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George Daramola
 Regional Environmental
 Engineer, Amazon Web
 Services Kennewick, WA, USA

Assessing environmental impacts of rapid data centre expansion on energy consumption, water resources, and emissions

George Daramola

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Abstract

The accelerating construction of hyperscale, cloud, and artificial-intelligence data centres is reshaping electricity demand, water consumption, and emissions profiles across energy systems, creating environmental pressures that conventional facility-level assessments may underestimate. This study develops an integrated environmental-impact assessment framework for quantifying how rapid data-centre capacity expansion translates into energy, water, and carbon consequences across different operating and infrastructure conditions. The methodology combines installed computing capacity, server utilisation, Power Usage Effectiveness (PUE), grid carbon intensity, Water Usage Effectiveness (WUE), cooling-system requirements, electricity-generation mix, and operational growth rates to estimate direct and indirect environmental burdens. Energy consumption is decomposed into computing and non-computing loads, while water accounting distinguishes on-site cooling demand from electricity-related water consumption. Scope 1 and Scope 2 emissions are evaluated alongside location-dependent grid characteristics to identify geographic disparities in environmental exposure. Scenario and sensitivity analyses test renewable-energy penetration, cooling efficiency, workload growth, utilisation, and water-stress conditions. The resulting framework identifies environmental thresholds at which capacity expansion intensifies resource constraints, providing evidence for sustainable siting, infrastructure planning, technology selection, and regulatory decision-making.

Keywords: Data centre expansion; Power Usage Effectiveness; Water Usage Effectiveness; Grid carbon intensity; Environmental impact assessment; Resource sustainability.

Introduction

1.1 Rapid Expansion of Data Centre Infrastructure

Data-centre infrastructure is expanding rapidly as cloud computing, digitalisation and data-intensive services become increasingly embedded within modern economies ^[1]. Growth in artificial intelligence (AI) and high-performance computing has accelerated this expansion because advanced computational workloads require increasingly powerful infrastructure ^[2]. Hyperscale facilities now accommodate extensive computing resources, while increasing server density concentrates substantial processing capacity within individual sites ^[3]. Development has also become geographically clustered around locations offering reliable electricity, fibre connectivity, suitable land and proximity to major digital markets ^[4]. These trends reinforce the importance of data centres as enabling infrastructure for digital services, technological innovation and economic development ^[5]. However, increasing computational capacity creates corresponding requirements for electricity, cooling systems and supporting infrastructure ^[6]. As deployment accelerates, environmental implications become increasingly significant, requiring assessment not only of technological efficiency but also of how large-scale data-centre development affects interconnected energy systems, water resources and environmental sustainability across regions hosting concentrated digital infrastructure ^[7].

1.2 Environmental Pressures of Data Centre Growth

Rapid data-centre expansion creates environmental pressures primarily through increasing energy consumption, water-resource use and greenhouse gas emissions ^[8]. Continuous operation of servers, storage systems, networking equipment and supporting infrastructure creates substantial electricity requirements that can increase both base-load demand and pressure during peak periods ^[6]. Higher server densities also generate greater heat loads,

Corresponding Author:
George Daramola
 Regional Environmental
 Engineer, Amazon Web
 Services Kennewick, WA, USA

Increasing cooling requirements and associated resource consumption [9]. Water impacts arise directly where facilities employ water-intensive cooling systems and indirectly through water consumed in electricity generation [5]. The emissions profile is similarly influenced by the carbon intensity of purchased electricity, facility efficiency and the operation of diesel or other backup generation systems [1]. Furthermore, concentrated development can necessitate expansion of electricity transmission, generation and water infrastructure [8]. Environmental consequences therefore extend beyond individual facilities, potentially intensifying regional electricity constraints, water-resource competition and emissions associated with supporting rapidly expanding digital infrastructure [4].

1.3 The integrated assessment problem and research gap

Existing research provides substantial evidence concerning individual dimensions of data-centre environmental performance, including energy efficiency, cooling technologies, carbon footprints and water consumption [7]. Energy-focused studies commonly evaluate electricity intensity and power usage effectiveness, while cooling research examines technologies capable of reducing thermal-management requirements [3]. Carbon assessments quantify emissions associated with electricity consumption, whereas water-focused studies evaluate cooling demand and regional water stress [9]. Although these approaches provide valuable insights, examining environmental dimensions independently can obscure important interactions and trade-offs among them [5]. Cooling strategies that reduce electricity requirements may increase direct water consumption, while water-conserving technologies can

potentially require additional energy [2]. Electricity sourcing also affects both operational emissions and indirect water requirements. A significant research gap therefore remains in assessing how rapid data-centre expansion simultaneously affects energy systems, water resources and greenhouse gas emissions, while explicitly accounting for interdependencies and potential environmental trade-offs [8].

