

©ASHRAE www.ashrae.org. Used with permission from ASHRAE Journal at <https://www.dlbassociates.com/>. This article may not be copied nor distributed in either paper or digital form without ASHRAE's permission. For more information about ASHRAE, visit www.ashrae.org.

Part 1

Data Centers and the Water-Energy Nexus

BY DAVID QUIRK, P.E., MEMBER ASHRAE; RAVEN JONES, P.E., ASSOCIATE MEMBER ASHRAE; KATE VAWTER, P.E., MEMBER ASHRAE

The rapid expansion of artificial intelligence (AI) infrastructure has intensified attention and public scrutiny on the energy consumption of data centers. However, energy only represents one dimension of the environmental impact of digital infrastructure. Water use is emerging as a critical factor in determining sustainability, site selection and ultimately construction of AI data centers.

This column begins a three-part series examining the water-energy nexus in data centers and the impacts associated with cooling system selection. As computing densities and thus thermal loads increase, cooling system selection is consequential for its impact on both energy and water consumption.

The column introduces industry water benchmarking metrics to compare different cooling strategies across geographic regions. It explores how the industry shift away from water-consuming adiabatic and evaporative cooling systems toward fully air-cooled systems is not a direct water-energy trade-off. As public attention shifts to the consumption of water resources due to AI expansion, the industry must respond with firm metrics that quantify water consumption in data centers that reflect the cooling technology, method of energy production and regional climate risk.

Water Metric Definitions: WUE and WUE_{source}

The Greenhouse Gas (GHG) Protocol classifies GHG emissions as Scope 1, direct emissions from site-level sources (i.e., fuel combustion from generators), and Scope 2, indirect emissions from purchased electricity.¹

In 2011, The Green Grid introduced analogous metrics: water usage effectiveness (WUE) and WUE_{source} .

Like Scope 1 and Scope 2 emissions, WUE frameworks distinguish site and source water consumption. WUE measures direct, site-level water use from data center operations. WUE_{source} quantifies the water required for energy production, considering regional interconnection and energy production methods. Together, these metrics calculate the total water footprint of data centers by quantifying both operational and upstream consumption. The formulas^{2,3} for WUE and WUE_{source} are detailed below:

$$WUE = \frac{\text{Annual Site Water Consumption (L)}}{\text{Annual IT Equipment Energy Consumption (kWh)}} = \frac{(I_w - O_w)}{E_{IT}}$$

where

I_w = Incoming water (L/yr)

O_w = Water returned or offset (L/yr)

E_{IT} = IT equipment energy consumption (kWh/yr)

David Quirk, P.E., is CEO, Raven Jones, P.E., is energy executive director and Kate Vawter, P.E., is energy engineer senior specialist at DLB Associates.

Note: WUE may be applied in mixed-use buildings when measurement of the difference between water used for the data center and that for other functions (like domestic water) is possible.

$$WUE_{\text{source}} = (EWIF \times PUE) + WUE$$

where

EWIF = energy water intensity factor, volume of water used for generating energy (L/kWh), which is discussed later in this column.

Similar to how power utilization effectiveness (PUE) is classified by the granularity of IT equipment energy measurement (E_{IT}), from the UPS to the PDU and individual IT equipment,⁴ WUE is classified by the granularity and scope of site water consumption measurement. ISO³ has three categories of WUE with the third functioning similarly to The Green Grid's WUE_{source} . See Table 1 for additional details.

Quantifying Water Scarcity: The WUI Metric

Water usage impact (WUI), also introduced by The Green Grid, extends WUE by incorporating regional water scarcity into the evaluation of data center water use. It uses a water stress factor (WSF) determined by the overall water risk (OWR) indicator from the Aquaduct Water Risk Atlas from the World Resources Institute (WRI).⁵ The OWR indicator is an aggregate of all other water risk indicators from the Aquaduct Water Risk Atlas. The formula for WUI is as follows^{6,7}:

$$WUI = WUE \times (WSF + 1)$$

where

WSF = water stress factor"; uses OWR ratings on a scale from 0 (low) to 5 (extremely high). For a high-level image of OWR values from the Water Risk Atlas, see Figure 1.

