Stack/OS Provides Environmental Engineering Guidelines for Sustainable Data Center Infrastructures

Building Standards, and Community Impact Mitigation Strategies

GreenPlex™ is a campus-based integration of data services, agriculture, and community outreach… each one making the others more valuable. The Data Center is to other campus facilities physically by heat, water, and power… and virtually by digital information exchange and knowledge sharing.

When a data center lives in a GreenPlex, it gains a community welcome that is not typically offered to stand-alone data centers that are seen as threats not a benefits to grass-roots communities. With GreenPlex, the indoor farming facility gains cheap, steady heat and a structural cost advantage with a moat around it. The region gains food, jobs, education, and an economic engine.

Data Centers should contribute to community quality of life

The unprecedented expansion of hyperscale computing, artificial intelligence (AI) workloads, and cloud infrastructure has positioned data centers as vital municipal assets within the global digital economy.

However, their physical presence introduces complex environmental, hydrological, atmospheric, and acoustic burdens on host communities. ***Designing, constructing, and operating a green data center requires an integrated engineering methodology that extends beyond operational efficiency to encompass holistic environmental stewardship***. This report synthesizes foundational academic literature, scientific papers, national energy studies, building standards, thermal guidelines, and community impact mitigation strategies to provide an exhaustive framework for mitigating risks to local air, water, land, and overall quality of life.

Foundational Literature and Macro-Scale Energy-Water Studies

A rigorous technical evaluation of sustainable data center design relies on benchmark academic and governmental literature quantifying energy, carbon, and water tradeoffs across spatial and temporal scales. The historical trajectory of data center energy consumption reflects a structural transition: early efficiency gains achieved through server virtualization and hyperscale consolidation during the 2010s have been superseded by rapid, power-dense computational demand driven by deep learning and large-scale data processing.

According to landmark research from Lawrence Berkeley National Laboratory (LBNL), annual U.S. data center electricity consumption reached approximately 176 Terawatt-hours (TWh) in 2023, accounting for roughly 4.4%of total domestic electricity consumption. Advanced bottom-up modeling projects that domestic data center electricity demand could reach between 325 TWhand 580 TWhby 2028, and potentially between 521 TWhand 843 TWh by 2030, representing up to 15.3%of total U.S. grid capacity. This accelerating load growth places acute pressure on regional power transmission grids, local distribution substations, and surrounding ecosystems.

Parallel research published in Environmental Research Letters and Nature Sustainability emphasizes that data center environmental impacts are bi-faceted, consisting of direct site-level impacts and indirect grid-level impacts. While operational energy efficiency improvements reduce on-site heat generation, they can inadvertently shift environmental degradation to regional power generation sources and distant supply chains.

Evaluating direct versus indirect ecological degradation requires tracking spatial decoupling. Direct impacts occur within the immediate watershed and airshed of the facility, driven by evaporative cooling water withdrawals, backup diesel generator emissions, and localized mechanical acoustic pollution. Indirect impacts manifest across regional power control areas, where off-site thermoelectric power plants consume massive quantities of water for steam condensation and emit greenhouse gases to supply the data center's continuous baseload power demand. (See appendix for references.)

Green Building Frameworks and Sustainability Governance Certifications

Achieving verifiable sustainability requires aligning data center site selection, architectural engineering, and operational management with international green building rating systems and formal management standards. Whole-building certifications evaluate the broad lifecycle impacts of design, procurement, and construction, whereas targeted energy management standards govern ongoing operational performance.

Whole-Building Certifications: LEED and BREEAM

The Leadership in Energy and Environmental Design (LEED) system, administered by the U.S. Green Building Council (USGBC), features specific rating mechanisms tailored to digital infrastructure. The LEED BD+C: Data Centers rating system applies specifically to new construction where at least $60\%$of the facility's gross floor area (GFA) is fully fit-out for critical computing occupancy at the time of certification. For wholesale colocation assets where more than $40\%$of the GFA remains incomplete shell space during initial buildout, project teams must utilize LEED BD+C: Core and Shell. Operating facilities occupied for at least twelve months are evaluated under LEED O+M (Existing Buildings), which incorporates real-time energy benchmarking via tools such as the U.S. Department of Energy DC PRO Profiling Tool.

LEED employs a 100-point scale across core categories including Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Design, Regional Priority, and Location and Transport. Projects earn rankings ranging from Certified (40--49 points), Silver (50--59 points), Gold (60--79 points), to Platinum ($80+$ points).

The Building Research Establishment Environmental Assessment Method (BREEAM), widely utilized across European and international markets, evaluates assets across ten weighted categories: Energy, Water, Health and Well-being, Pollution, Land Use and Ecology, Transport, Materials, Waste, Management, and Innovation. BREEAM ranks facilities on a percentage benchmark scale comprising Pass ($\geq 30\%$), Good ($\geq 45\%$), Very Good ($\geq 55\%$), Excellent ($\geq 70\%$), and Outstanding ($\geq 85\%$). Compared to LEED, BREEAM places greater structural weight on site ecology, land preservation, and localized pollution mitigation.