1.4 Research objectives and contribution

This study develops an integrated assessment of the environmental consequences associated with rapid data-centre infrastructure expansion [4]. Specifically, it seeks to quantify electricity-demand implications, evaluate pressure on water resources, estimate operational greenhouse gas emissions, examine energy–water–carbon interdependencies, and assess environmental outcomes under alternative growth and efficiency scenarios [6]. Three research questions guide the analysis: how does expanding computing capacity affect energy and water requirements; how do electricity sourcing and cooling efficiency influence operational emissions; and under what growth and efficiency scenarios can environmental pressures be moderated [1]? The study contributes by integrating these environmental dimensions within a common analytical framework rather than evaluating energy, water and carbon effects independently [7]. Scenario-based assessment further enables comparison of alternative development trajectories and efficiency interventions, providing evidence relevant to infrastructure planning, environmental management and sustainable digital development [9]. Section 2 establishes the evidence and measurement foundations required for the subsequent integrated assessment.

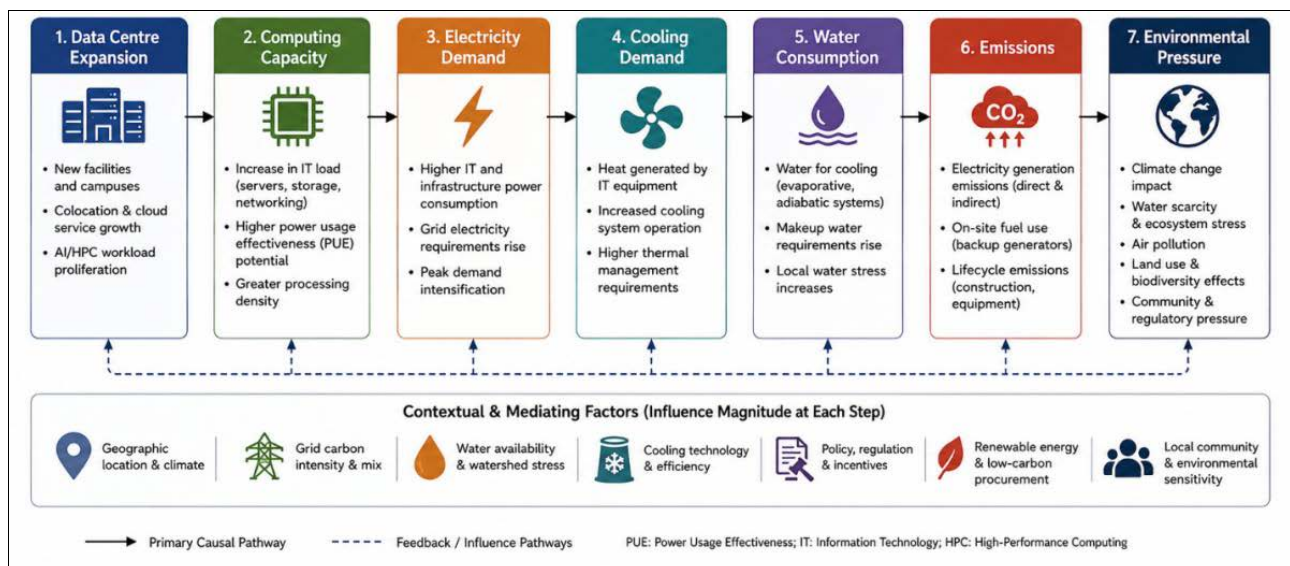


Fig 1: Integrated Environmental Impact Pathways of Data Centre Expansion

2. Literature review and environmental impact framework

2.1 Data centre energy demand and efficiency ‘

Data-centre energy demand reflects electricity consumed by information technology equipment and the supporting infrastructure required for continuous operation [6]. Servers represent a major component of facility electricity consumption, while storage and networking equipment contribute additional loads as data processing and transmission increase [11]. Cooling systems consume

electricity to remove heat generated by increasingly dense computing workloads, while uninterruptible power supply systems introduce further conversion and standby requirements [8]. Power Usage Effectiveness (PUE) measures facility efficiency by comparing total facility electricity consumption with electricity delivered to information technology equipment [14]. Lower PUE values indicate reduced supporting-energy overhead, and hyperscale facilities can achieve efficiency improvements through advanced cooling, workload management and

infrastructure optimisation ^[9]. Renewable electricity procurement can further reduce electricity-related environmental impacts ^[12]. However, facility efficiency should not be equated with declining aggregate electricity consumption. Rapid expansion of computing capacity, particularly artificial intelligence workloads, can increase total energy demand even when individual facilities achieve substantial efficiency improvements ^[15].