TABLE 1 WUE categories per ISO.³

SOURCE	CATEGORY 1 (WUE ₁) BASIC	CATEGORY 2 (WUE ₂) INTERMEDIATE	CATEGORY 3 (WUE ₃) ADVANCED
Water Input (I_w)	Physical water input of the DC.	Physical water input of the DC.	Water consumption of energy production and physical water input excluding rainwater.
Water Output (O_w)	No water reuse; water input equates to water use.	Water output of the DC for nonindustrial reuse.	Water output of the DC with measurement of nonindustrial and industrial reuse.
Additional Reporting	None.	None.	Regional water stress level and land consumption.

FIGURE 1 Overall water risk map from the World Resources Institute's Aquaduct Water Risk Atlas.⁵

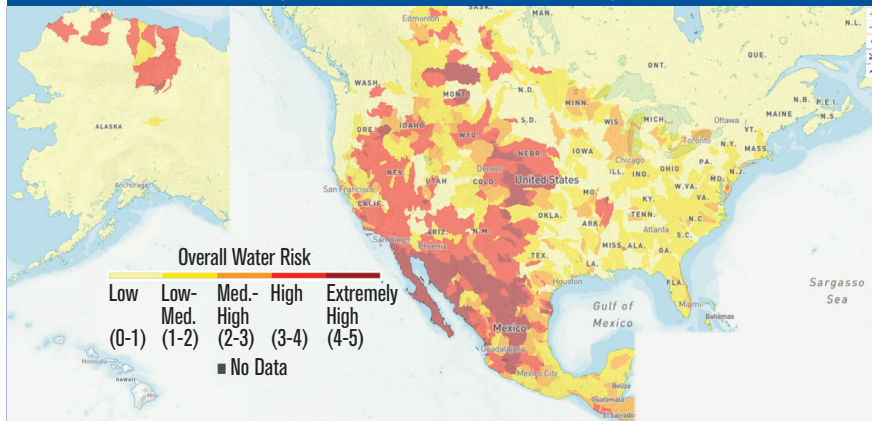


TABLE 2 Water use metrics summary.

WATER METRIC	DEFINITION	CALCULATION	USE	UNITS
WUE ^{2,3}	Water usage effectiveness	$\frac{(I_w - O_w)}{E_{IT}}$	(On-site) data center water use metric	$\frac{L}{kWh}$
WUE _{source} ³	WUE with energy source water use	$(EWIF \times PUE) + WUE$	(On-site + off-site) data center water use metric	$\frac{L}{kWh}$
WUI ^{6,7}	Water usage impact ^{6,7}	$WUE \times (WSF + 1)$	Measure regional impact of water use	$\frac{L}{kWh}$

The key differences between WUE, WUE_{source} and WUI are summarized in Table 2.

Upstream Water Use in Power Generation: Consumption vs. Withdrawal

For upstream water use, the distinction between water consumption and withdrawal is important. Consumption refers to the amount of water that is evaporated or otherwise removed from the immediate water environment.⁸ Withdrawal is defined as the amount of water removed from the ground or diverted from a water source for use.⁸ Consider a coal-fired power facility in the Eastern U.S. located near a river using once-through cooling that rejects heat directly to the water stream. Although this method consumes little-to-no water, it does withdraw and heat large

quantities of river water. In contrast, a nuclear power facility in the Western U.S. using a recirculating cooling cycle through evaporative cooling towers will consume or evaporate water but withdraws significantly less from the environment.

As a result, water consumption and EWIF for power generation facilities vary widely. The Green Grid recommends that EWIF values are obtained directly from the power generation facilities or the local utilities; otherwise, aggregate values can be used.² The NREL publishes EWIF values aggregated by power generation type, cooling technology, state and region.^{8,9} Ultimately, EWIF is critical to quantifying life-cycle-based water consumption in data centers. *Table 3* outlines median values of water consumption by generation type. (Calculation is explained in Note b.)

AI Data Center Cooling Systems: Recent Water Use Trends

Historically, many data centers used evaporative cooling strategies that minimized energy use but required significant on-site water consumption. Regional water constraints, permitting challenges and public concern have driven a shift toward fully air-cooled and adiabatic cooling technologies common to AI data centers.