Operational and Energy Management Standards

Whole-building frameworks are reinforced by process-oriented operational management standards that govern day-to-day facility performance. ISO 50001 (Energy Management Systems) provides a systematic framework for establishing energy baselines, setting operational targets, and executing continuous performance improvements. While ENERGY STAR certifies achievement within the top $25\%$of real-world energy performance relative to peer benchmarks, ISO 50001 verifies that an enterprise maintains structured operational protocols to sustain energy reductions.

Complementing ISO 50001, ISO 14001 establishes requirements for broader Environmental Management Systems (EMS), while ISO 14064 governs greenhouse gas accounting and audit verification. In response to regulatory shifts, regional initiatives such as the European Climate Neutral

Data Centre Pact (CNDCP) and the global iMason Climate Accord mandate strict operational commitments. The CNDCP establishes binding thresholds requiring new data centers to achieve strict Power Usage Effectiveness (PUE) limits, verified 100%clean energy matching, zero-waste diversion targets (e.g., UL 2799 validation), responsible Water Usage Effectiveness (WUE), and waste-heat integration into municipal district heating grids. Furthermore, the Open Compute Project (OCP) standardizes open-source hardware designs that optimize server power deliverability and facilitate high-density direct liquid cooling integration.

Certification / Standard	Governing Body	Structural Scope	Primary Assessment Categories	Quantitative Metrics & Benchmark Criteria
LEED BD+C: Data Centers [cite: 21]	USGBC	Whole-building new construction & major fit-outs.	Sustainable Sites, Energy/Atmosphere, Water Efficiency, Materials, IAQ.	100-pointscale; System Optimization credits; prerequisite efficiency baselines.
BREEAM Data Centers [cite: 8, 23]	BRE	Whole-building lifecycle & asset performance.	10 Weighted Categories (Land Use, Ecology, Pollution, Water, Energy, Waste).	Weighted score; Pass ($\geq 30\%$) to Outstanding ($\geq 85\%$); mandates ecological protection.
ISO 50001 [cite: 6, 20]	ISO	Organizational Energy Management Systems (EnMS).	Energy baseline policy, continual performance monitoring, and system audits.	Process-based certification verifying continuous energy management and reduction protocols.
ENERGY STAR [cite: 6, 20]	U.S. EPA	Operational energy benchmarking.	Empirical facility energy consumption relative to national peer dataset.	Must rank within the top $25\%$of national energy performance benchmarks.

Certification / Standard	Governing Body	Structural Scope	Primary Assessment Categories	Quantitative Metrics & Benchmark Criteria
Climate Neutral Data Centre Pact [cite: 23, 24]	CNDCP Signatories / EU	Operational sustainability targets across European assets.	Power usage, water efficiency, clean energy matching, waste heat reuse, circular economy.	Target $PUE \leq$ 1.3--1.4, verified 100%renewable matching, low WUE, UL 2799 waste diversion.

Thermal Engineering, HVAC Design, and ASHRAE TC 9.9 Standards

The primary driver of data center operational energy consumption and heat rejection infrastructure is the control of server intake micro-climates. Technical Committee 9.9 (TC 9.9) of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) publishes the authoritative global guidelines governing data center environmental conditions.

Environmental Classes and Operating Envelopes

The ASHRAE TC 9.9 Thermal Guidelines for Data Processing Environments defines operational envelope classes measured strictly at the IT equipment air inlet (Server Inlet), rather than relying on general room average or return air temperatures. Defining the boundary at the server intake ensures that HVAC systems deliver required thermal conditions directly to IT components, allowing operators to expand allowable room ambient conditions and maximize air-side and water-side economization (free cooling).

Air-side environmental classes are structured into four main tiers (A1 through A4). Across all classes, the recommended operating envelope maintains an inlet dry-bulb temperature between 18°C and 27°C(64.4°F to 80.6°F), with a dew point range of −9°C DP to 15°C DPand a relative humidity ceiling of 60%. The allowable envelopes extend these boundaries significantly: Class A1 allows 15°C to 32°C, Class A2 allows 10°C to 35°C, Class A3 allows 5°C to 40°C, and Class A4 permits intake temperatures up to 45°C(113°F). Expanding operations into Class A3 or A4 allowable bands enables year-round compressor-free air cooling in temperate climates. However, operators must balance free-cooling energy savings against increased internal server fan power draw and thermal throttling risks.

Liquid cooling environmental classes govern water-side thermal delivery. Classes W1 and W2 mandate facility water supply temperatures of 2--17°Cand 2--27°Crespectively, typically requiring chiller assistance during warmer ambient periods. Conversely, Classes W3 (2--40°C) and W4 (2--45°C) enable high-temperature liquid cooling that relies entirely on dry coolers or cooling towers year-round, completely eliminating compressor operation. The H1 class specifically addresses high-density AI accelerators (e.g., thermal loads exceeding 1 kWper socket), establishing a conservative coolant supply baseline of 18--22°Cto maintain silicon junction margins.

