Data Center High-Temperature Liquid Cooling and Heat Reuse Techno-Economic Study

William Becker, David Sickinger, Otto VanGeet, Shanti Pless, Grant Ellwood

The National Laboratory of the Rockies [1]

ABSTRACT

Data centers are energy-intensive facilities with growing demands for efficiency and cost-effective operations. Smaller, more distributed edge inference data centers are expected to proliferate as AI applications require low latency closer to the user of AI tools, which presents a growing opportunity to explore the systems implications of liquid cooling on water and energy use. This study analyzes the implementation of high-temperature liquid cooling systems in a prototypical inference 1-MW data center and explores the potential for heat reuse across varying climates with a goal to optimize energy efficiency, reduce capital and operational costs, and identify opportunities for high-performance cooling and water use reduction infrastructure. This analysis evaluated configurations utilizing a peak day hourly sizing and systems performance spreadsheet to evaluate design and operational conditions from which component sizes, installed cost, operational cost, and performance metrics were determined for the Base case and the Elevated case. The techno-economic analysis included heat reuse applications across a range of heat recovery temperatures and heat rejection options. The analysis shows that high-temperature liquid cooling allows for improved energy efficiency, lower water consumption, and lower capital costs compared to traditional cooling approaches. Transitioning to elevated water inlet/outlet temperatures (50°C/60°C) eliminates the need for chillers, cooling towers, and heat recovery equipment in many scenarios across three distinct climate zones. This results in up to 75% capital cost savings for the cooling and heat recovery equipment, and with significantly reduced water consumption, especially in non-heat reuse applications. Heat generated from data centers can also be repurposed for space heating, domestic hot water, and other applications, and is most cost-effective when data center outlet temperatures exceed 55–60°C.

Introduction

Data centers are energy and water intensive facilities (Mytton 2001). The adoption of liquid cooled systems brings tremendous gains in efficiency. Existing high-performance computing (HPC) systems, such as those deployed at the National Laboratory of the Rockies's (NLR) HPC data center, are almost exclusively liquid cooled (95% of IT load liquid cooled) due to ever-increasing rack power densities. And while the most energy-efficient data centers have a power utilization effectiveness (PUE) around 1.1 and approaching ever closer to the perfect

---

[1] *This work was authored by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Critical Minerals and Energy Innovation Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.*

value of 1.0 through the adoption of direct liquid cooling solutions**—the IT load will always be significant**, easily reaching 1 MW (Edge) to tens or even hundreds of MWs for a particular site. This has led to growing interest and requirements in reusing heat from data centers for beneficial use, instead of only rejecting this heat to atmosphere (OCP 2025). The goal of this evaluation is to explore the techno-economic performance of a prototypical 1-MW edge data center in various climate zones for heat reuse opportunities and temperatures. The evolving need for AI inference data centers of this size as close to the AI users as possible is becoming a well-researched concept with growing industry and research interests (Forbes 2025, Markets and Markets 2025, Garg et al. 2026).

As developed and formalized by the Green Grid in 2007 (Green Grid 2012), the PUE "family" of data center metrics has played a key role in defining energy and efficiency metrics in data centers. Key metrics (with typical ranges from most efficient to least) include:

PUE (1.0 – 2.5): power usage effectiveness $PUE = \frac{\text{"Facility energy"} + \text{"IT energy"}}{\text{"IT energy"}}$

ERE (0.2 – 2.5): energy reuse effectiveness $ERE = \frac{\text{"Facility energy"} + \text{"IT energy"} - \text{"Reuse energy"}}{\text{"IT energy"}}$

WUE (0.2 – 2.5): usage effectiveness $WUE = \frac{\text{"Annual site water usage"}}{\text{"IT energy"}} \quad \left(units\ \frac{L}{kWh}\right)$

NLR's 930-m^2 (10,000-ft^2) HPC data center is a liquid cooled high-performance computing facility achieving a trailing 12-month average PUE of 1.034 (NLR 2025). The data center features a chiller-less design, component-level warm water liquid cooling of 75°F, and heat reuse (NLR 2025). NLR made a commitment to direct liquid cooling during the design of its HPC data center. Since it became operational in 2013, several liquid cooling technologies have been deployed over the years (door heat exchangers, cold plates, and immersion) (Sickinger et al. 2014 and 2019; Kozubal 2017). By taking a holistic approach to data center energy use, through a combination of heat reuse (energy reuse effectiveness [ERE] of 0.929) and advanced dry cooling tower evaluations (Sickinger et al. 2018), NLR was able to cut water use in half (WUE of 0.7 L/kWh) from just using cooling towers alone. Based on this experience (along with interactions with industry partners, colleagues from other DOE HPC sites, and the HPC community in general), we have defined the following key approach to efficient data centers using the PUE family of performance metrics:

1. PUE: Reduce energy use by making systems as efficient as possible
    - Maximize liquid cooling supply water entering temperature to maximize energy efficiency
    - Use "free" cooling to reduce or eliminate compressor (chiller or direct expansion) based cooling:
        i. Install direct liquid cooled computers that use warm water
        ii. Capture as much heat as possible directly to the liquid cooling system
    - Optimize fan/pump speeds and electrical conversion losses in power supplies and backup power systems.

