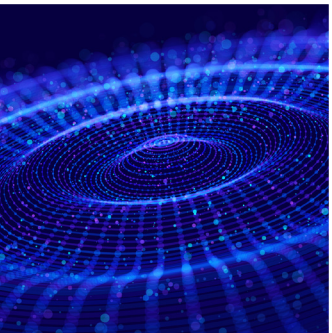
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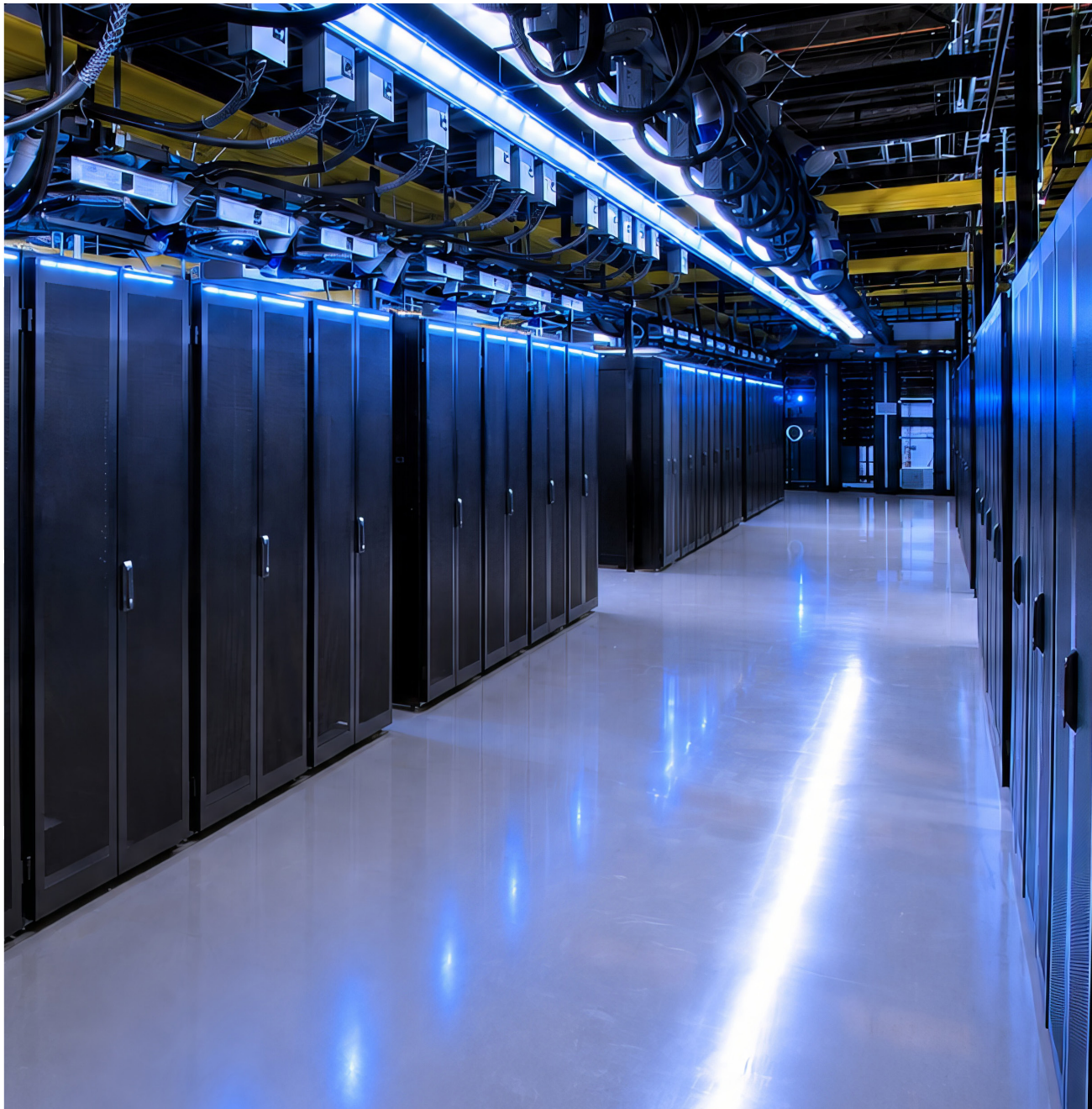
Evaluating External Heat Rejection Options for Liquid-Cooled Data Center Applications











OVERVIEW

The rise of AI and high-performance computing is pushing rack densities beyond what air cooling can support, driving rapid adoption of direct-to-chip liquid cooling. This shifts the primary thermal design challenge from heat removal inside the IT space to the efficient rejection of heat to the outside environment, making heat rejection strategy one of the most consequential decisions in modern data center design.

