Optimizing cooling cycles, water treatment, blowdown control, leak detection, and operating conditions can further reduce unnecessary losses [20]. Heat recovery introduces a circular-resource opportunity by capturing server-generated thermal energy for nearby buildings, industrial processes, or other suitable applications instead of simply rejecting it to the environment [26]. However, facility-level water efficiency does not necessarily indicate watershed sustainability [23]. Location-sensitive management should therefore consider drought risk, seasonal availability, ecological flows, cumulative withdrawals, and competing users [25]. Sustainable water management ultimately requires evaluating consumption within watershed boundaries while integrating alternative supplies, reuse, efficient cooling, and resource-recovery strategies [21].

5. CARBON EMISSIONS AND DATA CENTRE DECARBONIZATION

5.1 Operational and Embodied Carbon Sources

Data centre carbon footprints comprise operational and embodied emissions generated across interconnected infrastructure systems [23]. Purchased electricity commonly represents a major operational source because servers, networking equipment, storage, cooling, and power-distribution systems require continuous energy [26]. Associated emissions depend on the generation mix supplying that electricity and therefore vary geographically and temporally [28]. Backup generators create direct emissions through on-site fuel combustion during testing, outages, or grid disturbances [25]. Refrigerant leakage from cooling equipment can create additional climate impacts where refrigerants possess high global-warming potential [30]. Embodied emissions arise before and beyond facility operation through extraction of raw materials, manufacturing of servers and electrical equipment, production of concrete and steel, construction, transportation, and supporting infrastructure development [27]. Equipment replacement cycles further add embodied carbon as servers, batteries, cooling systems, and power electronics are periodically renewed [24]. Consequently, operational efficiency alone cannot characterize total climate impact. Comprehensive assessment should incorporate electricity, fuels, refrigerants, construction, equipment manufacturing, infrastructure expansion, replacement, and eventual end-of-life processes within lifecycle carbon boundaries [29].

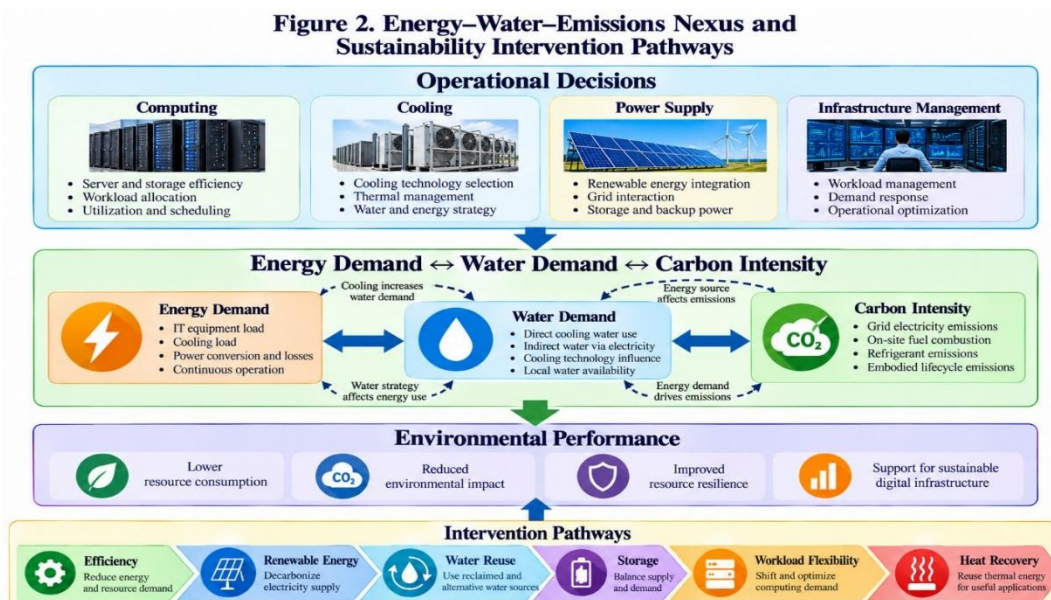
5.2 Carbon Intensity and Renewable Energy Matching

The emissions associated with data centre electricity depend not only on consumption but also on the carbon intensity of the electricity system supplying the facility [24]. Location-based accounting reflects emissions associated with the regional grid generation mix, whereas market-based approaches can incorporate contractual electricity instruments and renewable-energy procurement arrangements [27]. These approaches can therefore produce different representations of the same facility's electricity-related emissions [30]. Temporal variation creates an additional challenge because grid carbon intensity changes as renewable, nuclear, gas, coal, and other generation sources vary their output [25]. Annual renewable procurement can match the quantity of electricity consumed over a year without ensuring that renewable electricity is available during each hour of data centre operation [28]. A facility may therefore maintain renewable procurement claims while consuming grid electricity during periods characterized by higher operational carbon intensity [23]. More granular temporal matching can better align consumption with renewable-energy availability [26]. Credible decarbonization assessment should consequently distinguish contractual renewable claims from measurable operational emissions reductions and consider location, timing, additional renewable generation, grid conditions, and actual electricity-consumption profiles [29].