ASHRAE Class	Cooling Medium	Recommended Temp Range	Allowable Temp Limit	Primary Application
Class A1 [cite: 28]	Air	18°C to 27°C [cite: 28]	15°C to 32°C [cite: 28]	Enterprise servers, financial mainframes.
Class A2 [cite: 28]	Air	18°C to 27°C [cite: 28]	10°C to 35°C [cite: 28]	Volume commercial servers, cloud infrastructure.
Class A3/A4 [cite: 28]	Air	18°C to 27°C [cite: 28]	5°C to 40°C (A3) / 45°C(A4)	High-density modular builds, expanded economization.
Class W3/W4 [cite: 28]	Liquid	Supply Water 2°C to 40°C(W3) / 45°C(W4)	N/A (Liquid Loop)	High-efficiency liquid cold plate, dry-cooler rejection.
Class H1 [cite: 29]	Liquid	Coolant Supply 18°C to 22°C [cite: 29]	Conservative Thermal Margin	High-density AI silicon (B200/GB200/MI300X class).

Psychrometric Control and Contamination Limits

Maintaining atmospheric purity inside server halls is necessary to prevent hardware failure. ASHRAE TC 9.9 shifted its primary moisture control metric from relative humidity (RH) to dew point temperature (DP). Relative humidity varies with temperature, whereas dew point measures absolute moisture content, providing a precise metric for preventing electrostatic discharge (ESD) and surface condensation. ESD risks in low-humidity environments are controlled down to a lower dew point limit of -9°C DP(or -12°C DP/ 8% RHallowable). Upper moisture limits (15°C DP recommended) prevent condensation on chilled water piping and cold-aisle surfaces.

Gaseous and particulate pollutants present significant risks to microelectronics. When intake air contains sulfur dioxide (SO_2), hydrogen sulfide (H_2S), or chlorine (Cl_2), elevated humidity acts as a catalyst for copper and silver creep corrosion on circuit boards. Facilities must perform biannual corrosion monitoring using copper and silver test coupons. If coupon corrosion rates exceed 200 AA/monthfor silver or 300 AA/monthfor copper, operators must restrict maximum intake relative humidity to below 50%and install chemical air filtration scrubbers.

Water Resource Protection, Hydrological Metrics, and Closed-Loop Cooling

Data center water consumption has become a central focus of municipal environmental reviews. Water is consumed directly on-site for evaporative heat removal and indirectly off-site during thermo-electric power generation.

Direct On-Site Consumption (~25% of Total Hydrological Impact):

— Mechanism: Evaporative cooling towers & adiabatic air handlers

— Intensity: ~1.8 m^3 of water consumed per MWh of IT load [cite: 12]

— Environmental Risk: Local aquifer depletion & municipal water grid stress [cite: 3, 10, 19]

Indirect Off-Site Consumption (~75% of Total Hydrological Impact):

— Mechanism: Thermoelectric power plant cooling & fuel extraction [cite: 10, 14]

— Intensity: Varies by grid generation mix (hydroelectric, nuclear, fossil) [cite: 4, 18]

— Environmental Risk: Regional watershed stress in power control areas

Direct versus Indirect Hydrological Footprints

The standardized metric governing facility water efficiency is Water Usage Effectiveness (WUE), expressed as:

$$WUE = \frac{\text{Annual Site Water Consumption (Liters)}}{\text{IT Equipment Energy Consumption (kWh)}}$$

Facilities relying on traditional open-loop evaporative cooling towers achieve favorable Power Usage Effectiveness (PUE) metrics because water evaporation efficiently rejects heat. However, this approach consumes roughly 1.8 m^3 of water per MWh(1.8 L/kWh) of IT load directly on-site, extracting millions of gallons daily from local municipal supplies.

Synthesizing research from Harvard T.H. Chan School of Public Health and Virginia Tech demonstrates a fundamental engineering tradeoff: direct operational water use accounts for approximately 25%of a facility's overall hydrological footprint, whereas indirect water embedded in regional electricity generation accounts for roughly 75%. Deploying dry cooling systems eliminates direct operational water consumption ($WUE = 0$), but slightly increases facility electrical consumption during hot ambient periods. If the local utility grid relies on water-intensive thermal or hydroelectric power generation, total regional water consumption across the watershed can increase. Thus, water mitigation strategies must be tailored to regional grid characteristics.

Advanced Cooling Paradigms and Water Protection Strategies

To eliminate operational water extraction and safeguard local water bodies, modern facilities deploy alternative cooling technologies:

Closed-Loop Chilled Water Systems: Circulate a fixed volume of treated water within a sealed loop. Following an initial system fill, operational water consumption is limited to domestic building requirements.

Dry Coolers and Air-Side Economization: Rejects heat via air-to-fluid heat exchangers driven by high-efficiency fan arrays. These systems operate entirely dry under standard conditions, utilizing minor adiabatic misting only during peak summer temperatures.

Direct-to-Chip Liquid Cooling (DLC): Circulates dielectric fluids or treated water through closed cold plates mounted on high-power processors. Heat is transferred to secondary facility loops operating at elevated temperatures ($W3/W4$ classes up to $45°$C), allowing heat rejection via external dry coolers without water evaporation.

Immersion Cooling: Submerges server hardware directly in sealed tanks containing single-phase or two-phase non-conductive dielectric fluid. Immersion cooling eliminates internal server fans, reduces cooling energy consumption by up to 95%, operates with zero operational water consumption, and isolates IT components from atmospheric contaminants.

Alternative Water Procurement: When evaporative cooling is unavoidable due to extreme ambient climates, facilities preserve municipal drinking water by sourcing non-potable supplies, including treated municipal wastewater (reclaimed water), industrial effluent, and harvested stormwater.