This white paper presents a simulation-based study that quantitatively compares four heat rejection approaches across six climate zones to understand how climate, water availability, energy costs, and operational priorities influence performance, giving data center operators a data-driven basis for technology selection.

The findings show that no single technology is universally optimal, but rather that heat rejection should be treated as a site-specific design challenge. The best choice depends on each location's climate, water availability, utility costs, and electrical infrastructure capacity, as well as the operator's sustainability goals and long-term growth plans.



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1. Introduction

The data center industry is undergoing a fundamental transformation driven by the rapid growth of artificial intelligence (AI), high-performance computing (HPC), and increasingly dense compute architectures, as illustrated in Figures 1 and 2. Rack power densities that were once considered extreme are now becoming standard in next-generation facilities, necessitating the adoption of **liquid cooling technologies,** particularly direct-to-chip systems. As thermal loads increase and temperature control requirements become more stringent, the limiting factor in many designs is no longer heat removal within the IT space, but rather the **efficient rejection of heat to the ambient environment.**

This shift has redefined the role of facility infrastructure. In traditional data centers utilizing air-cooled server racks, efficiency improvements were largely limited to airflow management and internal system optimization. In contrast, liquid-cooled architectures transfer the majority of heat directly to a coolant loop, concentrating the performance and sustainability challenges at the **external heat rejection system.** As a result, the selection and configuration of heat rejection technologies—dry, adiabatic, or evaporative—has become one of the most critical design decisions influencing overall data center performance.