2.2 Water consumption and cooling dependence

Data-centre water requirements depend substantially on cooling technology, climatic conditions, operating intensity and local water-management practices ^[10]. Evaporative cooling and cooling towers can reduce electricity requirements by using water to dissipate heat, whereas chilled-water systems combine refrigeration and water circulation to maintain required operating temperatures ^[7]. Air cooling can reduce direct water dependence but may require greater electricity under particular climatic or workload conditions ^[13]. Direct liquid cooling is increasingly relevant for high-density computing because heat is removed closer to processors, potentially changing both energy and water requirements ^[9]. Facilities may use potable supplies or reclaimed water depending on infrastructure availability and water-quality requirements ^[6]. Seasonal temperatures further influence cooling demand and associated consumption. Importantly, direct on-site water consumption should be distinguished from indirect water consumption associated with electricity generation ^[15]. Assessing only facility water use can therefore underestimate the broader water-resource implications of data-centre operations.

2.3 Emissions and carbon-intensity pathways

Data-centre greenhouse gas emissions arise through several operational and infrastructure pathways ^[8]. Scope 1 emissions include direct emissions from facility-controlled sources, particularly backup diesel generators and other on-site fuel combustion ^[12]. Scope 2 emissions principally arise from purchased electricity and consequently depend on electricity consumption and the carbon intensity of the supplying grid ^[7]. Renewable electricity procurement can reduce reported electricity-related emissions, although results vary according to procurement structure and accounting methodology ^[14]. Location-based accounting reflects the emissions intensity of the physical electricity grid supplying a facility, whereas market-based accounting incorporates contractual instruments such as renewable electricity agreements ^[10]. This distinction can produce materially different estimates of operational carbon

performance. Data-centre expansion also creates embodied emissions through construction materials, servers, cooling equipment and supporting infrastructure ^[13]. Although operational emissions remain central to environmental assessment, embodied emissions become increasingly relevant where rapid construction substantially expands total infrastructure capacity ^[9].

2.4 Energy–water–carbon interdependencies

Energy, water and carbon indicators cannot always be optimised independently because interventions affecting one environmental dimension may alter another ^[11]. Water-saving cooling technologies, for example, can reduce direct consumption while increasing electricity requirements under particular operating conditions ^[6]. Conversely, efficient evaporative cooling may lower cooling-energy demand but increase on-site water consumption ^[13]. Renewable electricity procurement can reduce operational carbon intensity without necessarily reducing facility electricity consumption or direct cooling-water requirements ^[8]. Geographic relocation introduces another trade-off because transferring computing workloads between regions may reduce exposure to a water-stressed watershed while increasing dependence on a more carbon-intensive electricity grid ^[15]. Consequently, environmental performance cannot be reliably inferred from improvements in a single indicator. Integrated assessment is required to identify whether efficiency measures produce genuine system-wide improvements or merely transfer environmental pressure between energy systems, electricity-generation portfolios and regional water resources ^[10].

2.5 Research Gap and Analytical Framework

The literature demonstrates that energy consumption, water use and greenhouse gas emissions provide distinct but interconnected measures of data-centre environmental performance ^[7]. However, facility-level efficiency indicators alone cannot establish whether rapid infrastructure expansion produces lower aggregate environmental pressure ^[12]. Similarly, isolated water or carbon assessments may overlook cross-resource effects and geographic dependencies ^[14]. The principal research gap therefore concerns the consistent empirical integration of expansion, resource efficiency and environmental outcomes within a common analytical boundary. This study addresses that gap by evaluating energy demand, water-resource pressure and emissions simultaneously under alternative growth and efficiency conditions ^[9]. Section 3 develops the empirical approach required to connect expanding data-centre capacity with these environmental outcomes.

Table 1: Comparative Assessment of Data Centre Environmental Impact Measures

Dimension	Principal Measure	Key Driver	Typical Boundary	Strength	Limitation
Energy	Electricity consumption / PUE	Computing + cooling	Facility	Operationally measurable	Efficiency may conceal aggregate growth
Water	Water Usage Effectiveness (WUE) / water withdrawal	Cooling	Facility / watershed	Captures water pressure	Highly boundary-sensitive
Emissions	Carbon dioxide equivalent (CO ₂ e)	Grid electricity / fuels	Facility / grid	Direct climate relevance	Depends on accounting method
Integrated	Energy–water–carbon indicators	Multiple interacting drivers	System	Captures cross-resource trade-offs	Data intensive

3. Research methodology and environmental data integration

3.1 Research design and system boundary

The study adopts a quantitative longitudinal and scenario-based environmental assessment design to evaluate how data-centre expansion influences energy, water and emissions outcomes over time ^[13]. The study period encompasses both existing facilities and newly commissioned capacity, allowing incremental environmental pressures associated with expansion to be distinguished from established operational demand ^[18]. The geographic scope covers selected major data-centre markets and emerging development regions, enabling comparison across different electricity grids, climatic conditions and water-resource environments ^[21]. The primary unit of analysis is the individual data-centre facility, subsequently aggregated to regional level where appropriate. The principal system boundary covers operational electricity consumption, cooling requirements, water consumption and associated emissions ^[15]. Lifecycle impacts are treated separately where reliable construction and equipment data are available, preventing embodied impacts from being conflated with operational environmental performance ^[20].