Advancements in air-cooled chiller component design such as oil-free magnetic bearing compressors, high performance variable frequency drives (VFD) and refrigeration circuit optimization have significantly improved part-load efficiency. The rapid growth of AI and its associated high rack densities has further accelerated the adoption of direct liquid cooling, which can use higher chilled water supply temperatures and temperature differentials (ΔT). These advancements in cooling technology have resulted in lower data center PUE and nearly eliminated on-site water use.

However, different cooling technologies present nuances to the design of data center cooling systems that have both energy and water use impacts. An air-cooled data center, while locally water-efficient (WUE ~0), may indirectly increase water consumption through electricity production (WUE_{source}). Conversely, an adiabatic cooling system may reduce total water consumption across the energy system when reductions in upstream water use outweigh the on-site consumption.

Table 4 summarizes typical ranges of PUE and WUE

TABLE 3 Water consumption by power generation type.

GENERATION TYPE	U.S. CAPACITY SHARE (2024) ¹⁰	MEDIAN ^b WATER CONSUMPTION, (EWIF, L/kWh) ^{8,9}	MEDIAN ^b WATER WITHDRAWAL (L/kWh) ⁸
Natural Gas	45%	1.1	25.9
Coal	15%	1.8	39.8
Nuclear	20%	2.0	66.2
Hydro	5%	0 ^a	Unavailable
Solar (PV)	5%	0.1	Unavailable
Wind	10%	0	Unavailable
	Total: 100%	Weighted Average: 1.38, excluding hydro ^a and wind	Weighted Average: 38.6

^a The mechanism by which hydropower consumes water is largely due to reservoir surface water evaporation, which is highly variable and is independent from power generation.

^b Values are averaged from the median consumption/withdrawal values of power plants with particular cooling systems.

TABLE 4 Cooling system trade-offs for large-scale data centers.^{11,12}

FACILITY AND IT COOLING SYSTEM MIX	TYPICAL PUE RANGE ²	TYPICAL WUE ₁ RANGE (L/kWh)
Evaporative Cooling with Waterside Economizer with Air-Cooled Servers	1.15 – 1.23	1.7 – 2.8
Evaporative Cooling with Waterside Economizer with Liquid-Cooled Servers	1.05 – 1.25	1.7 – 2.5
Air-Cooled System with Air-Cooled Servers	1.3 – 1.6	0 ^a
Air-Cooled System with Liquid-Cooled Servers	1.05 – 1.2	0 ^a
Adiabatic Cooling with Airside Economizer with Air-Cooled Servers	1.02 – 1.32	0 – 0.2
Adiabatic Cooling with Liquid-Cooled Servers	1.01 – 1.15	0 – 0.4

^a WUE does not account for nonrecurring water uses, like initial chilled water system fill, allowing for a theoretical WUE of zero. In reality there are leaks, humidification control or other site specific uses.

across common facility and IT cooling architectures, which further illustrates the trade-offs between on-site water consumption and energy efficiency.

Regulatory Impacts

The outsized energy and water intensity of AI data centers are increasingly influencing how regulatory agencies and permitting authorities evaluate water use. These restrictions may include mandatory use of recycled or reclaimed water, adoption of air-cooled and closed loop cooling systems, mandatory water-use reporting, potable water withdrawal caps, aquifer modeling and multiagency reviews resulting in increased complexity and timeline of permitting.

ASHRAE Standard 90.4 and Water Consumption

ASHRAE Standard 90.4, *Energy Standard for Data Centers*, recently expanded its scope and purpose to include balancing the energy efficiency of data centers with the Society's commitment to decarbonization. Water consumption is explicitly mentioned in the standard. As such, a clear understanding of the water-energy nexus is critical to the ASHRAE SSPC 90.4 committee as it considers changes to the standard to incorporate water consumption. This process is underway.

Summary

Water use in data centers has been a persistent concern in the data center industry for more than two decades. With significant growth expected over the next decade, understanding the water-energy nexus is essential to stakeholders including governing bodies, electric utilities, planning boards, data center owners, design, energy and environmental engineers and standards organizations. Without this understanding, misallocation of water and energy resources will occur. An essential component of the required knowledge base is developing an understanding of various metrics that have been designed to quantify water use in the industry, such as The Green Grid's WUE, WUE_{source} and WUI. The next column in this series will explore how the industry has addressed water conservation and introduces an emerging framework for tracking water

use across data centers: water use credits (WUC).