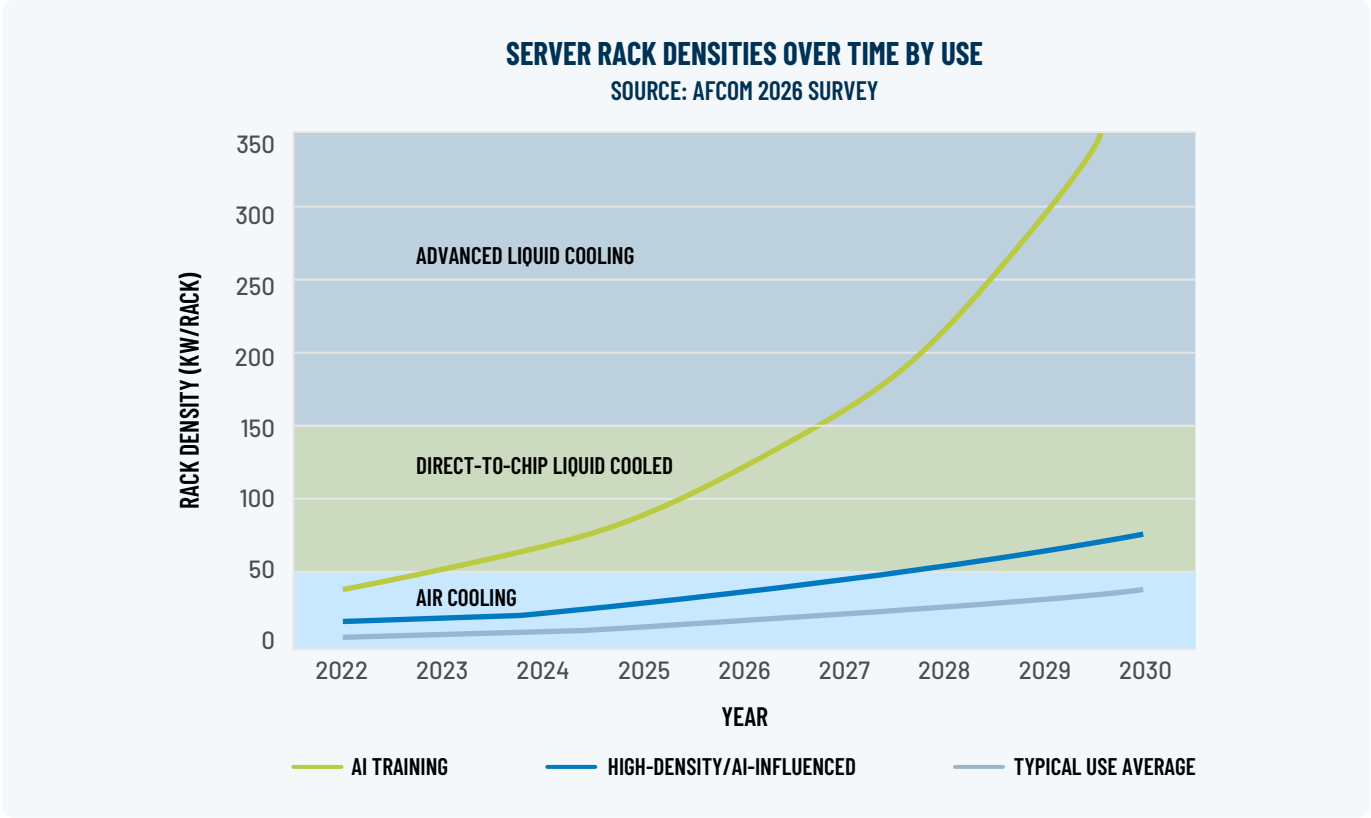


Figure 1: Server rack densities by use case, 2022–2030 (AFCOM 2026 Survey). AI training power densities are projected to exceed 350 kW/rack by 2030, far surpassing air cooling limits (~50 kW/rack) and requiring direct-to-chip liquid cooling as the only viable thermal architecture at scale.