3.2 Data acquisition and variable construction

Data acquisition integrates facility, energy, water and environmental information from multiple sources to construct a harmonised longitudinal dataset ^[16]. Data-centre records provide facility location, commissioned capacity, development status, computing capacity and operational characteristics. Electricity-consumption information is obtained from facility disclosures, utility records and regional electricity-system datasets where available ^[19]. Cooling-system characteristics identify technologies such as evaporative, air, chilled-water and direct liquid cooling, while water records capture facility withdrawals and consumption ^[14]. Watershed indicators provide information on local water availability and stress conditions, enabling resource use to be interpreted within its geographic context ^[22]. Grid-generation mix and emissions factors are matched geographically to facility electricity consumption, while renewable-energy procurement information identifies contractual or operational reductions in electricity-related carbon exposure ^[17]. Variables are organised into four analytical categories: Expansion Drivers, including new capacity and computing growth; Operational Inputs, including electricity and cooling requirements; Environmental Outcomes, including energy, water and emissions; and Contextual Controls, including climate, grid characteristics, facility type and watershed conditions ^[13]. This structure enables expansion effects to be distinguished from environmental conditions that independently influence resource intensity ^[20].

3.3 Environmental performance indicators

Environmental performance is evaluated using consistent absolute and intensity-based indicators to prevent efficiency improvements from obscuring growth in total resource consumption ^[15]. Total electricity consumption measures aggregate facility energy demand, while electricity consumption per unit of computing capacity captures changes in energy intensity as infrastructure expands ^[18]. Power Usage Effectiveness (PUE), introduced previously,

measures the relationship between total facility electricity and electricity consumed by information technology equipment. Total water consumption measures absolute operational water demand, while Water Usage Effectiveness (WUE), also defined previously, evaluates water consumption relative to information technology energy use ^[21]. Greenhouse gas impacts are expressed as carbon dioxide equivalent (CO₂e), introduced previously, allowing different greenhouse gases to be represented using a common climate-impact measure. Emissions intensity is calculated relative to electricity consumption or computing capacity to support comparisons across facilities and regions ^[16]. Evaluating absolute and intensity indicators together distinguishes whether environmental improvements reflect genuine reductions in resource requirements or are offset by rapid growth in total computing capacity ^[22].

3.4 Baseline and expansion scenarios

Scenario construction evaluates how alternative development trajectories and environmental interventions influence aggregate outcomes ^[14]. The baseline/no-expansion scenario maintains existing capacity and operational conditions, providing a reference against which incremental impacts are assessed. A moderate-growth scenario represents controlled capacity additions, whereas a rapid-expansion scenario captures accelerated development associated with increasing cloud and AI workloads ^[19]. The efficiency-improvement scenario reduces energy or cooling intensity while allowing computing capacity to increase, enabling efficiency effects to be separated from growth effects ^[13]. A renewable-energy scenario evaluates changes in emissions where a greater proportion of electricity demand is supplied through lower-carbon sources ^[17]. Finally, a water-constrained scenario examines operations in regions where cooling-water availability is restricted or subject to increased resource stress ^[22]. Comparing these scenarios reveals whether technological efficiency and cleaner energy procurement are sufficient to offset the environmental pressures generated by continued capacity expansion ^[15].

3.5 Analytical and validation strategy

The analytical strategy combines descriptive, comparative and uncertainty-based methods to evaluate environmental consequences across facilities, regions and scenarios ^[20]. Descriptive trend analysis examines changes in computing capacity, electricity consumption, water demand and emissions over the study period. Intensity analysis evaluates whether resource requirements per unit of computing capacity improve as facilities expand ^[16]. Comparative scenario analysis estimates incremental environmental impacts relative to the no-expansion baseline, while regional comparisons identify differences associated with climate, grid composition and water availability ^[14]. Sensitivity testing varies assumptions concerning growth rates, efficiency improvements, cooling performance, renewable procurement and emissions factors to determine whether conclusions remain stable ^[21]. Uncertainty analysis further evaluates plausible ranges around incomplete or estimated parameters rather than treating individual assumptions as deterministic ^[18]. Together, these methods provide a transparent basis for validating the environmental consequences attributed to data-centre expansion ^[13].