2. ERE: Heat reuse – achieve as low an ERE as possible, which results in maximizing beneficial heat reuse
    - Maximize data center compute leaving return temperature to maximize heat energy reuse

3. WUE: Reject as much remaining heat to dry coolers as possible, which results in minimizing water use for cooling in cooling towers or evaporative pre-cooling adiabatic towers.
    - Maximize compute <u>leaving</u> temperature to maximize <u>heat rejected in dry cooling and heat reuse.</u>

Industry Scaling Challenges

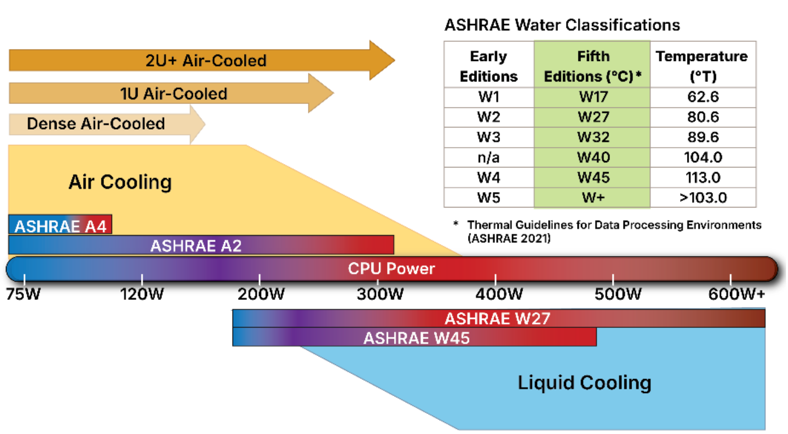
To scale these best practices in liquid cooled, energy and water efficient data centers, we identified a set of current (as of 2025) barriers to scaling for liquid cooling and heat reuse:

- Challenge 1: Historically limited adoption of direct liquid cooling outside of the HPC community.
- Challenge 2: Relatively low data center water inlet temperature is still required, less than 32°C (89.6°F), to support most of the existing air and liquid cooled systems.
- Challenge 3: Lack of a method to clarify economic and other benefits from maximizing entering and leaving temperatures and associated heat reuse opportunities.

Currently, these challenges are being addressed as follows:

Addressing Challenge 1: Historically limited adoption of direct liquid cooling outside of the HPC community.

ASHRAE Technical Committee 9.9 is a leader in data center environmental knowledge and industry best practices. A 2021 ASHRAE TC 9.9 white paper, *Emergence and Expansion of Liquid Cooling in Mainstream Data Centers* (ASHRAE 2021), indicates liquid cooling will become more mainstream due to increasing socket power (CPU/GPU/TPU). The graphic in Figure 1 is from the ASHRAE white paper that shows when a transition from air to liquid cooling based on socket power is likely. Note that ASHRAE has also recently renamed the ASHRAE water classifications to clearly define the facility supply temperature range; the authors of this report added the reference table in the upper right of Figure 1 for convenience. The upper temperature limits for facility supply (water inlet temperature) to the data center are now included in the W number (listed in degrees Celsius, green highlighted column of the table). ASHRAE has also developed Technology Cooling System Supply Temperature Classes (S-Classes) for IT equipment. These S-Classes (in degrees Celsius) are S20, S25, S30, S35, S40, S45, and S50.



Early Editions	Fifth Editions (°C)*	Temperature (°T)
W1	W17	62.6
W2	W27	80.6
W3	W32	89.6
n/a	W40	104.0
W4	W45	113.0
W5	W+	>103.0

Figure 1. Air cooling versus liquid cooling, transition, and temperatures (ASHRAE 2021)

The ASHRAE TC9.9 2021 white paper (ASHRAE 2021) states that liquid cooling "should be strongly and quickly considered" due to current and future IT equipment challenges and recommends that any future data center include the capability to add liquid cooling in the design.

Addressing Challenge 2: Relatively low data center water inlet temperature is still required, less than 32°C (89.6°F), to support most of the existing air and liquid cooled systems.

Liquid cooling re-emerged around 2012, with many successful deployments found in the HPC data center community. However, most liquid cooled systems today still require ASHRAE water class W32 or lower to operate. Maximizing a data center's inlet and exiting cooling system temperatures brings a host of benefits from a facility perspective, and innovative solutions that include heat reuse and cooling thermal systems that can work with ASHRAE water class W+ at greater than 45°C (113.0°F) are creating new opportunities to increase heat reuse, eliminate cooling water use, and maximize cooling system first cost and operational costs.

Addressing Challenge 3: Lack of a method to clarify economic and other benefits from maximizing entering and leaving temperatures and associated heat reuse opportunities.

The intent of this evaluation has been to quantify the economic benefits and energy/water savings from allowing higher data center inlet and outlet water temperatures. By providing a screening tool to clarify economic and other benefits from maximizing temperatures, the authors of this paper hope data center decision makers (executive staff, site energy/water champions, operational staff, etc.) pursue liquid cooling solutions that work with ASHRAE water class W+, greater than 45°C (113.0°F). As a result, higher temperature heat opens more opportunities for heat reuse—within the building where the data center is located or tied into a campus or district heating loop.

Analysis Methods

Data centers can be designed and operated with a variety of facility cooling infrastructure options. Figure 2 captures the options typically considered for a data center. Along the left-hand side, two facility cooling loops are shown. The Medium Temp Water Loop is intended to support air cooled IT equipment and handle the comfort cooling, whereas the High Temp Water Loop is intended to support cold plate and immersion based liquid cooled systems that can work at higher temperatures. Along the right-hand side, the hierarchy of facility heat rejection options are shown and placed in order of precedence from top to bottom (top often considered the most energy and water efficient options). By considering two separate loops in the design, the facility cooling infrastructure can be optimized to the data center liquid cooled systems deployed.

For this evaluation, the focus was on the High Temp Water Loop, with all the facility heat rejection options analyzed to minimize capital expenditures (CapEx) and operating expenses (OpEx)—with varying temperatures of the High Temp Water Loop that work with higher temperatures compared to several existing liquid cooled systems. Figure 3 captures the options considered for this evaluation that cover both the retrofit of an existing data center along with new build scenarios. For the retrofit scenario, the assumption was made that a Medium Temp Water Loop already exists to support air cooled IT equipment and handle the comfort cooling. This results in the ability for the new facility cooling infrastructure to be added to create a second

High Temp Water Loop dedicated to liquid cooled systems. The PUE "Family" of data center metrics can combine existing data center metric values (if data is available) along with the modeled metrics for the addition. For the new build scenario, considering an edge modular data center implementing only liquid cooled systems, the analysis utilizing Figure 3 still applies. For the PUE "family" of data center metrics in this scenario, the only thing that might be missing is comfort cooling contributions along with minuscule lights and plug loads (compared to IT and other facility energy contributions).