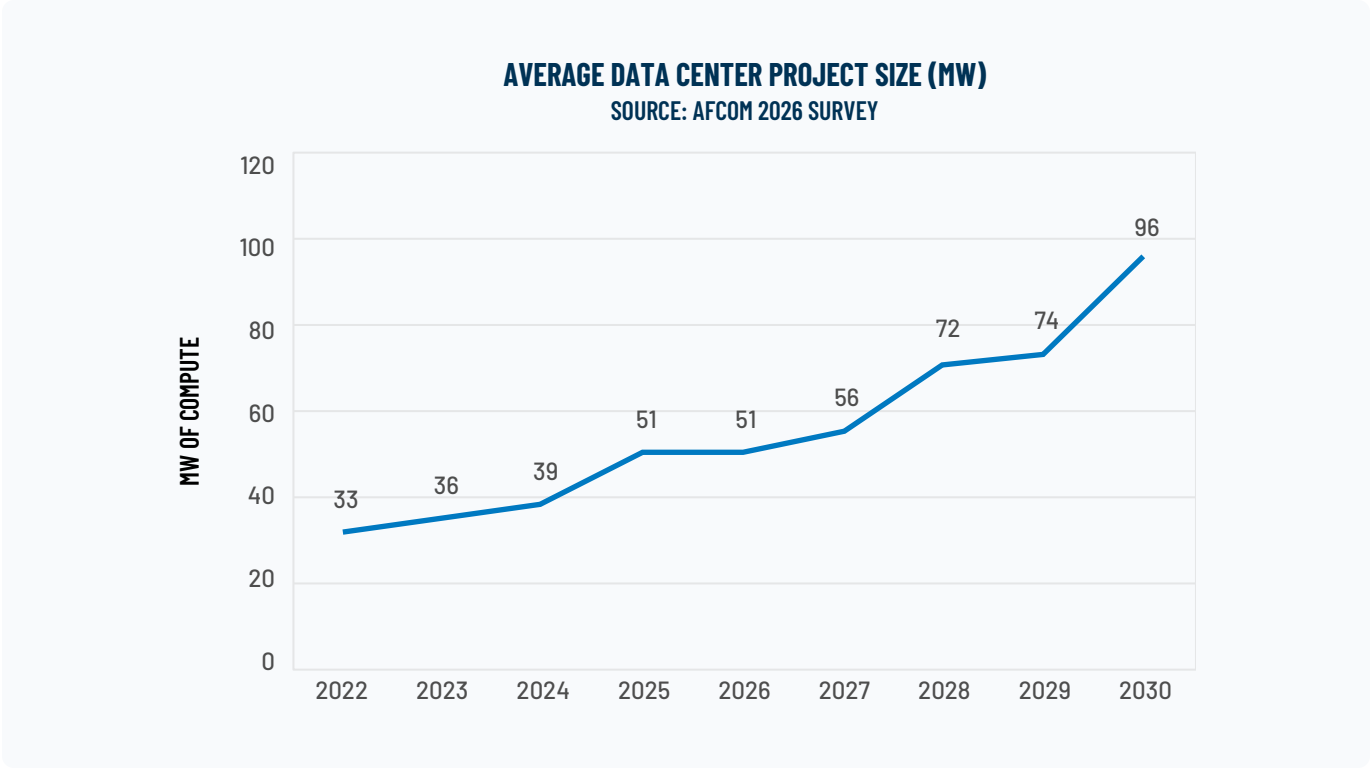


Figure 2: Average data center project size (MW), 2022–2030. Facility scale is projected to nearly triple from 33 MW to 96 MW over the period, reflecting the economic viability of hyperscale deployments in meeting current AI-driven compute demand.

1.1 Evolving Thermal Design Priorities

The transition to liquid cooling introduces new design considerations that extend beyond conventional energy-efficiency metrics. While reducing power usage effectiveness (PUE) remains important, increased attention is now being given to:

- **Water usage effectiveness (WUE)**
- **Peak electrical demand and infrastructure sizing**
- **System footprint and land utilization**
- **Resiliency, redundancy, and long-term scalability**
- **Community and environmental impact**

At the same time, the industry is increasingly challenged by competing priorities. For example, solutions designed to minimize water consumption may result in higher energy usage and increased electrical infrastructure requirements, while systems optimized for energy efficiency may rely on the controlled use of water. These tradeoffs highlight the need to move beyond simplified classifications of "air versus water" and instead adopt a more holistic, site-specific evaluation framework.

1.2 Reframing the "Air versus Water" Debate

Much of the current industry discussion surrounding data center cooling has been framed as a binary comparison between air-cooled and water-cooled heat rejection systems. However, such comparisons often overlook the complexity of modern heat rejection strategies and the significant influence of climate and operating conditions.

In practice, heat rejection performance is determined by a combination of factors, including:

- Ambient dry-bulb and wet-bulb temperature distributions
- Allowed system operating temperatures
- Heat rejection design approach temperatures
- Control strategies and economization thresholds
- The interaction between mechanical systems and site layout

As a result, no single technology can be universally identified as optimal for all sites. Instead, the most effective solution depends on how well a system is able to **balance energy consumption, water usage, capital cost, and infrastructure constraints** within a given climate.

1.3 Study Objective and Scope

The objective of this study was to understand how each heat rejection technology performed under different conditions and to quantify the tradeoffs required to meet specific design priorities. To that end, it presented a **quantitative comparison of external heat rejection technologies** serving a liquid-cooled data center. The analysis focused specifically on the portion of the system **upstream of the coolant distribution unit (CDU),** isolating the performance of heat rejection equipment and associated chiller interactions.

The study evaluated an **18 MW data center module** operating with supply and return temperatures of **69.8°F and 87.8°F,** respectively, between the outdoor heat rejection equipment and the CDU. These conditions reflect current industry practice for direct-to-chip liquid cooling applications (77°F supply to the chip) and provide a consistent baseline for comparison across technologies.