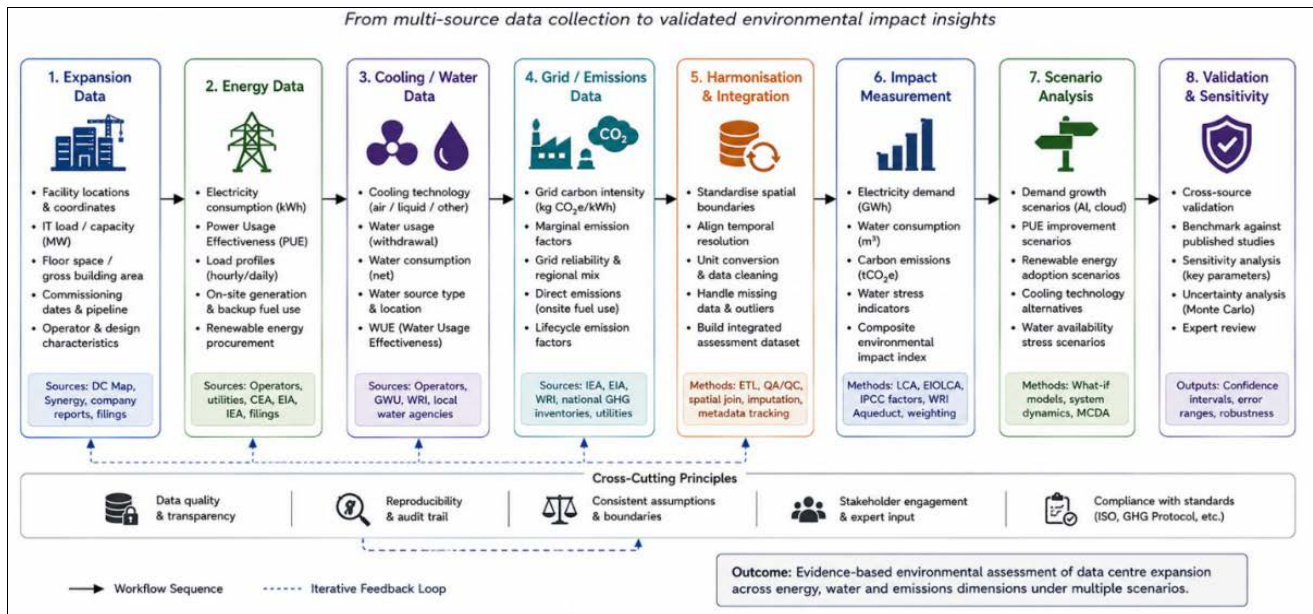


Fig 2: Data Centre Environmental Impact Assessment Workflow

The methodology allows the environmental consequences of expansion to be evaluated first through changes in energy demand and subsequently through their interconnected effects on water consumption and greenhouse gas emissions.

4. Energy consumption impacts of data centre expansion

4.1 Growth in computing capacity and electricity demand

Growth in data-centre computing capacity increases electricity demand through new facility construction, hyperscale expansion and intensification of computational workloads [20]. New facilities add servers, storage, networking and supporting infrastructure, while hyperscale development concentrates substantial computing capacity within large campuses [24]. AI workloads can further increase electricity requirements because model training and inference depend on high-performance processors operating at substantially greater power densities than conventional workloads [27]. Increasing server density consequently raises both direct computing demand and the electricity required for thermal management [22]. However, installed capacity should be distinguished from actual electricity consumption. Installed capacity represents the maximum or designed electrical capability of a facility, whereas realised consumption depends on server utilisation, workload intensity, equipment efficiency and operating conditions [29]. A facility with substantial installed capacity may therefore consume considerably less electricity when utilisation is low. Environmental assessment should consequently estimate realised operational demand rather than infer consumption directly from nameplate capacity [25].

4.2 Facility efficiency and aggregate energy consumption

Improvements in PUE can reduce the electricity overhead associated with cooling, power conversion and other non-computing infrastructure [23]. Hyperscale facilities may achieve additional efficiencies through workload optimisation, advanced cooling, efficient processors and improved power-management systems [28]. Nevertheless, declining energy intensity does not necessarily produce declining aggregate electricity consumption when

computing capacity expands rapidly [21]. The relationship can be represented conceptually as:
Higher Efficiency + Rapid Capacity Growth ≠ Lower Total Electricity Demand

For example, a reduction in electricity consumed per unit of computing capacity can be outweighed by a larger proportional increase in installed and utilised computing capacity [26]. This creates a potential rebound effect in which technological efficiency moderates, but does not reverse, growth in aggregate energy demand. Consequently, assessment based exclusively on PUE or energy intensity may present an incomplete picture of environmental performance [30]. Absolute electricity consumption must therefore be evaluated alongside efficiency indicators to establish whether improvements translate into system-level reductions [24].

4.3 Grid-Level and Regional Energy Impacts

The electricity consequences of data-centre expansion extend beyond individual facilities to the regional grids supplying concentrated computing infrastructure [25]. Large facilities can increase peak electricity demand, particularly where high utilisation coincides with periods of elevated system-wide consumption [29]. Rapid development may consequently increase generation requirements, intensify grid congestion and expose transmission constraints where network expansion does not keep pace with new load [22]. Geographic clustering can magnify these effects because multiple hyperscale facilities may connect within the same electricity market or transmission area [27]. Reliability implications arise where additional demand reduces available reserve margins or increases dependence on constrained generation and network infrastructure [20]. Importantly, identical data centres can create different environmental pressures depending on location [28]. A facility supplied by a low-carbon grid with substantial available capacity may produce lower emissions and infrastructure stress than an equivalent facility located within a carbon-intensive or capacity-constrained electricity system [23]. Regional context is therefore essential to interpreting aggregate energy impacts.