5.3 Integrated Data Centre Decarbonization Strategies

Effective data centre decarbonization requires coordinated interventions addressing electricity supply, computing demand, cooling, water use, and lifecycle infrastructure impacts [23]. Renewable electricity can lower operational carbon intensity, while energy storage can shift clean electricity toward periods when renewable generation is insufficient or grid emissions are higher [28]. Efficient servers, workload consolidation, power management, and optimized electrical infrastructure can reduce the electricity required for useful computation [25]. Low-carbon cooling strategies should minimize energy consumption without transferring environmental burdens toward unsustainable water consumption [30]. Workload management can shift suitable computational activities toward periods or locations with lower-carbon electricity, strengthening alignment between digital demand and renewable availability [26]. Waste-heat utilization can recover server-generated thermal energy for buildings or industrial applications rather than rejecting it unused [24]. Lifecycle-oriented infrastructure planning should additionally address low-carbon construction, durable equipment, responsible replacement schedules, supply-chain impacts, and end-of-life recovery [29]. These interventions are most effective when evaluated collectively because improvements in one domain can alter performance elsewhere. Integrated decarbonization therefore requires optimization across energy, water, carbon, reliability, computing performance, and infrastructure lifecycle considerations [27].

Figure 2. Energy–Water–Emissions Nexus and Sustainability Intervention Pathways



6. INTEGRATED ENVIRONMENTAL SUSTAINABILITY FRAMEWORK

6.1 Framework Architecture and Core Sustainability Dimensions

An integrated data centre sustainability framework should connect energy efficiency, renewable integration, water efficiency, carbon intensity, resource availability, operational resilience, and lifecycle environmental performance rather than optimizing these dimensions independently [28]. Energy efficiency establishes how effectively electricity is converted into useful computing activity while minimizing losses from cooling, power conversion, and auxiliary infrastructure [30]. Renewable integration addresses the carbon characteristics of electricity supply and the temporal alignment between clean generation and facility demand [32]. Water efficiency captures direct cooling consumption and indirect resource requirements while accounting for local freshwater availability and watershed stress [29]. Carbon intensity connects electricity, fuels, refrigerants, construction, and equipment lifecycles with greenhouse gas emissions [31]. Resource availability introduces geographical constraints because electricity capacity, renewable resources, water availability, and climatic conditions vary between locations [34]. Operational resilience ensures that environmental improvements do not compromise computing availability or infrastructure reliability [33]. Lifecycle environmental performance extends assessment beyond operations to construction, equipment manufacturing, replacement, resource recovery, and decommissioning [28]. These dimensions form an interconnected architecture in which computing growth, infrastructure decisions, resource conditions, environmental impacts, and operational requirements are evaluated simultaneously [30].

6.2 Sustainability Indicators and Performance Measurement

Integrated sustainability assessment requires complementary indicators because no individual metric captures the complete environmental performance of a data centre [29]. PUE measures facility energy overhead relative to IT-equipment energy but does not directly reveal electricity carbon intensity or absolute consumption [32]. WUE characterizes operational water use relative to IT energy, although it does not independently indicate freshwater scarcity or watershed consequences [30]. Carbon Usage Effectiveness or comparable emissions-intensity measures can relate carbon emissions to IT energy consumption and provide a climate-oriented complement to PUE and WUE [33]. Renewable-energy share indicates the proportion of electricity associated with renewable sources, while temporal renewable matching provides stronger information about when clean generation corresponds with consumption [34]. Water-stress exposure contextualizes consumption according to local resource scarcity [31]. Resource-reuse indicators can quantify reclaimed water, recovered heat, or other circular-resource flows [28]. Workload-efficiency measures can relate electricity and emissions to useful computational activity [30]. Sustainability therefore requires a multidimensional indicator portfolio combining efficiency, absolute consumption, resource context, emissions, renewable integration, reuse, and computational productivity [29].