References

1. World Resources Institute. 2004. "A Corporate Accounting and Reporting Standard the Greenhouse Gas Protocol." World Resources Institute. <https://tinyurl.com/3hat8dhe>
2. The Green Grid. 2011. "WP#35 - Water Usage Effectiveness (WUE): A Green Grid Data Center Sustainability Metric." The Green Grid. <https://tinyurl.com/95wf2jex>
3. ISO/IEC Standard 30134-9:2022, *Information Technology — Data Centres Key Performance Indicators*.
4. ISO/IEC 30134-2:2026, *Information Technology — Data Centres Key Performance Indicators*. <https://tinyurl.com/ka4vyjy5>
5. World Resources Institute. 2025. "Aqueduct." World Resources Institute. <https://tinyurl.com/38f54jts>
6. The Green Grid. 2025. "WP#95 Water Usage Impact (WUI) v1 Metric." The Green Grid. <https://tinyurl.com/5a9mrmpu>
7. The Green Grid. 2025. "WP#93 Data Center Resource Effectiveness (DCRE) v1 Metric." The Green Grid. <https://tinyurl.com/3dsy32tw>
8. Macknick, J., R. Newmark, G. Heath, K. Hallett. 2011. "A review of operational water consumption and withdrawal factors for electricity generating technologies." National Renewable Energy Laboratory. <https://tinyurl.com/snkja8np>
9. Torcellini, P., N. Long, R. Judkoff. 2003. "Consumptive Water Use for U.S. Power Production." National Renewable Energy Laboratory. <https://tinyurl.com/yx9xjhuv>
10. EIA. Undated. "Electricity in the U.S." U.S. Energy Information Administration. <https://tinyurl.com/238vvdttf>
11. Shehabi, A., et al. 2024. "2024 United States Data Center Energy Usage Report." Lawrence Berkeley National Laboratory. <https://tinyurl.com/46m98yp3>
12. Lei, N., E. Masanet. 2022. "Climate- and technology-specific PUE and WUE estimations for U.S. data centers using a hybrid statistical and thermodynamics-based approach." *Resources Conservation and Recycling* 182:106323. <https://doi.org/10.1016/j.resconrec.2022.106323> ■

Answering the Water Minimization Question

Which uses less water: air-cooled, adiabatic or evaporative cooling technologies? The answer to the water minimization question is site-specific and requires data on three metrics to provide an answer: the PUE of a cooling option, the WUE of a cooling option and the energy water intensity factor (EWIF) of the electricity delivered to the facility. *Table 5* provides an example of a 1 MW data center located in Georgia ($EWIF = 2.27 \text{ L/kWh}$)² with 50% system utilization. The lowest WUE_{source} system could be either the air-cooled chiller or the indirect adiabatic system depending on the values of PUE, WUE and EWIF. One hundred percent evaporative cooling, on the other hand, will almost always have a higher WUE and WUE_{source} when compared to other cooling options unless the EWIF is extremely high. ■

TABLE 5 Example WUE and WUE_{source} calculation with different minimums for WUE and WUE_{source}

COOLING SYSTEM	ANNUALIZED AVERAGE PUE	ANNUAL SITE ENERGY CONSUMPTION (kWh/yr)	AVERAGE ON-SITE WUE (L/kWh)	ANNUAL ON-SITE WATER CONSUMPTION (L/yr)	AVERAGE ANNUAL WUE_{source} (L/kWh)	POWER PLANT ANNUAL WATER CONSUMPTION (L/yr)	FACILITY + POWER PLANT ANNUAL WATER CONSUMPTION (L/yr)
Air-Cooled Chillers	1.30	5,694,000	0.00	0	2.95	12,925,380	12,925,380
Indirect Adiabatic with Dry Operation Most of Year	1.15	5,037,000	0.25	1,095,000	2.86	11,433,990	12,528,990
Evaporative Cooling with Wet Operation the Entire Year	1.05	4,599,000	2.30	10,074,000	4.68	10,439,730	20,513,730