4.4 Energy-Demand Scenario Results

Energy-demand scenarios compare the no-expansion baseline with moderate-growth, rapid-expansion and efficiency-improvement trajectories ^[21]. The baseline establishes electricity consumption under existing capacity, while expansion scenarios estimate incremental demand associated with additional computing infrastructure ^[26]. Absolute consumption captures total electricity requirements, whereas percentage growth identifies the scale of change relative to baseline conditions. Efficiency-adjusted demand incorporates improvements in PUE and computing-energy intensity to determine whether technological gains offset additional capacity ^[30]. Regional comparisons further identify where identical growth trajectories create substantially different electricity-system pressures because of utilisation patterns, climatic conditions and existing grid constraints ^[24]. The expected comparison therefore distinguishes capacity-driven demand growth from efficiency-driven demand reduction, allowing the net energy effect of expansion to be quantified ^[28]. Electricity demand, however, represents only part of the environmental burden because thermal management creates a parallel dependence on water resources ^[22].

5. Water-resource impacts and cooling trade-offs

5.1 Direct water consumption

Data centres consume water directly through cooling and supporting facility operations, with requirements varying according to cooling technology, climate and computing intensity ^[29]. Cooling towers and evaporative systems use water to remove heat generated by servers and other equipment, making consumption sensitive to thermal loads and ambient conditions ^[32]. Water may also support humidification, equipment maintenance and other facility processes, although cooling generally represents the principal operational requirement ^[35]. Importantly, water withdrawal should be distinguished from consumptive use. Withdrawal represents the total volume removed from a water source, whereas consumptive use refers to the portion not immediately returned because it is evaporated, incorporated into processes or otherwise unavailable for immediate reuse ^[30]. This distinction affects environmental interpretation because facilities with similar withdrawals may have substantially different consumptive impacts. Assessment should therefore quantify both measures where data permit and evaluate them relative to computing activity, cooling configuration and seasonal operating conditions ^[33].

5.2 Indirect water footprint

The water footprint of data-centre operations extends beyond water consumed within facility boundaries ^[31]. Electricity generation can require substantial water for fuel processing, steam production and thermal-power-plant cooling, meaning that electricity consumed by data centres creates an indirect water footprint ^[34]. Its magnitude depends on facility electricity demand and the generation technologies supplying the relevant grid. Consequently, two facilities with comparable direct water consumption can produce different total water footprints where their electricity mixes differ ^[29]. Evaluating only on-site consumption may therefore underestimate the broader water-resource implications of data-centre operation,

particularly in regions dependent on water-intensive thermal generation ^[35]. An integrated assessment should distinguish direct facility consumption from electricity-related indirect consumption before combining them where appropriate. This approach prevents operational efficiency at the facility boundary from obscuring water requirements transferred upstream through electricity supply ^[32].

5.3 Geographic Water Stress and Resource Competition

The environmental significance of data-centre water consumption depends strongly on the geographic and hydrological conditions surrounding each facility ^[30]. Watersheds with abundant renewable water resources may accommodate additional demand differently from regions already experiencing drought, groundwater depletion or seasonal scarcity ^[33]. Consequently, identical quantities of water consumption cannot be interpreted as producing equivalent environmental pressure across locations ^[35]. Data-centre demand may also interact with competing municipal, agricultural and industrial requirements. During drought periods, increased cooling demand can coincide with reduced water availability and heightened requirements for household consumption or agricultural production ^[31]. Geographic assessment should therefore consider watershed availability, drought exposure, seasonal variability and existing demand from competing users rather than relying exclusively on absolute consumption ^[34]. Facilities located in highly water-stressed regions may generate substantial environmental and social pressure even when their absolute consumption is lower than facilities operating in water-abundant areas ^[29]. Incorporating location-specific water conditions therefore provides a more meaningful measure of resource pressure associated with rapid data-centre expansion ^[32].

5.4 Cooling technology and water–energy trade-offs

Cooling technology determines how data centres distribute environmental pressure between water and electricity consumption ^[33]. Air-cooling systems can minimise direct water requirements but may consume more electricity when ambient temperatures are high or computing loads become increasingly dense ^[30]. Evaporative cooling can reduce cooling-related electricity consumption by exploiting water evaporation for heat rejection, although this advantage increases direct consumptive water use ^[35]. Chilled-water systems provide controlled thermal management but require electricity for chillers, pumps and associated equipment while potentially maintaining substantial water requirements through cooling towers ^[31]. Direct liquid cooling can improve heat removal from high-density computing equipment and may reduce certain cooling-energy requirements, although performance depends on system design and heat-rejection configuration ^[34]. Hybrid technologies can dynamically combine cooling approaches according to climatic and operational conditions ^[29]. Consequently, reducing water consumption may increase electricity requirements in some configurations, while energy-efficient cooling may increase water dependence. Technology selection should therefore evaluate combined water–energy performance rather than optimising either resource independently ^[32]. These water–energy interactions directly influence the third major environmental dimension: greenhouse gas emissions.