The following heat rejection configurations were analyzed:

- **Air-Cooled Chillers with Integrated Air-Cooled Condensers (ACC)**
- **Water-Cooled Chillers with Dry Coolers (WCC + DAC)**
- **Water-Cooled Chillers with Adiabatic Dry Coolers (WCC + ADAC)**
- **Water-Cooled Chillers with Closed Circuit Cooling Towers (WCC + CCCT)**

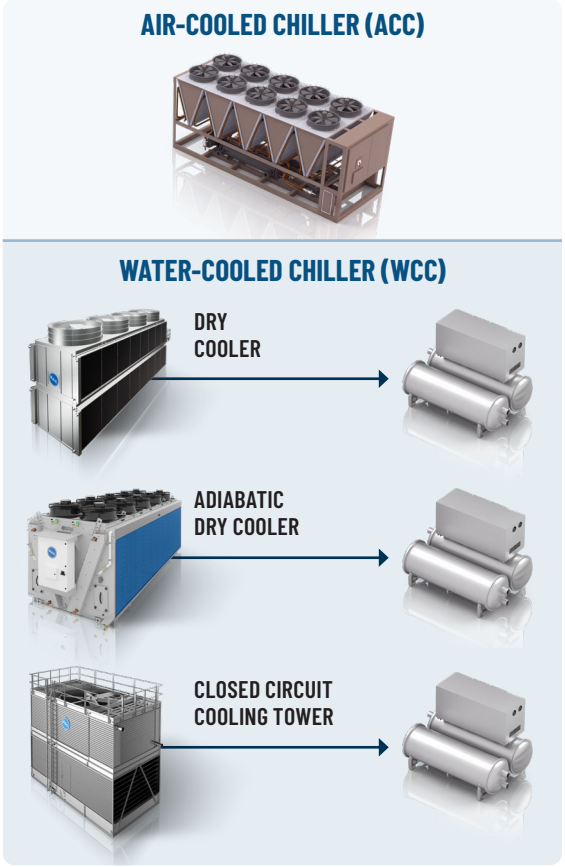


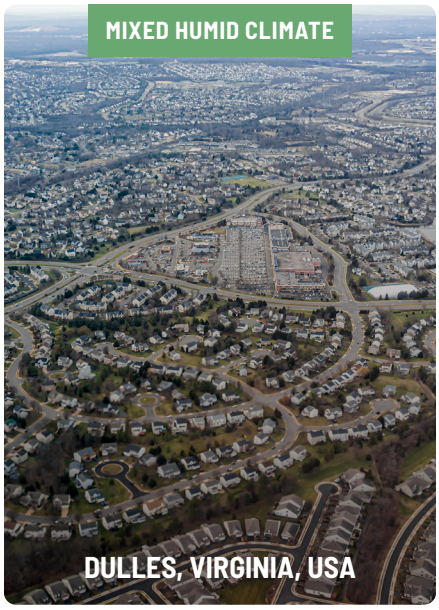
Figure 3: External heat rejection technology configurations for air-cooled chillers and water-cooled chillers upstream of the CDU that were compared in this study.

To capture the impact of climate, each system is evaluated across six geographically diverse locations:

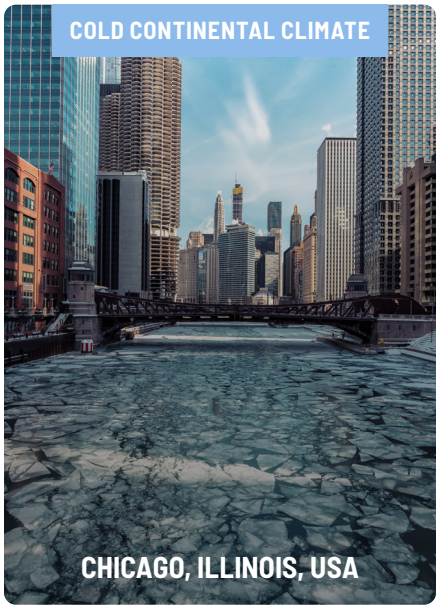












All simulations are based on **ASHRAE 2025 bin weather data,** enabling a detailed assessment of system performance across the full annual distribution of ambient conditions rather than at peak design points alone.

While the heat rejection metrics evaluated in this study may suggest that some sites are better suited than others for a data center, site selection involves far more variables than are examined here. These include factors such as proximity to high-speed communications infrastructure, data latency, security, availability of technical staff, and proximity to key markets.