Atmospheric Emission Controls, On-Site Microgrids, and Grid Integration

Mitigating data center atmospheric emissions requires addressing Scope 1 direct operational emissions, Scope 2 indirect energy emissions, and Scope 3 supply chain carbon. On-site emission performance is tracked alongside efficiency metrics using Carbon Usage Effectiveness (CUE):

$$CUE = \frac{\text{Total Operational CO}_2\text{ Emissions (kg)}}{\text{IT Equipment Energy (kWh)}}$$

Permitting Backup Diesel Generators and Air Quality Compliance

Scope 1 direct emissions primary stem from emergency diesel generators during routine maintenance testing and grid outage operations. Regulatory agencies, including the U.S. Environmental Protection Agency (EPA) under Clean Air Act provisions, regulate backup power installations based on Potential to Emit (PTE) calculations for criteria pollutants: Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Particulate Matter ($PM_{10}/PM_{2.5}$), and Volatile Organic Compounds (VOCs).

To obtain air quality construction and operating permits, facility designs incorporate emission control measures:

Tier 4 Final Certified Engines: Diesel generators equipped with Selective Catalytic Reduction (SCR) systems using Diesel Exhaust Fluid (DEF) to reduce NO_xemissions by over 90%, combined with Diesel Particulate Filters (DPF) to capture soot.

Hydrotreated Vegetable Oil (HVO): Replacing fossil diesel with HVO (renewable diesel) reduces net lifecycle carbon emissions by up to 90%, lowers exhaust particulate matter, and eliminates fuel-bound sulfur emissions without requiring engine modifications.

Battery Energy Storage Systems (BESS) and Fuel Cells: Modern microgrids pair lithium-ion or sodium-ion BESS with proton-exchange membrane (PEM) hydrogen fuel cells. BESS provides immediate ride-through power during short duration grid sags, while fuel cells support extended back-up operation, eliminating diesel combustion during routine operations.

Grid Integration and Decarbonization

Data centers interface with regional electric grids as high-capacity, high-load-factor consumers. Scope 2 emissions are addressed through clean power procurement frameworks:

24/7 Hourly Carbon-Free Energy (CFE): Moving beyond annual net-zero matching, operators procure local renewable energy matched on an hourly basis to real-time facility demand, utilizing smart-grid tracking.

Power Purchase Agreements (PPAs): Operators execute long-term physical or virtual PPAs that directly fund utility-scale solar, wind, and geothermal projects within the same grid region.

Waste Heat Repurposing: Facilities capture high-grade thermal exhaust from liquid-cooled rack loops (40--$60°$C) and export it to local district heating networks, industrial facilities, or agricultural greenhouses, reducing regional fossil fuel usage.

Emission Tier / Scope	Primary Operational Source	Dominant Atmospheric Pollutants	Engineering Control & Decarbonization Mechanism
Scope 1 (Direct) [cite: 14]	Emergency backup generators, fuel storage.	NO_x, CO, $PM_{10/2.5}$, VOCs, fossil CO_2.	EPA Tier 4 Final SCR/DPF systems, HVO renewable diesel fuel switching, BESS/Fuel Cell substitution.
Scope 2 (Indirect Grid)	Utility electricity consumption for servers and cooling.	Systemic power grid	24/7 Hourly Carbon-Free Energy matching, regional

Emission Tier / Scope	Primary Operational Source	Dominant Atmospheric Pollutants	Engineering Control & Decarbonization Mechanism
[cite: 14]		CO_2, SO_2, and NO_xemissions.	PPAs, high-temperature heat reuse export.
Scope 3 (Supply Chain) [cite: 14]	Upstream server manufacturing, semiconductor fabrication, structural concrete.	Embodied carbon, manufacturing chemical emissions.	Low-carbon concrete, recycled structural steel, EPD-verified hardware, hardware lifecycle extending.

Acoustic Attenuation, Structural Vibration Isolation, and Community Quality of Life

The proximity of data centers to residential zones makes operational noise and low-frequency vibration primary sources of community concern. Addressing these factors requires pre-construction acoustic modeling, mechanical vibration isolation, and compliance with property line noise limits.   Primary Mechanical Sources:

— Rooftop Dry Coolers & Chillers: Continuous low-frequency drone (63-250 Hz) [cite: 5, 34, 35]

— High-RPM Rack/ASIC Fans: High-frequency directional whine (>85 dBA) [cite: 5]

— Backup Diesel Generators: Intermittent combustion noise & exhaust pulsation

— Electrical Transformers: Narrow-band magnetostrictive hum (120 Hz harmonics) [cite: 35]

Acoustic Physics and Exterior Noise Propagation

Operational sound from data centers originates from primary mechanical and electrical subsystems. Sound pressure propagation across open terrain follows the inverse square law, yielding a 6 dBAreduction per doubling of distance from a point source:

$$L_{p2} = L_{p1} - 20\log_{10}\left(\frac{d_2}{d_1}\right)$$

However, low-frequency sound waves (< 125 Hz) generated by massive air-handling arrays experience minimal atmospheric attenuation and readily pass through light building structures, creating indoor acoustic annoyance for neighboring residents.