6. Emissions, integrated environmental results and discussion

6.1 Operational and electricity-related emissions

Data-centre emissions arise from both direct facility operations and electricity purchased from external power systems [34]. Direct operational emissions principally originate from on-site fuel combustion, particularly backup diesel generators used during grid outages, testing and emergency operations [37]. Electricity-related emissions arise from the generation required to supply servers, storage, networking and cooling infrastructure, making regional grid carbon intensity a major determinant of operational carbon performance [40]. Facilities connected to electricity systems dominated by fossil-fuel generation can therefore generate substantially higher indirect emissions than comparable facilities operating on lower-carbon grids [35]. Renewable electricity procurement can reduce exposure to carbon-intensive generation through power-purchase arrangements, on-site renewable generation or other contractual mechanisms [38]. However, the resulting emissions profile depends on the accounting boundary and characteristics of the electricity supply. Consequently, direct operational emissions should be evaluated separately from electricity-related emissions before assessing their combined contribution to the overall carbon consequences of data-centre expansion [36].

6.2 Expansion versus decarbonisation

The relationship between data-centre expansion and emissions depends on whether decarbonisation and efficiency improvements occur rapidly enough to counteract growth in computing demand [39]. Renewable electricity procurement can lower emissions intensity, while broader grid decarbonisation reduces the carbon consequences of each unit of electricity consumed [34]. Energy-efficiency improvements similarly reduce electricity requirements per unit of computing capacity [37]. However, none of these developments necessarily guarantees an absolute decline in

emissions. Rapid increases in AI workloads, server deployment and facility capacity can outweigh reductions achieved through lower energy or carbon intensity [40]. A facility portfolio may therefore become more efficient and less carbon intensive while still generating greater aggregate emissions as total electricity consumption expands [35]. Assessment must consequently distinguish relative improvements in emissions intensity from absolute changes in total emissions, particularly under rapid-expansion scenarios where growth and decarbonisation occur simultaneously [38].

6.3 Integrated energy–water–emissions assessment

Integrated assessment evaluates data-centre environmental performance across energy demand, water consumption and carbon emissions simultaneously rather than interpreting each dimension independently [36]. Scenario comparisons quantify absolute electricity consumption alongside PUE, total water consumption alongside WUE, and aggregate CO₂e alongside relevant environmental-intensity measures [39]. This approach reveals potential synergies where an intervention improves several environmental outcomes simultaneously. For example, higher computing efficiency combined with low-carbon electricity can reduce both energy intensity and electricity-related emissions [34]. Trade-offs arise where improvements in one dimension increase pressure elsewhere. Evaporative cooling may reduce cooling electricity requirements and associated emissions while increasing direct water consumption, whereas water-conserving cooling can potentially increase electricity demand [40]. Geographic differences further influence outcomes because grid carbon intensity and water availability vary between regions [37]. Integrated comparison therefore determines whether apparent environmental improvements represent genuine system-wide benefits or transfers of environmental pressure between energy systems, water resources and atmospheric emissions [35].

Table 2: Integrated environmental performance across data centre expansion scenarios

Scenario	Energy Consumption	PUE	Water Consumption	WUE	CO ₂ e	Environmental Trade-Off
Baseline/No Expansion	Reference	Baseline	Reference	Baseline	Reference	Existing environmental burden
Moderate Growth	Moderate increase	Improved	Moderate increase	Improved	Moderate increase	Growth partly offset by efficiency
Rapid Expansion	High increase	Improved	High increase	Variable	High increase	Scale outweighs intensity improvements
Efficiency Improvement	Lower than equivalent growth	Lower	Technology-dependent	Improved/variable	Lower	Efficiency may shift water–energy balance
Renewable Energy	Similar demand	Similar	Grid-dependent	Similar	Substantially lower	Carbon benefit without demand reduction
Water-Constrained	Technology-dependent	Variable	Lower	Improved	Potentially higher	Water savings may increase electricity use

6.4 Sensitivity and Uncertainty Analysis

Sensitivity and uncertainty analysis determines whether estimated environmental impacts remain stable under alternative assumptions [38]. Utilisation rates are varied because installed computing capacity does not necessarily translate proportionately into realised electricity consumption [34]. Alternative growth assumptions test moderate and accelerated expansion trajectories, while cooling-efficiency parameters examine how technological performance changes energy and water requirements [36].

Water availability is varied across regional scarcity conditions, and grid carbon intensity is adjusted to represent different electricity-generation mixes and decarbonisation pathways [40]. Renewable penetration is similarly varied to evaluate the influence of cleaner electricity supply on operational emissions. Technology-improvement assumptions capture potential advances in processors, cooling systems and power-management infrastructure [35]. Results remaining directionally consistent across these variations are interpreted as robust findings. Conversely,

outcomes changing substantially under plausible parameter adjustments are reported as uncertainty-sensitive, preventing scenario-specific assumptions from being presented as universally applicable conclusions^[39].