1.4 Key Evaluation Metrics

System performance is evaluated using a consistent modeling approach that incorporates:

- Manufacturer-based performance curves for chillers and heat rejection
- Climate-dependent heat rejection capability
- Free cooling (economizer) operation when conditions permit
- Location-specific utility costs (energy and water)
- Industry-standard assumptions for equipment layout, footprint, and costs

The analysis focuses on the following key metrics:



1.5 Study Conclusions

The results of this study are intended to support **early-stage system selection and strategic decision-making,** where the ability to balance competing constraints is critical. By comparing technologies across multiple climates and performance metrics, the study leads to the following conclusion:

Heat rejection system selection is inherently climate-dependent and must be evaluated as a multi-variable optimization challenge rather than a technology preference.

The findings provide a foundation for more advanced analysis, including hybrid system design, high-temperature operation, and future technologies such as immersion cooling and chiller-less architectures.

2. Climate Characterization of Study Locations

Six distinct climate zones were selected to ensure a representative and globally relevant comparison. Each location exhibits unique dry-bulb (DB) and mean coincident wet-bulb (MCWB) temperature distributions, as shown in Figures 4–9 on the following pages. The difference between these two values is an indicator of relative humidity. Both metrics directly influence the performance of all heat rejection systems evaluated in this study.

The bin weather profiles highlight not only peak design conditions, but the **distribution of ambient conditions over the year,** which determines the availability of economizer operation, the effectiveness of evaporative cooling, and the overall efficiency of each technology.

Note: The DB and MCWB charts in this section let readers compare climate profiles across all six locations using the same format. The actual performance calculations, however, used different inputs depending on the technology: dry-bulb temperature for air-cooled chillers and dry coolers, and wet-bulb temperature for the evaporative cooling in adiabatic dry coolers and closed circuit cooling towers.

COOL MARITIME CLIMATE

2.1 London, United Kingdom

London exhibits a **narrow temperature distribution centered in the 41°F to 68°F range,** with relatively few hours at extreme conditions. The DB and MCWB curves are closely aligned, indicating **moderate humidity levels throughout the year.**

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
■ Mild summers with limited high-temperature extremes ■ Cool winters, generally above severe freezing conditions ■ High frequency of hours in mid-temperature bins (41°F to 59°F) ■ Moderate wet-bulb depression	■ Strong potential for **free cooling and dry operation** across much of the year ■ Stable operating conditions favor **high annual efficiency with low system stress** ■ Evaporative systems provide incremental benefit, but not always required