To ensure compliance with local ordinances—which typically enforce property line limits of $45\text{--}55\text{ dBA}$at night and $60\text{--}70\text{ dBA}$during daytime—project teams employ engineering controls:

3D Predictive Computer Acoustic Modeling: Using ISO 9613-2 propagation algorithms, acoustic engineers construct 3D sound models prior to site construction. The model incorporates equipment sound power data, terrain topography, building geometry, reflective surfaces, and local weather patterns to generate sound contour maps.

Acoustic Barrier Walls and Earthen Berms: Perimeter sound walls and earthen berms break the line-of-sight between equipment and sensitive receptors. A barrier breaking direct line-of-sight achieves a baseline 5 dBAnoise reduction; increasing barrier height to force sound wave diffraction can achieve total noise reductions of 10--11 dBA, cutting perceived loudness in half. Sound walls require a minimum surface density of 20--25 kg/$m^2$to prevent sound transmission through the structure.

Louver and Baffle Silencers: Generator room air intake/exhaust openings and air handler plenums are fitted with internal silencers. These components contain sound-absorbing fibrous insulation encased in perforated metal baffles, engineered to attenuate targeted noise frequencies without causing excessive static pressure drops.

Fan Equipment Selection: Selecting larger-diameter fans running at lower rotational speeds reduces sound generation at the source while maintaining required airflow volume.

Structural Vibration Control and Internal Occupational Safety

Low-frequency mechanical vibration propagates through structural concrete, radiating as noise and potentially impacting sensitive computing hardware. High sound pressure levels ($>$ 80 dBA) and ground vibration can induce resonance in Hard Disk Drive (HDD) head assemblies, leading to read/write performance degradation.

To isolate vibration, mechanical equipment—including chillers, pumps, and generators—is mounted on heavy concrete inertia bases supported by steel spring isolators, elastomeric pads, and flexible pipe connectors. To protect facilities from external ground vibration caused by nearby rail or truck traffic, engineers construct perimeter isolation trenches (1.0 m deep by 0.5 mwide) backfilled with vibration-absorbing foam, attenuating incoming low-frequency vibration amplitudes by up to 85%.

Occupational noise levels within server rooms frequently reach 70--80 dBAin cold aisles and can exceed 80--85 dBAin hot aisles due to high-density rack fan exhaust. Under occupational safety guidelines (e.g., OSHA standards), permissible exposure durations drop rapidly as sound levels rise, calculated using a 3 dBAor 5 dBAexchange rate:

$$t = \frac{480}{2^{(L-85)/3}}$$

Where $t$represents maximum allowable exposure duration in minutes, and $L$is the noise level in dBA. Facilities maintain occupational safety by deploying sound-dampening server cabinets lined with fire-rated acoustic foam, establishing quiet maintenance zones, and requiring hearing protection programs for technicians working in active halls.

OSHA Permissible Noise Exposure Limits (3 dBA Exchange Rate):

— 85 dBA: Maximum allowable duration = 8 hours (480 minutes)

— 88 dBA: Maximum allowable duration = 4 hours (240 minutes)

— 91 dBA: Maximum allowable duration = 2 hours (120 minutes)

— 94 dBA: Maximum allowable duration = 1 hour (60 minutes) [cite: 42]

Community Integration, Grid Stability, and Economic Impact

Data centers affect community quality of life through infrastructure demands, land use adjustments, and municipal utility interactions. Managing community impacts requires structured utility agreements and transparent engagement:

Utility Tariff Structures and Ratepayer Insulation: To prevent large data center loads from inflating electrical costs for local residents, utilities require facilities to subscribe to specialized industrial rate schedules. These agreements mandate that data centers directly pay for all necessary transmission line upgrades, dedicated substations, and grid stability assets, protecting local residential ratepayers from capital improvement costs.

Traffic Management Protocols: Facilities generate high traffic during construction, followed by negligible operational traffic profiles. Site development plans specify heavy construction traffic routing away from residential streets and require on-site vehicle queuing areas.

Community Benefit Agreements (CBAs): Operators engage local authorities through binding CBAs. These agreements establish clear standards for sound monitoring, fund local environmental initiatives, support public infrastructure upgrades, and guarantee regular environmental reporting to host communities.

Comprehensive Environmental Synthesis and Operational Recommendations

Designing a green data center requires balancing thermal management, energy efficiency, water stewardship, emission reduction, and community quality of life. Because optimization in one area can affect performance in another—such as zero-water dry cooling increasing fan power demand—facility design must rely on an integrated systems engineering approach.

SITE SELECTION & PLANNING:

— Evaluate localized watershed stress & grid carbon intensity

— Verify zoning buffer distances to residential property lines

— Execute 3D predictive acoustic modeling (ISO 9613-2)

BUILDING & THERMAL ENGINEERING:

— Pursue LEED BD+C Data Centers / BREEAM certifications

— Align HVAC operating boundaries with ASHRAE TC 9.9 Class A2-A4 / H1

— Deploy closed-loop direct-to-chip or liquid immersion cooling [cite: 7, 27]

RESOURCE PROTECTION & DECARBONIZATION:

— Mandate dry-cooler heat rejection to eliminate operational water use [cite: 3, 7]

— Permitting Tier 4 backup engines fueled by Hydrotreated Vegetable Oil

— Implement 24/7 Hourly Carbon-Free Energy matching & local PPAs

— Export waste heat to regional district heating infrastructure

COMMUNITY QUALITY OF LIFE:

— Install perimeter acoustic barrier walls & louver silencers

— Isolate heavy machinery using spring isolators & foam trenches

— Establish industrial utility tariffs to protect residential ratepayers

To ensure long-term environmental compatibility and operational resilience, data center developers, structural engineers, and operating enterprises should execute the following core recommendations:

Conduct Integrated Site Selection: Site selection must evaluate localized watershed stress alongside power grid carbon intensity. Placing data centers in cooler regions with low water stress and abundant renewable power minimizes direct cooling demands while reducing indirect off-site carbon impacts.