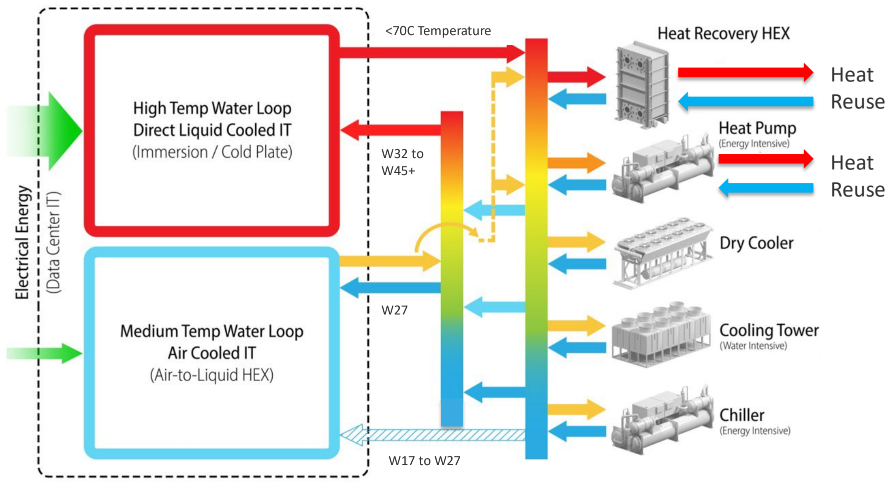


Figure 2. Facility cooling infrastructure, with options typically considered for a data center
(Note: HEX = heat exchanger)

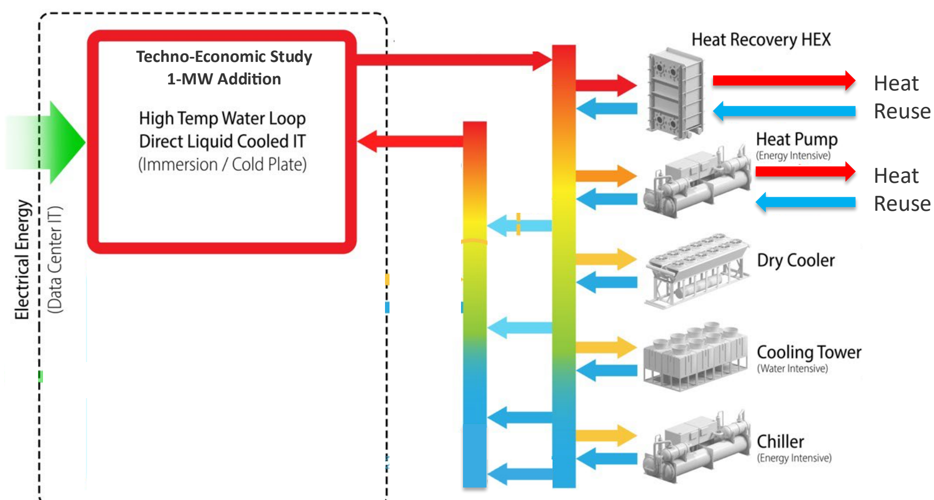


Figure 3. Facility cooling infrastructure, with high-temperature cooling and heat reuse options considered for new 1-MW addition

This analysis evaluated the following configurations:

- Heat Reuse applications:
  - The Heat Reuse application modeled was space heating, including reheat with a hot water supply temperature of 60°C (140°F) and a return temperature of 49°C (120°F)

- All options available, starting with sequence of Heat Recovery Heat Exchanger – Heat Pump – Dry Cooler – Cooling Tower – Chiller as options
- Non-reuse applications: This means the Heat Reuse options shown in Figure 3 were removed from consideration, leaving only Dry Cooler – Cooling Tower – Chiller as options.

Table 1 shows the Base case water temperatures used for this evaluation, representing ASHRAE water class W32 and an outlet temperature of 40°C (104°F) based on several existing liquid cooled systems (Sickinger et al. 2018, Carter et al. 2017). The Base case was used to compare to a set of heat reuse applications operating at elevated cooling inlet water cases, as shown in Table 1. For the Elevated case, water inlet temperature is assumed to be in the W+ class of 50°C (122°F) and water outlet temperature at 60°C (140°F). Note that the Base case still offers significant efficiency gains over data centers that are only air cooled. The data center addition was sized at 1 MW, with a year-round continuous heating load assumed sized larger at 1.5 MW.

Table 1. Data center water inlet and outlet temperature for Base and Elevated cases

	Base (W32)	**Elevated (W+)**
Water inlet temperature	32°C (89.6°F)	50°C (122°F)
Water outlet temperature	40°C (104°F)	60°C (140°F)

Techno-Economic Model Development

Figure 4 shows a diagram of the data center cooling and reuse system configuration that was evaluated for different site locations of Chicago, IL, Miami, FL, and Alexandria, VA. The different site locations were used to represent variation in outdoor air conditions and prices for commodities such as energy and water. A model was developed in a spreadsheet to evaluate design and operational conditions from which component sizes, installed cost, operational cost, and performance metrics were determined for the Base case (W32) and the Elevated case (W+). The energy (Q_{out} and P_{in} Figure 4) and water usage of different cooling technologies, driven by the required water inlet (state 6 in Figure 4) and outlet (state 1 in Figure 4) temperatures of the data center, were evaluated in the model. This model contains engineering calculations along with a fluid property model CoolProp developed by NIST (Bell et al. 2014) to determine water and air properties at different state points in the system, including the facility and data center loop temperatures connected through the cooling distribution unit (CDU) heat exchanger (HX). Note that for some of the cases evaluated, not all the components in the diagram are present in the system. For example, the non-reuse applications do not have the *Reuse Heat Loop* components, and the Elevated cooling technology does not require a chiller or a cooling tower.

For reuse applications, the reuse heating loop requires a supply temperature of 60°C (140°F) (state 15 in Figure 4), and the return water back to the reuse heat exchanger is 49°C (120°F) (state 17 in Figure 4).

