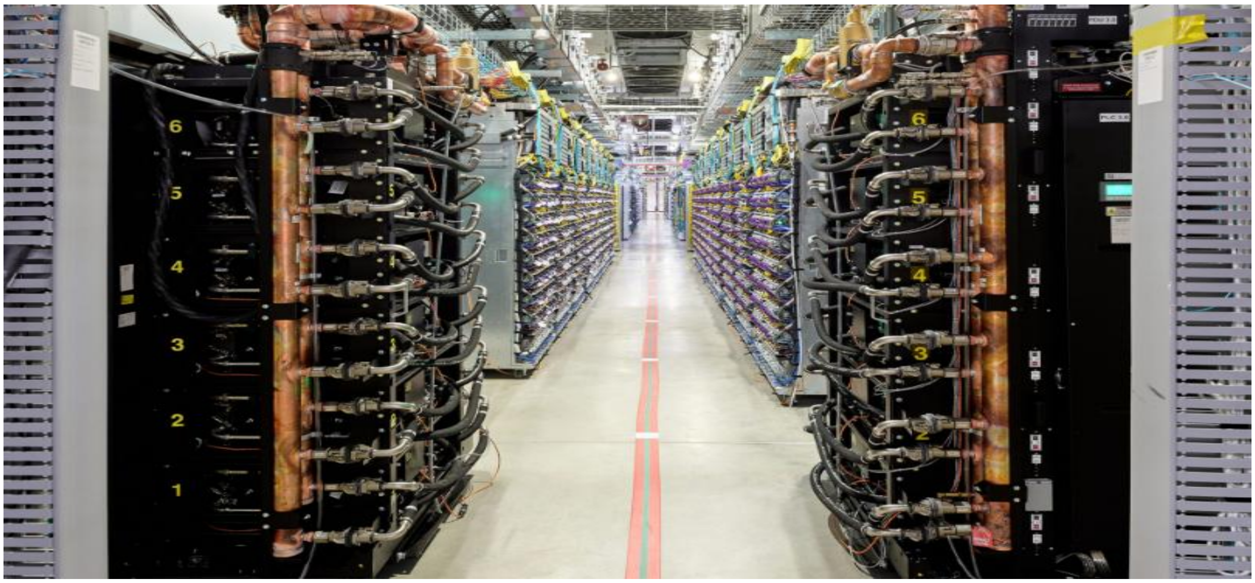
White Paper

Fresh Water Consumption in Traditional Air-Cooled Systems and Advancing to Closed-Loop, Hybrid, Dielectric, and Quantum Solutions



Executive Summary

Data centers are the backbone of the digital economy, powering cloud computing, AI, and emerging Quantum Technologies. However, traditional air-cooled facilities rely heavily on evaporative cooling towers and chillers, consuming vast quantities of fresh water-----often hundreds of millions of gallons annually per medium-sized site and billions across the U.S. This exacerbates water scarcity in stressed regions, with direct on-site consumption rivaling that of small cities.

Modern alternatives, closed-loop liquid cooling, hybrid systems, dielectric immersion cooling, and cryogenic dilution refrigerators for quantum computing, dramatically reduce or eliminate fresh water use while improving energy efficiency (measured by Power Usage Effectiveness, or PUE). These technologies achieve **Water Usage Effectiveness (WUE) near zero**, enable higher computing densities for AI workloads, and support sustainability goals. This White Paper compares these approaches, highlighting technical, environmental, and economic benefits toward water-resilient infrastructure.