Deploy Advanced Liquid Cooling: Implement direct-to-chip or liquid immersion cooling architectures for high-density compute workloads. These technologies reduce internal fan power consumption, lower operational noise, improve facility PUE toward 1.1, and enable year-round dry-cooler heat rejection without consuming local potable water ($WUE \to 0$). In-rack liquid cooling for AI GPU clusters and outdoor dry-cooler heat rejection work together as part of a single system

Execute Pre-Construction Acoustic and Vibration Isolation: Perform ISO 9613-2 compliant 3D computer acoustic modeling prior to finalizing site layouts. Integrate perimeter sound walls, louver silencers, and foam-filled ground isolation trenches to ensure operational noise remains within strict residential property-line limits.

Decarbonize On-Site Backup Power: Equip emergency power systems with EPA Tier 4 Final engines utilizing Selective Catalytic Reduction. Transition generator fuel supplies to Hydrotreated Vegetable Oil (HVO) and integrate Battery Energy Storage Systems (BESS) to support microgrid frequency response and reduce diesel combustion testing.

Formalize Sustainability Governance and Community Agreements: Certify facilities under LEED BD+C or BREEAM whole-building standards alongside ISO 50001 energy management frameworks. Maintain transparent reporting of key operational metrics—Power Usage Effectiveness (PUE), Water Usage Effectiveness (WUE), and Carbon Usage Effectiveness (CUE)—and enter into legally binding Community Benefit Agreements to support local infrastructure and ensure long-term community alignment.

APPENDIX – Data Center / Indoor Farm Heat Integration

The liquid-to-dry exchanger approach is well suited for interfacing with a Controlled Environment Agriculture (CEA) facility.

In fact, combining **in-rack liquid cooling for high-density AI clusters** with an **outdoor dry cooler** provides the right thermal profile and operational flexibility needed to run a continuous, year-round indoor greenhouse or robotic farm.

1. High-Density AI Liquid Cooling Solves the "Low-Grade Heat" Problem

Historically, air-cooled data centers were poor candidates for greenhouse integration because they rejected low-grade heat: large volumes of lukewarm exhaust air (25°C to 35°C). Transferring heat from lukewarm air into greenhouse water systems required capital-intensive industrial heat pumps.

In-rack liquid cooling on high-density AI workloads (such as NVIDIA B200/GB200 or AMD MI300 clusters) changes the thermal physics:

- **High Exit Temperatures:** Direct-to-chip cold plates return fluid at $45°C$ **to** $60°C+$ **(**$113°C$ **to** $140°F+$**)**.
- **Direct Thermal Utility:** Water at $50°C+$ can be piped directly into a CEA facility's hydronic heating network—such as root-zone bench heating, radiant floor piping, or air-handler heating coils—via standard stainless-steel heat exchangers without needing heat pumps to boost the temperature.

2. The Outdoor Dry Cooler Is Essential as a "Thermal Safety Valve"

The primary engineering challenge of data center-greenhouse co-location is **thermal load mismatch**:

- **The AI Data Center Load:** High-density GPU clusters run continuous AI training jobs, generating a flat, constant thermal load 24/7/365.
- **The CEA Greenhouse Load:** A greenhouse's heating demand varies wildly based on ambient outdoor temperatures and solar irradiance. Demand peaks on cold winter nights and drops to zero on hot summer days.

This is where the outdoor dry cooler plays a crucial role: It acts as the primary backup heat dump. A 3-way motorized modulating valve splits the hot water coming from the data center's Coolant Distribution Unit (CDU):

1. **When the greenhouse needs heat (e.g., Winter/Night):** 80--100% of the hot facility fluid is routed to the greenhouse's liquid-to-liquid heat exchanger.
2. **When the greenhouse needs no heat (e.g., Summer/Day):** The fluid bypasses the greenhouse and is routed to the outdoor dry cooler, which vents the heat into the outside air without consuming water.

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                    +--> [CEA Greenhouse Hydronic Loop] (Winter/Night Demand)
[AI GPUs] --> [CDU Exchanger] --(Modulating Valve)
                    +--> [Outdoor Dry Cooler] (Summer/Excess Heat Relief)
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3. Integrated Architecture and Best Practices

To make the interface between an AI liquid-cooled facility and a robotic CEA farm reliable and efficient, incorporate these structural design practices:

A. Intermediate Plate-and-Frame Heat Exchangers

Never mix the fluid loops. Keep three separate closed circuits:

1. **IT Secondary Loop:** Deionized water or dielectric fluid running through GPU cold plates.
2. **Data Center Primary Facility Loop:** Treated water/glycol running between the CDU, dry cooler, and greenhouse plant interface.
3. **Greenhouse Agricultural Loop:** Clean irrigation or hydronic heating water circulating through the indoor farm. An intermediate stainless-steel plate heat exchanger transfers thermal energy safely between the facility loop and the agricultural loop without risk of cross-contamination or pressure imbalance.