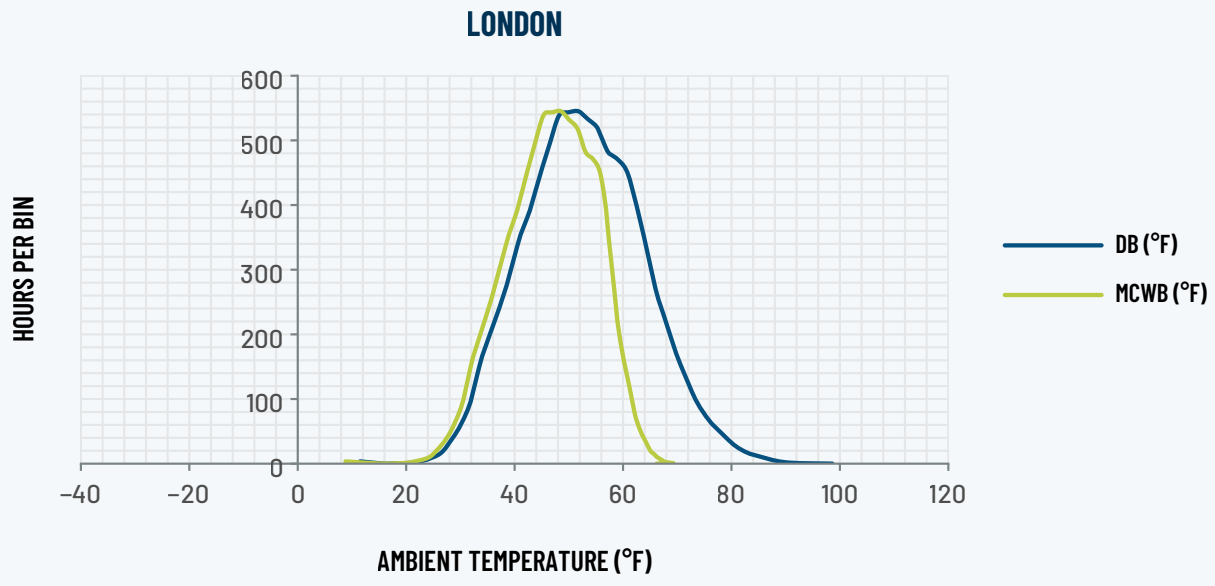


Figure 4: DB and MCWB temperature distributions for London, United Kingdom, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

COOL MARITIME CLIMATE

2.2 Amsterdam, Netherlands

Amsterdam shows a similar profile to London, but with a **slightly broader temperature distribution and marginally cooler overall conditions.** The DB curve extends slightly lower and the MCWB curve remains closely coupled, confirming a **consistently humid environment.**

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
■ Cool climate with long shoulder seasons ■ Moderate humidity with small dry-bulb–wet-bulb (DB–WB) separation ■ Significant portion of the year in low- to mid-ambient temperatures (<59°F)	■ **Very favorable for air-side or water-side free cooling** ■ Limited advantage from adiabatic operation due to small wet-bulb depression ■ Systems can be optimized for **energy efficiency with minimal water use**

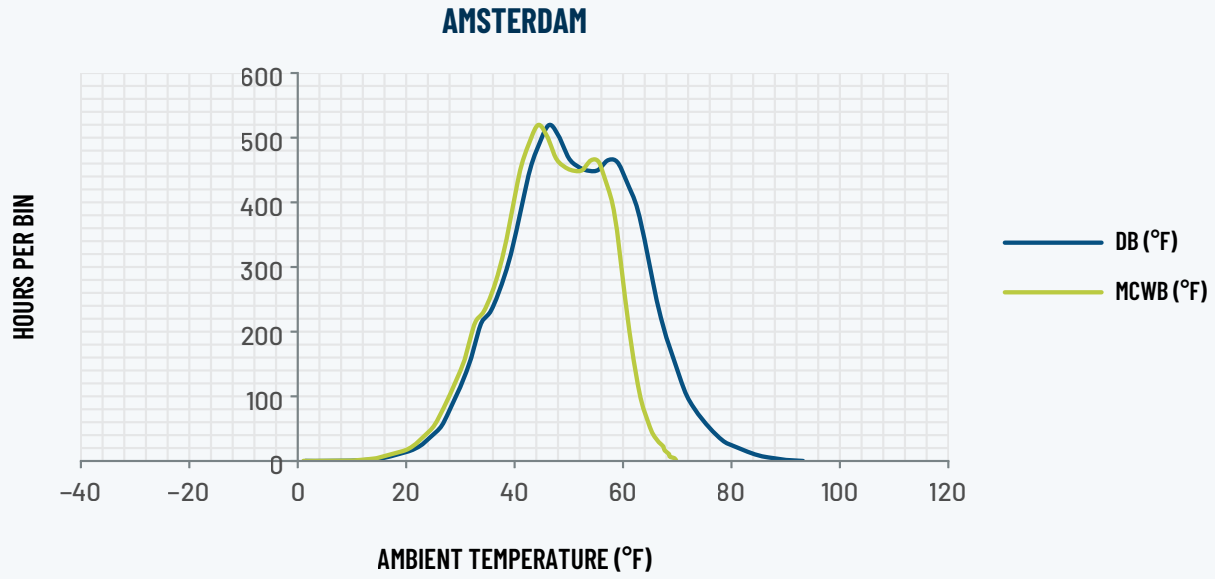


Figure 5: DB and MCWB temperature distributions for Amsterdam, Netherlands, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

HOT ARID CLIMATE

2.3 Dubai, UAE

Dubai represents a **high dry-bulb, relatively high peak wet-bulb environment with a strong concentration of hours at elevated temperatures.** The DB distribution is centered in the 77°F to 104°F range, with extended tails into extreme heat. The noticeable separation between the DB curve and the MCWB curve reflects **significant evaporative cooling potential,** although absolute wet-bulb temperatures relatively remain high.