6.5 Interpretation and Environmental Implications

The integrated findings indicate that the environmental consequences of data-centre expansion are determined by the interaction of scale, efficiency, geographic concentration, electricity source, cooling technology and resource availability^[37]. Scale determines the aggregate computing and infrastructure requirements imposed on regional systems, while efficiency determines the resources required per unit of computational output^[34]. Geographic concentration can intensify local electricity-network and water-resource pressures even when individual facilities demonstrate strong efficiency performance^[40]. Electricity

source strongly influences carbon outcomes because equivalent consumption can produce markedly different emissions across grids with different generation portfolios^[36]. Cooling technology similarly determines whether thermal management places greater pressure on electricity or water resources, while regional water availability determines the environmental significance of consumption^[38]. Consequently, efficiency improvements may reduce PUE, WUE or emissions intensity without reducing absolute environmental pressure when computing capacity grows faster than resource intensity declines^[35]. Sustainable expansion therefore requires simultaneous consideration of total demand, facility efficiency, infrastructure location, electricity decarbonisation and local resource constraints rather than reliance on any single environmental-performance indicator^[39].

Scenario	Electricity Demand (Relative Change) 	Water Pressure (Relative Change / Risk) 	Emissions (GHG, Relative Change) 	Overall Implication (Net Environmental Effect) 
 Rapid Expansion	↑↑	↑↑	↑↑	Scale-driven environmental pressure
 Efficiency Improvement	↓ per unit	Variable	↓ per unit	Intensity gains may not offset growth
 Renewable Energy	↔	Grid-dependent	↓↓	Strong carbon benefit
 Water-Constrained	Potentially ↑	↓↓	Potentially ↑	Water-energy trade-off
 Integrated Efficiency	↓	↓	↓	Strongest multi-dimensional improvement

Legend: ↓↓ Large Decrease ↓ Decrease ↔ No Significant Change ↑ Increase ↑↑ Large Increase

Note: Arrows indicate relative change compared to current baseline conditions. "Per unit" refers to intensity (e.g., per MWh of computing output).

Fig 3: Integrated Energy–Water–Emissions Impacts and Environmental Trade-Offs under Different Data Centre Scenarios

The integrated findings provide the evidence required to identify policy and industry responses capable of supporting continued digital growth within environmental and infrastructure constraints.

7. Policy implications, limitations and conclusion

7.1 Policy and industry implications

The findings indicate that sustainable data-centre expansion requires coordinated planning among developers, utilities, grid operators, water authorities, environmental regulators and local governments^[37]. Developers should incorporate location-sensitive environmental assessment into site selection, particularly where electricity networks or water resources face existing constraints^[40]. Utilities and grid operators should integrate projected data-centre loads into generation, transmission and reliability planning while supporting renewable electricity integration^[38]. Water authorities should encourage water-efficient cooling, reclaimed-water use and operational practices appropriate to

local watershed conditions^[39]. Environmental regulators and local governments can strengthen location-sensitive permitting by evaluating cumulative energy, water and emissions pressures rather than facility impacts independently^[37]. Improved disclosure of electricity consumption, cooling technologies, water use and emissions would also strengthen environmental oversight, infrastructure planning and comparison of development alternatives^[40]. Collectively, these measures can better align digital infrastructure growth with regional resource availability.

7.2 Study limitations and future research

Several limitations affect the scope and interpretation of the analysis^[38]. Facility-level electricity, water and operational data remain incomplete because commercially sensitive information is frequently proprietary, while water reporting practices differ across facilities and jurisdictions^[40]. Future AI-driven computing demand also remains uncertain,

complicating long-term expansion projections^[37]. Renewable-energy accounting methods can produce different emissions estimates, while geographic heterogeneity limits direct comparison across grids, climates and watersheds^[39]. Future research should therefore employ higher-resolution facility, electricity-grid and watershed datasets, incorporate hourly operational variability, and extend the analytical boundary through lifecycle assessment of construction, computing equipment, cooling infrastructure and associated embodied environmental impacts^[38].

7.3 Concluding remarks

Environmental sustainability of data-centre expansion cannot be determined from efficiency metrics alone. Improvements in energy, water or emissions intensity may reduce environmental pressure per unit of computing capacity while absolute resource consumption continues increasing as infrastructure expands. Meaningful assessment must therefore consider total electricity demand, absolute water consumption, greenhouse gas emissions, geographic resource conditions and cross-resource trade-offs alongside conventional efficiency indicators. Balancing rapid digital-infrastructure growth with environmental sustainability consequently requires integrated planning that recognises regional energy security, water-resource availability and emissions-reduction objectives while supporting the computing capacity increasingly required by digitalisation and artificial intelligence.

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