B. Thermal Energy Storage Tanks (Hot Water Buffers)

Installing insulated hot water storage tanks between the data center and the CEA farm acts as a thermal flywheel. Excess heat generated during sunny late-afternoon hours can be stored in the tanks and discharged into the greenhouse during freezing overnight temperatures, dampening load spikes.

C. Full Circularity Potential (Power, Heat, and CO_2)

Advanced "Farm Park" models pair data centers and CEA facilities with clean combined heat and power (CHP) microgrids or fuel cells:

- Electricity from the microgrid powers the AI servers and robotic farm systems.
- Waste heat from both the GPUs (high-temperature liquid) and the microgrid exhaust warms the greenhouse.
- Scrubbed CO_2 exhaust from cleaner power generation is piped into the sealed greenhouse atmosphere to boost crop yields by $20\text{--}30\%$.

In-rack liquid cooling provides the **high temperature fluid** needed to make indoor greenhouse heating economically viable, while the outdoor dry cooler provides the **operational safeguard** to ensure AI servers never overheat when the farm doesn't need the thermal energy.

Sub-surface thermal storage

Subsurface thermal storage can enable farm/data center energy reduction by integrating an underground cold storage system (Cold UTES) with a combined data center and indoor farm creates a balanced, year-round microclimate loop.

In this setup, the underground storage operates like a **seasonal thermal battery** that flips functions between winter and summer.

How the Integrated 4-Season Loop Works

WINTER MODE

Data Center Heat ------------> Heats the Greenhouse

Freezing Outdoor Air ---------> Charges the Underground "Cold Store"

SUMMER MODE

Underground Cold Store -------> Cools BOTH the Data Center & Greenhouse

Excess Heat Discharged --------> Pumped to "Hot Well" or Vented at Night

1. Winter Mode: Heating the Farm & Charging the Cold Store

- **Greenhouse Heating:** The AI GPU clusters generate continuous high-temperature liquid (45--60°C). This heat is piped directly into the greenhouse's hydronic heating system to warm the plants during cold months.
- **Cold Storage Charging:** At the same time, freezing outdoor winter air runs through dry coolers to chill water cheaply without mechanical refrigeration. This chilled water is pumped deep underground into the subsurface reservoir, "charging" the ground with cold thermal energy for the coming months.

2. Summer Mode: Cooling Both Facilities from One Cold Store

During peak summer heatwaves (35--40°C +), both facilities face cooling challenges:

- **Data Center Need:** Outdoor air is too hot for dry coolers to keep GPUs at safe operating temperatures.
- **Greenhouse Need:** Solar radiation and indoor lighting turn greenhouses into ovens, causing crop heat stress and humidity spikes.

The Solution: The system pumps stored chilled water (10--15°C) up from the subsurface cold store and splits it into two secondary heat exchangers:

1. **Loop A (Data Center):** Absorbs heat from the GPU coolant loop, allowing the data center to operate without power-hungry chillers or evaporative water consumption.
2. **Loop B (Greenhouse):** Drives the farm's chilled-water air handlers to cool and dehumidify the growing space.

Why This Synergy Works So Well

1. **Solves the Greenhouse Summer Cooling Problem:** Heating greenhouses in winter is straightforward, but cooling and dehumidifying them during summer afternoons is traditionally capital- and energy-intensive. Tapping into the data center's Cold UTES reservoir gives the farm essentially "free" low-carbon cooling.
2. **Eliminates Thermal Saturation:** Standard geothermal systems fail when they constantly dump heat underground without removing it. Because the greenhouse extracts large amounts of heat from the system during winter, and cold winter air actively recharges the subsurface, the underground reservoir stays thermally balanced year after year.
3. **Double Duty on Infrastructure:** The same pumps, boreholes, and piping infrastructure serve both the data center and the farm, significantly improving the overall return on investment (ROI) of the geothermal drilling costs.

Key Design Requirement: A "Two-Well" or "Warm/Cold Zone" Layout

To make this work in practice, the subsurface system must be designed as a **doublet system (a Cold Well and a Warm Return Well)**:

- Chilled water is extracted from the **Cold Well** to cool the data center and farm.
- The water absorbs heat from both facilities and is pumped into a separate **Warm Return Well** underground.
- During the following winter, the warm water is drawn out, cooled by cold outdoor air, and injected back into the Cold Well to reset the system for the next summer.