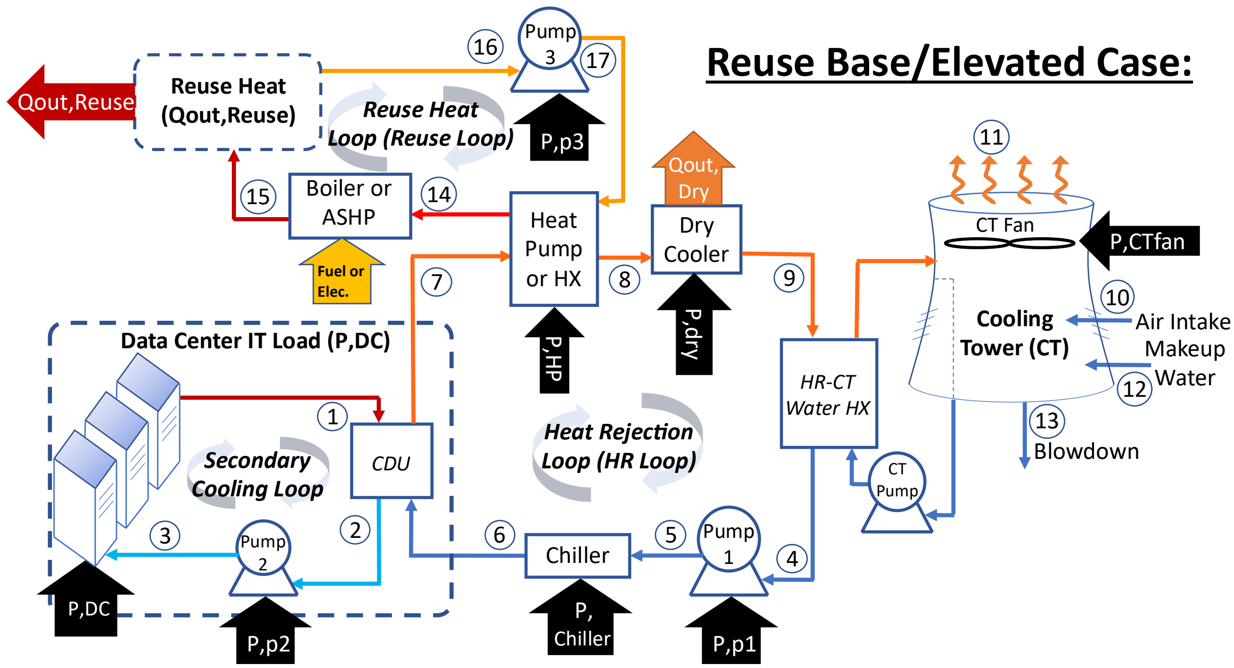


Figure 4. System diagram illustrating the liquid cooling portion of the data center, including heat reuse, dry cooler, cooling tower, and chiller

Analysis Inputs

Table 2 and Table 3 list the cost and performance inputs used in the analysis for the data center cooling system and heat reuse equipment and infrastructure. Equipment cost estimates were derived from a combination of RSMeans (RSMeans 2022) and engineering estimates, and performance values are based on engineering estimates.

Table 2. Cost and performance inputs used in the analysis for conventional data center cooling system equipment

	Units	Value
Water-to-Water Heat Exchangers (plate-frame)		
Minimum approach temperature	°F	3
Pressure drop	bar	1.0
Installed cost	$/gpm	140
Cooling Towers		
Approach to wet bulb, including HX	°F	7
Fan and pumps power consumption	kWe/kWt	0.02
Installed cost	$/ton	300
O&M cost, fixed	$/ton/yr	11.7
O&M cost, water treatment and disposal	$/kgal-blowdown	14.9
Dry Coolers		
Minimum approach temperature	°F	20.0
Fan power consumption	kWe/kWt	0.045
Installed cost	$/ton	264

O&M cost	$/ton/yr	2.0
Chillers		
Coefficient of performance (COP), including cooling	kWt/kWe	4.5
Installed cost	$/ton	800
O&M cost	$/ton/yr	10.0
Pumps		
Isentropic efficiency	%	70%
Motor efficiency	%	90%

Table 3. Heat reuse equipment and infrastructure cost and performance inputs used in the analysis

	Units	**Value**
Conventional heating equipment serving the heating load		
Boiler efficiency, conversion of fuel to heat	%-HHV	80%
Air-source heat pump, COP	kWt/kWe	1.5-4
Heat pump		
COP	kWt/kWe	2.5-5
Installed cost	$/ton	1,200
O&M cost	$/ton/yr	10.0
Reuse piping		
Pressure drop	bar	3
Heat loss	kWt/kWt	0%
Installed cost intercept	$	100,000
Installed cost slope	$/gpm	100
O&M fixed cost as % of installed cost per year	%	10%

The Extreme Annual Design Conditions from the ASHRAE handbook for hot and humid outdoor air conditions was used based on the location as the design point for worst-case cooling equipment sizing, and these conditions are listed in Table 4. Worst-case cooling equipment sizing is often at the highest wet-bulb design conditions. Low peak wet-bulb design conditions, such as in dry arid climate zones, were not included due to smaller relative cooling systems in low wet-bulb sizing conditions.

Table 4. Design conditions for each data center location used in the analysis

	Alexandria, VA	**Chicago, IL**	**Miami, FL**
Dry-bulb temperature	98.2°F	96.3°F	94.5°F
Relative humidity	57%	59%	68%
Wet-bulb temp (calculated)	84.4°F	83.4°F	84.7°F

While the design condition described above was used for sizing the equipment, each site location was evaluated at representative seasonal (four) outdoor air conditions to estimate the operational cost and performance for a year. For example, in Alexandria, VA, Table 5 lists the four seasonal outdoor air conditions.

Table 5. Example (Alexandria, VA) average seasonal outdoor air conditions used for operating cost and performance in the analysis

	Spring	Summer	Fall	Winter
Temperature, dry bulb (°F)	52.7	75.6	56.7	34.7
Relative humidity (%)	79%	70%	78%	79%

Aside from outdoor air conditions to inform the design and operating performance, the commodity prices also vary by site location, as listed in Table 6.