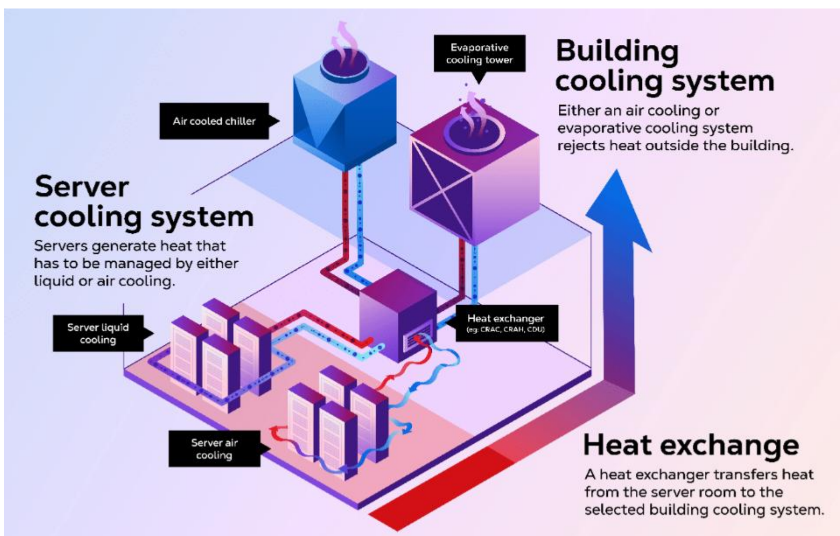
Ted J. Pappas, Director of Operations

1. Introduction: The Cooling Challenge in Data Centers

Global Data Center electricity demand is surging due to AI and Hyperscale computing, with cooling accounting for up to 40% of energy use. Traditional designs prioritize air circulation but depend on water evaporation for heat rejection in most climates. As facilities scale to support Exascale (ultra large scale -10^{18} (one quintillion) floating-point operations per second) AI training and quantum systems, water footprints have become a critical constraint alongside energy and land use. Metrics like WUE (liters of water per kWh of IT energy) quantify this: traditional systems average 1.9 L/kWh (liters per kilowatt hours), while advanced designs approach the ideal of 0.

2. Traditional Air-Cooled Data Centers and Fresh Water Consumption

Conventional air-cooled Data Centers use Computer Room Air Conditioning (CRAC) units, Computer Room Air Handlers (CRAH), chillers, and evaporative cooling towers. Hot air from servers is cooled by chilled water loops; heat is ultimately rejected via cooling towers where water evaporates, absorbing thermal energy.



This open-loop process leads to significant "consumptive" losses (*water not returned to the source*).

Key Impacts:

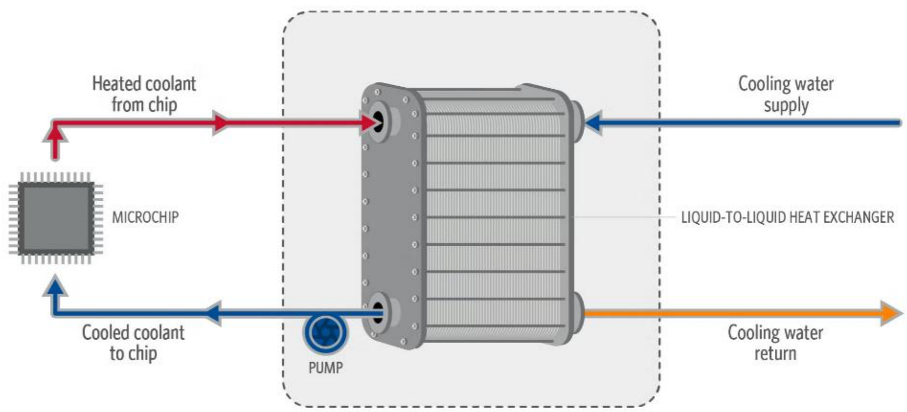
- A medium-sized (e.g., 1 MW) facility can consume 25.5 million liters (6.7 million gallons) of water per year; larger hyperscale sites may use 5 million gallons per day, equivalent to a town of 10,000–50,000 people. U.S. data centers collectively consume tens to hundreds of billions of gallons annually.
- WUE typically ranges 1.5–2.5 L/kWh in evaporative systems (vs. near-zero for pure dry air cooling, which trades off higher PUE).

- Environmental and societal costs include competition with agriculture/municipal needs in drought-prone areas, plus indirect water use for electricity generation. Projections show water demand rising 870% in coming years without intervention.

While air cooling is mature and lower-cost upfront, its water intensity is unsustainable amid pressures and AI-driven density growth.