6.3 Managing Cross-Domain Environmental Trade-offs

Integrated assessment is particularly important because environmental interventions can transfer burdens between sustainability domains [28]. Dry or water-efficient cooling can reduce direct freshwater consumption while requiring additional electricity for mechanical heat rejection, potentially increasing carbon emissions where grid electricity remains carbon intensive [31]. Conversely, evaporative cooling may reduce electricity requirements while increasing consumptive water use and watershed pressure [30]. Greater renewable penetration can reduce operational emissions but intermittency may require batteries, backup capacity, transmission infrastructure, or other flexibility resources carrying additional economic and embodied environmental impacts [34]. Computational efficiency creates another potential trade-off: more efficient hardware can reduce energy per workload while lowering the effective cost of computation and enabling additional workloads that increase aggregate electricity demand [32]. Redundancy can strengthen resilience while increasing equipment, energy, and material requirements [33]. These interactions demonstrate why improvements in individual indicators cannot automatically be interpreted as overall sustainability gains [29]. Multi-criteria evaluation can address this limitation by assessing energy consumption, water use, carbon emissions, resource scarcity, reliability, lifecycle impacts, cost, and computational performance simultaneously [28]. Decisions can then prioritize solutions producing net environmental improvements rather than merely transferring impacts between domains [31].

6.4 Decision-Making and Sustainability Optimization

The framework becomes operational when integrated environmental indicators inform infrastructure and management decisions [30]. Facility location should be evaluated against grid capacity and carbon intensity, renewable availability, climate, water stress, transmission constraints, and long-term resource risks [34]. Cooling technology selection should consider both energy and water consequences rather than optimizing either resource independently [29]. Renewable procurement decisions should incorporate additionality, geographic relevance, and temporal matching alongside reported renewable-energy share [32]. Capacity expansion should assess whether efficiency improvements can offset additional electricity, cooling, water, and infrastructure requirements [31]. Workload allocation can incorporate carbon intensity, renewable availability, cooling conditions, latency, and resource constraints when temporal or geographical flexibility exists [33]. Infrastructure investment decisions should similarly compare storage, advanced cooling, water reuse, heat recovery, efficient computing, and grid-interactive technologies using common sustainability objectives [28]. Optimization can assign context-specific priorities to carbon reduction, water conservation, energy efficiency, resilience, and lifecycle impacts [30]. Continuous monitoring then allows decisions to adapt as workloads, environmental conditions, resource availability, technologies, and electricity systems change [34].

Table 2. Integrated Indicators for Environmental Sustainability Assessment of Data Centres

Sustainability Dimension	Indicator	Measurement Focus	Management Application	Potential Trade-off
Energy	PUE	Facility efficiency	Energy optimization	Does not measure carbon
Water	WUE	Water consumption	Cooling/water strategy	May conflict with energy efficiency
Carbon	Emissions intensity	Climate impact	Decarbonization	Grid dependent
Renewable energy	Renewable share/matching	Clean electricity	Procurement strategy	Intermittency
Circularity	Water/heat reuse	Resource recovery	Resource management	Infrastructure cost
Resilience	Supply/resource exposure	Operational continuity	Location/investment	Redundancy impacts

Figure 3. Integrated Environmental Sustainability Framework for Expanding Data Centres

Figure 3. Integrated Environmental Sustainability Framework for Expanding Data Centres



7. IMPLEMENTATION, GOVERNANCE, AND FUTURE DATA CENTRE DEVELOPMENT

7.1 Applying the Framework Across Data Centre Planning and Operations

The integrated sustainability framework should be applied throughout the data centre lifecycle rather than introduced only after facilities become operational [33]. Site selection should evaluate grid capacity and carbon intensity, renewable-energy availability, ambient temperature and humidity, watershed conditions, water stress, and exposure to future climate risks [36]. During design, these location-specific conditions should inform cooling architecture, electrical systems, renewable integration, storage capacity, water reuse, and infrastructure redundancy [34]. Construction decisions should consider material requirements, embodied carbon, equipment efficiency, and opportunities for lower-impact infrastructure [39]. During operation,

continuous monitoring of electricity, water, cooling performance, renewable supply, and carbon emissions can support adaptive resource management [37]. Expansion decisions should assess whether additional computing capacity creates disproportionate grid, water, or environmental pressures [40]. Technology replacement should balance efficiency improvements against embodied impacts associated with manufacturing and premature equipment retirement [35]. Decommissioning should prioritize equipment reuse, material recovery, recycling, and responsible waste management [38]. Lifecycle application therefore enables sustainability decisions to reflect changing workloads, technologies, resource conditions, and environmental constraints from initial planning through final infrastructure retirement [33].