Table 6. Commodity prices for the site locations used in the analysis

	Alexandria, VA	Chicago, IL	Miami, FL
Electricity price ($/kWh)	0.052	0.070	0.062
Natural gas price ($/MMBtu)	8.1	8.0	11.5
Water cost ($/kgal)	4.9	7.8	5.8

Analysis Results

For each of the three climate zones, we performed sizing runs, calculated operating costs, capital costs, and water use for the Base case and for the Elevated cooling supply water cases, with and without heat reuse considered. A 10-MW IT load exploration is provided to explore first cost of cooling equipment sensitivities, and a sensitivity analysis to cooling water temperatures was performed to understand key step changes to cooling system sizes and heat reuse types. Variations in heat reuse approaches are also explored to understand cost tradeoffs in systems and fuel costs.

Economic Results

Table 7 shows the summary of benefits of the Elevated case with reuse compared to the Base case with reuse, for each climate zone and for a 10-MW alternative. The Base case requires a heat pump because the data center outlet temperature is lower than the reuse heating loop return temperature. Elevated achieves a significant amount of heat reuse by preheating the reuse return water up to about 57°C (135°F). The avoidance of a heat pump for Elevated adds to the capital cost savings on top of not needing a chiller or cooling tower. However, the high price of natural gas relative to electricity prices makes the operating cost increase with the Elevated case's lower reuse amount compared to the Base case with heat pump. The variation in operating cost savings across locations is a function of the location's electricity and natural gas prices. The much larger reduction in capital cost relative to the increase in operating cost makes Elevated still a more economically beneficial solution, as any opportunity to eliminate expensive capital equipment due to warmer cooling water configurations is a primary driver for lowest life cycle costs.

To understand the impact on the economics of reuse applications of data center outlet temperatures, a sensitivity analysis was performed. Figure 5 shows the operating cost and capital cost savings for various data center outlet temperatures. All data points use a 10°C (18°F) temperature rise across the data center, so the lowest temperature case of 55°C (131°F) outlet temperature has a 45°C inlet temperature. The coldest condition of 55°C (131°F) has higher capital cost savings because it has a much lower reuse amount and therefore the reuse equipment and piping are less expensive, but the operating cost is significantly higher. The capital cost savings levels out around 74% as the outlet temperature rises above 60°C (140°F), and the operating cost savings increases up to about 10% as the full reuse is achieved above about 64°C (147°F). Full reuse reduces natural gas consumption and cost for serving the heating load. If the reuse supply temperature requirement was higher, the trend would be increasing operating cost savings above 64°C.

Table 7. Elevated case with reuse savings compared to the Base case with reuse

	Chicago, IL, 1 MW	Miami, FL, 1 MW	Alexandria, VA, 1 MW	Alexandria, VA, 10 MW
Operating Cost Savings %	2%	-4%	-1%	-2%
Capital Cost Savings %	75%	75%	75%	78%
Water Savings %	N/A	N/A	N/A	N/A

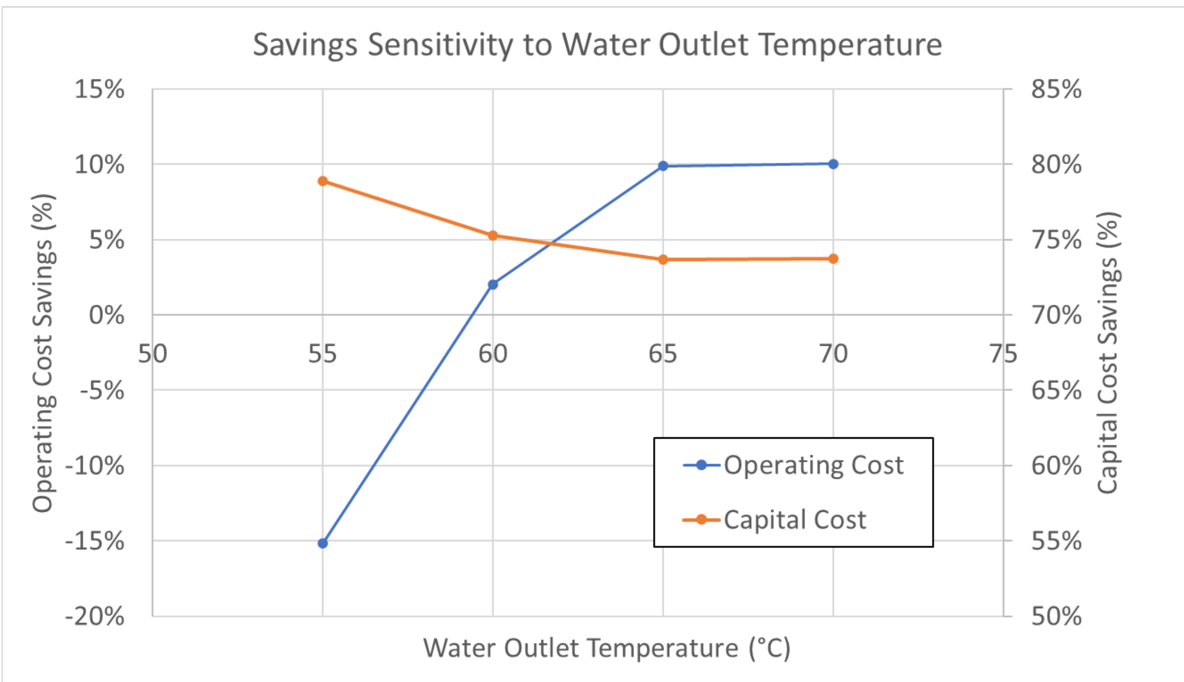


Figure 5. Sensitivity of savings on operating cost and capital cost on data center outlet temperature for reuse applications

Table 8 shows the summary of benefits of higher water inlet and outlet temperature for capital and operating savings with the Elevated case without reuse. Elevated achieves all its cooling with a dry cooler, so water consumption is reduced to zero. There is a small net decrease in operating cost with the avoidance of water cost and cooling tower O&M cost, but higher electricity consumption from the dry cooler compared to the cooling tower. There is a large cost savings due to the removal of the cooling tower and the chiller.