3. Closed-Loop Cooling Systems: Recirculation for Major Water Savings

Closed-loop systems circulate coolant (often water or water-glycol mixes) in sealed pipes or Direct-to-Chip Cold Plates, rejecting heat via dry coolers, heat exchangers, or external loops without intentional evaporation. Makeup water is minimal (for rare leaks or maintenance).



Advantages:

- Freshwater reduction of up to 70–90% (or zero evaporation in optimized designs like Microsoft's next-generation facilities). A single site can save over 125 million liters annually.
- Lower WUE (<0.03–0.1 L/kWh) with PUE improvements (often 1.1–1.3).
- Compatible with high-density AI racks; integrates with free cooling in moderate climates.

4. Hybrid Cooling: Balancing Efficiency and Resilience

Hybrids combine liquid (direct-to-chip or rear-door) for high-heat components (80–85% of load) with air or selective evaporative assistance for peaks or lower-density areas. Adaptive controls switch modes based on climate/load. Performance:

- Water savings of 90%+ vs. traditional evaporative towers while maintaining energy efficiency.
- Energy savings of 20–50% in seasonal free-cooling modes; supports AI densities without full infrastructure overhauls.

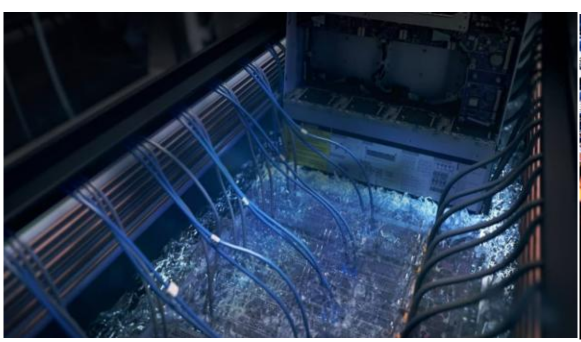
This approach offers flexibility for retrofits and regions with variable weather.

5. Dielectric Immersion Cooling: Water-Free, High-Efficiency Liquid Cooling

Immersion cooling submerges servers entirely in non-conductive dielectric fluids (synthetic oils or engineered liquids). Heat transfers directly to the fluid, which is pumped through heat exchangers. Single-phase (liquid only) or two-phase (boiling/vapor) variants exist.

Key Benefits:

- **Zero fresh water use for cooling**—fluids are recycled indefinitely with negligible loss.
- Dramatic efficiency: PUE as low as 1.05–1.10 (vs. 1.4–1.8 for air); cooling energy reduced by up to 50%, enabling 2–3x higher rack densities.
- Quieter operation, smaller footprint, and simplified maintenance (*no air filters/fans*).




Dielectric fluids are non-corrosive and environmentally manageable, making this ideal for Hyperscale AI deployments.

6. Quantum Computing Data Centers: Dilution Refrigerators and Cryogenic Cooling

Quantum processors require millikelvin (mK) temperatures to maintain superposition and coherence, achieved via dilution refrigerators using a $^{3}He/^{4}He$ mixture.

These cryogen-free (or closed-loop) systems employ pulse-tube pre-coolers, heat exchangers, and vacuum pumps—**no evaporative water towers**.

Characteristics:

- Negligible freshwater consumption: Cooling relies on helium isotopes and electrical/mechanical processes. Any support water (e.g., for compressor chillers) is minimal and often closed-loop.
- Challenges center on helium scarcity (especially ^{3}He) and high electrical power for cryogenics but scaling via centralized plants or cryogen-free designs minimizes resource intensity.
- Future Quantum Data Centers (hundreds/thousands of dilution units) will prioritize energy efficiency and helium recycling over water.

Conclusion and Recommendations

Traditional air-cooled Data Centers impose unsustainable fresh water demands that conflict most municipality sustainability targets. Closed-loop, hybrid, dielectric immersion, and cryogenic quantum systems offer proven pathways to **near-zero WUE** while enhancing performance and reducing total energy use. Adoption requires upfront investment but delivers long-term savings, regulatory compliance, and community goodwill.