7.2 Environmental Governance, Transparency, and Reporting

Effective environmental governance requires consistent measurement and transparent reporting of the resources consumed and emissions generated by data centre infrastructure [34]. Operators should disclose absolute electricity consumption alongside PUE so that efficiency improvements can be distinguished from growth in total energy demand [37]. Water reporting should similarly combine absolute consumption, WUE, freshwater dependency, alternative-water use, and location-specific water-stress exposure [36]. Renewable-energy reporting should identify procurement mechanisms and, where possible, distinguish annual contractual matching from temporally aligned renewable electricity consumption [40]. Carbon disclosure should encompass operational emissions and relevant lifecycle impacts associated with construction, equipment, replacement, and supply chains [39]. Transparent sustainability targets can establish measurable trajectories for energy efficiency, freshwater reduction, renewable integration, emissions reduction, and resource recovery [35]. Standardized reporting methodologies would additionally improve comparisons between facilities, operators, regions, and technologies [38]. Lifecycle accountability is particularly important because operational improvements can otherwise obscure environmental burdens transferred upstream or downstream [33]. Governance systems should therefore combine measurable targets, consistent boundaries, transparent methodologies, independent verification where appropriate, and periodic reassessment of environmental performance [34].

7.3 Emerging Technologies and Future Sustainability Priorities

Future data centre sustainability will increasingly depend on technologies capable of coordinating computing activity with dynamic energy, water, and environmental conditions [35]. AI-driven resource optimization can integrate workload forecasts, cooling requirements, renewable availability, electricity prices, carbon intensity, and environmental conditions to support adaptive operating decisions [37]. Advanced direct-to-chip liquid cooling and immersion systems can improve thermal management for increasingly dense computing infrastructure while potentially reducing conventional cooling-energy requirements [36]. Energy storage can strengthen renewable integration and grid flexibility by shifting electricity across time and supporting peak-load management [40]. Waste-heat recovery provides opportunities to convert rejected server heat into useful energy for buildings, district heating, or compatible industrial applications [38]. Low-carbon computing, renewable-powered infrastructure, and grid-responsive operations can further align computational growth with electricity-system decarbonization [39]. However, technological efficiency does not guarantee declining environmental impact when rapid growth in computing demand increases aggregate electricity, water, equipment, and infrastructure requirements [33]. Future assessment should therefore explicitly examine rebound effects and absolute resource consumption alongside efficiency improvements [34]. Sustainable innovation must ultimately reduce system-wide environmental pressures rather than simply improve individual performance ratios while total infrastructure demand continues expanding [35].

8. CONCLUSION

8.1 Synthesis of Environmental Sustainability Challenges

Rapid data centre expansion creates interconnected environmental pressures that extend across energy systems, water resources, and greenhouse gas emissions. Increasing computational capacity raises electricity requirements for servers, networking, storage, cooling, and supporting infrastructure, while greater heat generation intensifies thermal-management requirements. Cooling decisions consequently influence both electricity consumption and water demand, creating trade-offs between energy efficiency and freshwater conservation. Electricity sourcing further determines the carbon consequences of computing and cooling, while construction, equipment manufacturing, replacement, and supporting infrastructure add lifecycle environmental impacts. These relationships demonstrate that energy, water, and carbon cannot be sustainably managed as independent environmental categories. An intervention that improves one dimension may increase pressures elsewhere or shift impacts across locations and lifecycle stages. Effective sustainability assessment must therefore move beyond isolated efficiency metrics toward integrated evaluation of absolute resource consumption, environmental intensity, local resource availability, infrastructure resilience, lifecycle impacts, and interactions among energy, water, and emissions.

8.2 Strategic Pathway Toward Sustainable Data Centre Expansion

Sustainable data centre expansion requires coordinated management of computing growth and its associated environmental consequences. Integrated measurement should combine energy efficiency, water consumption, carbon intensity, renewable-energy utilization, resource scarcity, reuse, and lifecycle performance rather than relying on individual indicators. Renewable electricity and carbon-aware operations can reduce emissions, while efficient cooling and responsible water stewardship can limit energy and freshwater pressures. Storage, workload flexibility, heat recovery, reclaimed water, and other circular-resource strategies can further reduce environmental burdens while supporting operational resilience. Transparent reporting is necessary to distinguish relative efficiency improvements from changes in absolute resource consumption and to strengthen accountability across

infrastructure lifecycles. Decisions concerning facility location, cooling architecture, electricity sourcing, capacity expansion, and technology investment should additionally reflect local grid characteristics, climate conditions, water availability, and future resource risks. The integrated framework developed in this study provides a structured mechanism for balancing continued digital infrastructure growth with decarbonization, grid resilience, water-resource protection, resource circularity, and long-term environmental sustainability.

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