The key benefit of Elevated for non-reuse applications is the higher data center water inlet temperature to avoid the requirement for a chiller and a cooling tower. This benefit is dependent on the design (maximum) outdoor air wet-bulb and dry-bulb temperature, which varies based on the climate of the site's location. The maximum wet-bulb temperature (driver for the water temperature achieved by the cooling tower) determines the requirement for the chiller, and the maximum dry-bulb temperature (driver for the water temperature achieved by the dry cooler) determines the requirement for the cooling tower. Figure 6 shows the relationship between the data center water inlet temperature required to avoid a chiller and cooling tower based on the maximum wet-bulb and dry-bulb temperature, respectively. This assumes a wet-bulb approach temperature of about 4°C (7°F) for the cooling tower and a dry-bulb approach temperature of about 11°C (20°F) for the dry cooler. The chart highlights the water inlet temperature of the Base case (32°C) and Elevated case (50°C) with a horizontal blue and green line, respectively, for reference.

Table 8. Elevated case without reuse savings compared to the Base case without reuse

	Chicago, IL, 1 MW	Miami, FL, 1 MW	Alexandria, VA, 1 MW	Alexandria, VA, 10 MW
Operating Cost Savings %	1%	1%	1%	1%
Capital Cost Savings %	69%	69%	69%	69%
Water Savings %	100%	100%	100%	100%

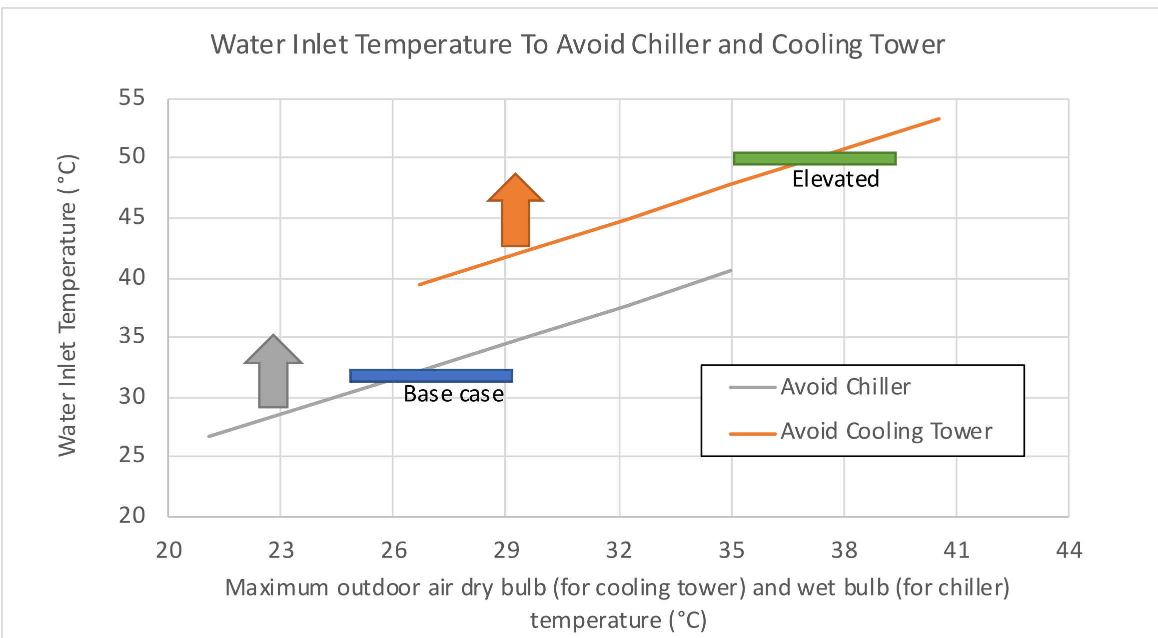


Figure 6. Data center water inlet temperature requirement to avoid a chiller and cooling tower

Sensitivity Analysis Findings

Three different locations were evaluated to explore the dependence on climate, energy costs, etc., on the evaluation results, but the analysis findings show only small variation in the key results across the locations. The key drivers are around the opportunities to increase cooling water temperatures, eliminating capital cost in cooling equipment. This holds true for all three climate zones we considered, with energy costs only slightly varying site-specific results. For low wet-bulb hot arid climate zones, we expect similar results, with slight differences in sizing and operating costs for the air cooled chillers. The results for Alexandria, VA, are shown below, first with heat reuse, and then without heat reuse, and similar results were found for the other locations.

With Heat Reuse

The results for a 1-MW liquid cooled data center with air cooled chillers in Alexandria, VA, are shown in the table below. The Elevated system achieves significant (75%) capital cost savings compared to the Base case, while most other metrics are very similar. The large capital cost savings are from the avoidance of a heat pump, air cooled tower, and chiller; the Elevated system only requires a heat exchanger instead of a heat pump to transfer the data center heat to the heat reuse loop because the temperature is high enough. Both systems require heat distribution piping.

Alexandria, VA			**Reuse**	
Category	**Results**	**Units**	**Base**	**Elevated**
Financial *(new addition)*	Total operating cost per year	$k/year	$ 1,035	$ 1,051
	Total installed capital cost	$k	$ 1,444	$ 357
	Operating cost savings % from Base	%		-1%
	Installed cost savings % from Base	%		75%
Water usage	Water usage per year	m^3/year	0	0
Metrics *(new addition)*	PUE		1.02	1.03
	ERE		0.23	0.25
	WUE_{site}	L/kWh	0	0