APPENDIX: Modeling geothermal and subsurface thermal management

Modeling frameworks, algorithms, and simulation libraries are openly available across several key repositories and academic artifact distributions:

1. NREL / NLR Subsurface & Techno-Economic Modeling Libraries

- **GEOPHIRES-X (NREL/GEOPHIRES-X on GitHub):**

[cite: 3]

  - **What it is:** The primary open-source Python tool developed by NREL to model the thermodynamics and levelized cost of geothermal and thermal energy storage systems.
  - **Function in Cold UTES:** It models reservoir drawdown, surface heat exchangers, wellbore dynamics, and economic trade-offs for direct-use thermal storage and subsurface energy dispatch.
- **NREL Thermal Energy Storage & Building Energy Simulation Tools:**
  - NREL integrates GEOPHIRES-X alongside **OpenStudio** / **EnergyPlus** and specialized Modelica libraries (e.g., Buildings library from LBNL) to simulate the building-to-ground heat transfer mechanisms used in their published Cold UTES data center reports.

2. UChicago Large-Scale Sustainable Systems Group (LSSG) / Prof. Andrew Chien

Prof. Chien's group at the University of Chicago releases code, dataset traces, and simulation artifacts through the **LSSG GitHub organization** and their **Zero-Carbon Cloud (ZCCloud)** project portal:

- **FlexCoolDC Framework:**

[cite: 2]

  - **What it is:** Code developed by Chien and collaborators (including Wedan Emmanuel Gnibga) to simulate data center cooling flexibility.
  - **Function in Cold UTES:** It evaluates multi-objective trade-offs between server power draw, ambient weather, dry-cooler capacity, and thermal storage dispatches to harmonize water usage, carbon emissions, and operational cost.

- **ZCCloud & Middlebox Simulation Artifacts:**

[cite: 2, 6]

  - **What it is:** Repositories supporting workload scheduling on variable-capacity or thermal-constrained data centers.
  - **Function in Cold UTES:** Used in their paper (*"Improving Datacenter IT Capacity, Cooling Efficiency and Lifetime with Underground Thermal Energy Storage Systems"*) to calculate how shifting peak cooling loads to subsurface storage allows data centers to safely increase their IT capacity ($+9.8\%$ to 20%) within fixed grid interconnect limits.

3. Subsurface Geothermal Solvers Used in DOE/LBNL Co-Studies

For the physics of underground thermal recharge and fluid transport in boreholes (BTES) and aquifers (ATES), the national laboratories pair these data center models with open-source subsurface numerical solvers:

- **OpenGeoSys (OGS):** An open-source finite-element solver widely used for coupled thermo-hydro-mechanical (THM) processes in subsurface thermal energy storage.
- **PyTOUGH / TOUGH3:** Python scripting interfaces developed at Lawrence Berkeley National Laboratory (LBNL) to simulate multi-phase fluid flow and heat transfer in porous media and fractured rock reservoirs.

How to Access & Reproduce

1. **For GEOPHIRES-X:** Clone directly from GitHub via git clone https://github.com/NREL/GEOPHIRES-X.git or install via PyPI (pip install geophires-x).
2. **For UChicago LSSG Artifacts:** Access published computational artifacts and traces directly from the **Large-Scale Sustainable Systems Group** project page at people.cs.uchicago.edu/~aachien/lssg/.

REFERENCES – Green Data Center Methods & Standards

Author / Institution	Publication Source & Identifiers	Primary Focus & System Boundary	Key Environmental Findings & Quantitative Baselines
Shehabi et al. (Lawrence Berkeley National Laboratory)	United States Data Center Energy Usage Report (2016, 2024, 2025 Updates)	Bottom-up national accounting of server shipments, infrastructure power draw, and future growth scenarios.	U.S. data center load expanded from 76 TWh(1.9% of national electricity) in 2018 to 176 TWh(4.4%) in 2023. Forecasted to reach 9.5% to 15.3%of total U.S. electricity by 2030.
Siddik, Shehabi, & Marston [cite: 4, 12]	The environmental footprint of data centers in the United States (Environmental Research Letters, 2021)	Spatially detailed bottom-up assessment of direct/indirect water and carbon footprints across 2,110 U.S. sub-basins.	Data centers accounted for ~ 0.5%of U.S. GHG emissions. One-fifth of direct water footprints draw from moderately to highly water-stressed watersheds; nearly half of facility electricity originates in water-stressed power control areas.
Guidi & Dominici (Harvard T.H. Chan School of Public Health)	Study Maps Water Footprint of AI Data Centers (2026)	Empirical evaluation of 472 large U.S. facilities separating direct cooling consumption from off-site power generation water use.	Operational water use totals ~ 300 billion liters/yearacross sample facilities. Approximately 75%of the total hydrological footprint is embedded in off-site electricity generation rather than direct facility cooling.

Author / Institution	Publication Source & Identifiers	Primary Focus & System Boundary	Key Environmental Findings & Quantitative Baselines
Ristic, Madani, & Makuch [cite: 3, 18]	The Water Footprint of Data Centers (Sustainability, 2015)	Lifecycle water footprint accounting per unit of computational throughput and energy consumption.	Data center water footprints range from 1,047 to 151,061 m^3/TJ. Outbound data traffic generates a water footprint of 1 to 205 liters per gigabyte, dominated by the upstream power generation mix.
Privette et al. (Veolia Institute / EOS)	Toward a Sustainable Digital Future: The Multi-Faceted Water Footprint of Data Centers (2026)	Multidisciplinary framework tracking direct cooling, power-embedded water, and hardware embodied water.	Global data center water consumption projected to increase from 148 billion gallons/year(560 billion liters) to 317 billion gallons/year(1,200 billion liters) by 2030.

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