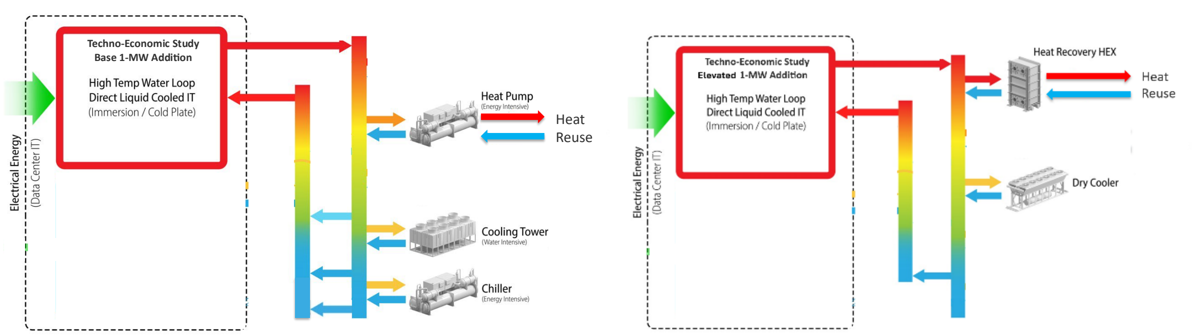


Figure 7. Facility cooling infrastructure for Base (left) vs. Elevated (right) thermal energy storage results

(*with heat reuse*)

Without Heat Reuse

A configuration that does not include heat reuse, and all heat is rejected through the cooling system, is also explored. For the without heat reuse case that includes water-cooled chillers in the Base case, the Elevated case still achieves significant (69%) capital cost savings while reducing water usage to zero compared to this Base case. The capital cost savings are from the avoidance of a cooling tower and a chiller. Both cases do not need heat distribution piping without the reuse, but the Base case also avoids the heat pump without reuse, so the capital cost savings are slightly less for Elevated compared to the reuse comparison. Water savings are achieved by using a dry cooler instead of a cooling tower, which is enabled by the higher inlet temperature. The PUE for Elevated is slightly higher because dry coolers consume more electricity than cooling towers for the same heat rejection, as air cooled chillers reject heat to the ambient outside air, which is hotter than the wet-bulb temperatures utilized by water-cooled cooling towers.

Alexandria, VA			**No Reuse**	
Category	**Results**	**Units**	**Base**	**Elevated**
Financial *(new addition)*	Total operating cost per year	$k/year	$ 1,384	$ 1,374
	Total installed capital cost	$k	$ 572	$ 178
	Operating cost savings % from Base	%		1%
	Installed cost savings % from Base	%		69%
Water usage	Water usage per year	m^3/year	12,359	0
Metrics *(new addition)*	PUE		1.02	1.06
	ERE		n/a	n/a
	WUE_{site}	L/kWh	1.41	0

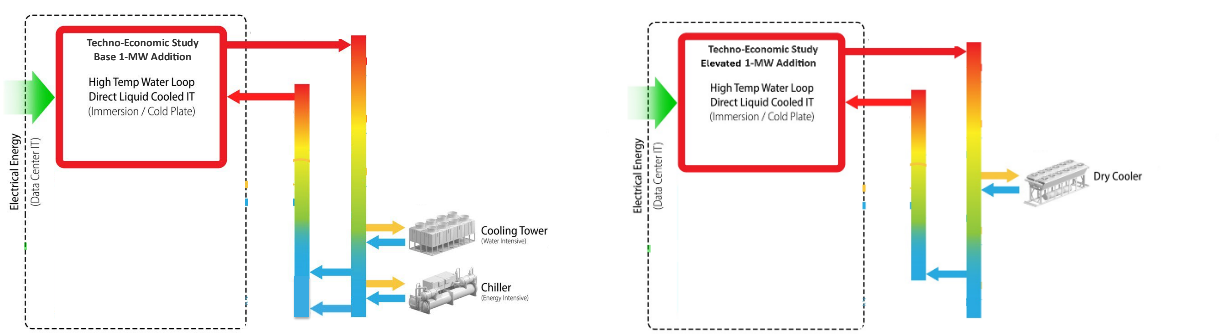


Figure 8. Facility cooling infrastructure for Base (left) vs Elevated (right) thermal energy storage results

(*without any heat reuse*)

Variations Explored

A larger, 10-MW data center application was also explored. The economy of scale (lower per-unit cost) of cooling equipment and heat reuse infrastructure was modeled. The cooling system configurations and heat reuse opportunities would be similar in a 10-MW vs. 1-MW edge inference data center. This economy of scale benefits the Base case more than Elevated because the Base case requires more equipment from the chiller, cooling tower, and reuse heat pump (if applicable). This implies that Elevated is particularly beneficial for edge facilities (~1-MW IT load) because of the reduced equipment capital cost and the practical simplicity of the cooling infrastructure by just needing a dry cooler.

Conclusions

For heat reuse applications, the following benefits are achieved if the IT cooling water outlet temperature is greater than 55°–60°C (131°–140°F), which can be provided by the Elevated system considered in this study:

- Eliminates the need for a booster heat pump while directly supplying the reuse heating loop in a building with a significant portion of the data center heat. This eliminates the electricity consumption of the booster heat pump and avoids the capital cost of the heat pump.
- Less heat is delivered to the reuse heating loop without a heat pump, but this is still a net benefit with the reduction in capital and operating cost, especially if a heat reuse off-taker can beneficially directly use these available hot water temperatures.

The key benefit of Elevated system for non-reuse applications is from the higher data center water inlet temperature to avoid the requirement for a chiller and a cooling tower, which achieves significant capital cost savings. This benefit is dependent on the design (maximum) outdoor air wet-bulb and dry-bulb temperature, which varies based on the climate of the site's location. In general, our evaluation shows:

- The Elevated system does not need a chiller with IT cooling water inlet temperature greater than about (33°C ± 1–2°C) (91.4°F).
- The Elevated system does not need a cooling tower with IT cooling water inlet temperature greater than about 50°C (122°F).

The Elevated case therefore achieves all cooling with a dry cooler, and this provides the following benefits:

- Dry coolers provide significant water savings, eliminating cooling towers and associated water use.
- A small net operating cost savings is achieved with the reduction in water and cooling tower O&M cost, balanced against some additional fan power consumption of the dry coolers compared to cooling towers.

Three different locations were evaluated to explore the dependence on climate, energy costs, and economic performance. However, the analysis findings show only small variation in the key results across the locations, demonstrating the general nature to the benefits of heat reuse and high-temperature liquid cooling systems. In addition, operating a cooling loop at these elevated temperatures would place additional scrutiny on the data center manager to ensure any hot spots are sufficiently cooled and handled, as these issues typically are easily addressed with colder supply water configurations. As industry explores warmer and warmer supply water temperatures, this means beneficial heat reuse, cooling system capital reductions, and water savings will have to be balanced with practical implementation considerations of cooling data centers that have historically used chilled water at 45°–55°F (7.2°–12.8°C).

Strategic Heat Reuse Applications

To ensure useable heat in the heat reuse applications, which can achieve IT cooling water outlet temperature is greater than 55°–60°C (131°–140°F), suitable heat loads will need to be identified. Heat reuse performance and economics are highly dependent on co-locating data centers with suitable heat loads. This analysis assumes all recovered heat can be beneficially used year-round. In actual applications, heat loads most suitable for data center reuse would have to be statically identified to have a high-capacity factor and be served by Elevated temperatures. Future work could include further exploration of heat load seasonal and daily variability, and implications and opportunities for thermal energy storage to better match heat sources with loads.

As this analysis has shown, alignment of data center supply temperatures with heat load temperatures maximizes the cost-effectiveness of reuse approaches. Heat loads that are higher than this analysis assumed (>140°F) and require booster heat pumps, or with seasonal heat demand, or that are located significant distance from the data center and require extensive water piping distribution, all will increase system paybacks and reduce key performance metrics. Historically, lower temperature available waste heat combined with intermittent heat demand and poor co-location of data center heat reuse with heat demands have limited the economics and cost-effectiveness of data center heat reuse efforts.

Ideal applications for heat reuse include large-scale domestic hot water heating systems, with year-round 49°–60°C (120°–140°F) hot water draws. Such heat reuse applications are a leading candidate for co-locating a data center heat reuse system. Other water heating applications such as large pool heating, outdoor hot springs, greenhouses, or industrial drying have similar supply temperature requirements and year-round heat loads. Emerging waste heat reuse approaches to consider include technologies such as regeneration of a liquid desiccant air drying system that need >65°C (148°F) heat for regeneration of the desiccant (Kozubal et al. 2014). Additional heat reuse information including designs, economics, policies and presentations can be found at the OCP Heat Reuse Sub-Project (OCP 2025).

References

ASHRAE 2021. *Emergence and Expansion of Liquid Cooling in Mainstream Data Centers.* ASHRAE TC 9.9 White Paper. https://www.ashrae.org/file%20library/technical%20resources/bookstore/emergence-and-expansion-of-liquid-cooling-in-mainstream-data-centers_wp.pdf.

Bell, I. H., Wronski, J., Quoilin, S., & Lemort, V. 2014. “Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp.” *Industrial & Engineering Chemistry Research*, *53*(6), 2498–2508. doi:10.1021/ie4033999.

Carter, Thomas, et al. 2017. "Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Modeling and Installation: Preprint." NREL/CP-2C00-66690. Presented at the 2017 ASHRAE Winter Conference, 28 January–1 February 2017. https://docs.nlr.gov/docs/fy17osti/66690.pdf.

Forbes. 2025. *The Current And Future Path To AI Inference Data Center Optimizati*on. https://www.forbes.com/councils/forbestechcouncil/2025/01/28/the-current-and-future-path-to-ai-inference-data-center-optimization/. Accessed January 2026.

Garg, Aditie, Chuck Booten, Otto VanGeet, Shanti Pless, Katelyn Stenger, Judith Vidal, Roderick Jackson, Luke Lavin, and Kumaraguru Prabakar. 2026. *Considerations for Distributed Edge Data Centers and Use of Building Loads to Support Large Interconnections*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-96700. https://www.nlr.gov/docs/fy26osti/96700.pdf.

Green Grid, 2012. *WP#49 - PUE: A Comprehensive Examination of the Metric*. https://www.thegreengrid.org/en/resources/library-and-tools/237-WP%2349---PUE%3A-A-Comprehensive-Examination-of-the-Metric. October 2012.

Kozubal, E., Herrmann, L., Deru, M., Clark, J., and Lowenstein, A. 2014. *Low-Flow Liquid Desiccant Air-Conditioning: Demonstrated Performance and Cost Implications*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-60695. https://docs.nlr.gov/docs/fy14osti/60695.pdf.

Kozubal, E. 2017. *Innovation Incubator: LiquidCool Solutions Technical Evaluation. Laboratory Study and Demonstration Results of a Directed-Flow, Liquid Submerged Server for High-Efficiency Data Centers*. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1413900.

Markets and Markets 2025. *AI Inference Market Size, Share & Trends*, *2025 to 2030*. Retrieved from https://www.marketsandmarkets.com/Market-Reports/ai-inference-market-189921964.html January 2026.

Mytton, David. 2001. "Data center water consumption." *npj Clean Water* **4**, 11, https://doi.org/10.1038/s41545-021-00101-w.

NLR. 2025. https://www.nlr.gov/computational-science/measuring-efficiency-pue. Last accessed July 2026.

OCP. 2025. *Policies to Accelerate Data Center Heat Reuse: Achieving Economic and Climate Change Goals*. The Open Compute Project (OCP) Heat Reuse subgroup (created in 2021, accessed in 2026). https://www.opencompute.org/community/heat-reuse.

RSMeans 2022. RSMeans Online Subscription cost database for capital costs. (Requires subscription to access.)

Sickinger, D., Van Geet, O., and Ravenscroft, C. 2014. *Energy Performance Testing of Asetek's Rack CDU System at NREL's High Performance Computing Data Center*. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1164105.

Sickinger, D., Martinez, D., and Bolz, B. 2019. *Energy Performance Evaluation of Aquila's Aquarius Fixed Cold Plate Cooling System at NREL's High Performance Computing Center*. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1497991.

Sickinger, David, Otto Van Geet, Suzanne Belmont, Thomas Carter, and David Martinez. 2018. *Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Results from 24 Months and Impact on WUE*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-2C00-72196. https://www.nlr.gov/docs/fy18osti/72196.pdf.