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
▪ Prolonged periods of high ambient temperature ▪ Relatively high wet-bulb temperatures, particularly in peak summer ▪ Limited hours in low ambient conditions ▪ Large DB–WB separation	▪ Systems must be designed for **high peak loads and sustained operation at elevated temperatures** ▪ **Minimal opportunity for free cooling without either mechanical assistance or using water for adiabatic or evaporative solutions** ▪ Strong dependence on chiller operation for much of the year ▪ Significant evaporative and adiabatic cooling potential due to wet-bulb depression

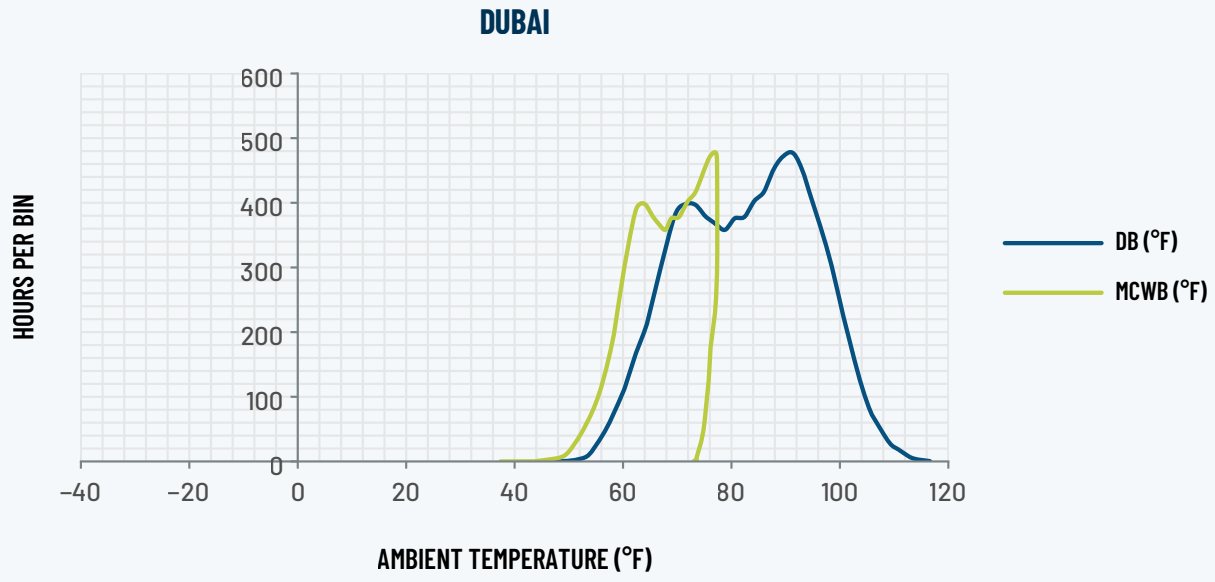


Figure 6: DB and MCWB temperature distributions for Dubai, United Arab Emirates, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

MIXED HUMID CLIMATE

2.4 Dulles, Virginia, USA

The Dulles profile shows a **wide and relatively balanced distribution** across cold, moderate, and hot temperatures. The DB curve spans from sub-zero winter conditions to summer peaks approaching 95°F to 104°F. The MCWB curve indicates **moderate to high humidity in the summer,** reducing evaporative cooling potential at peak conditions compared to regions with a greater wet-bulb depression.

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
▪ Four distinct seasons with broad temperature variation ▪ Meaningful number of hours in both low and high ambient conditions ▪ Moderate wet-bulb depression in shoulder seasons, reduced in peak summer ▪ Balanced distribution across bins	▪ Requires **flexible design to balance seasonal performance** ▪ **Similar performance characteristics** across all technologies ▪ Significant free cooling potential in winter and shoulder seasons ▪ Evaporative systems provide benefit, especially during peak summer humidity

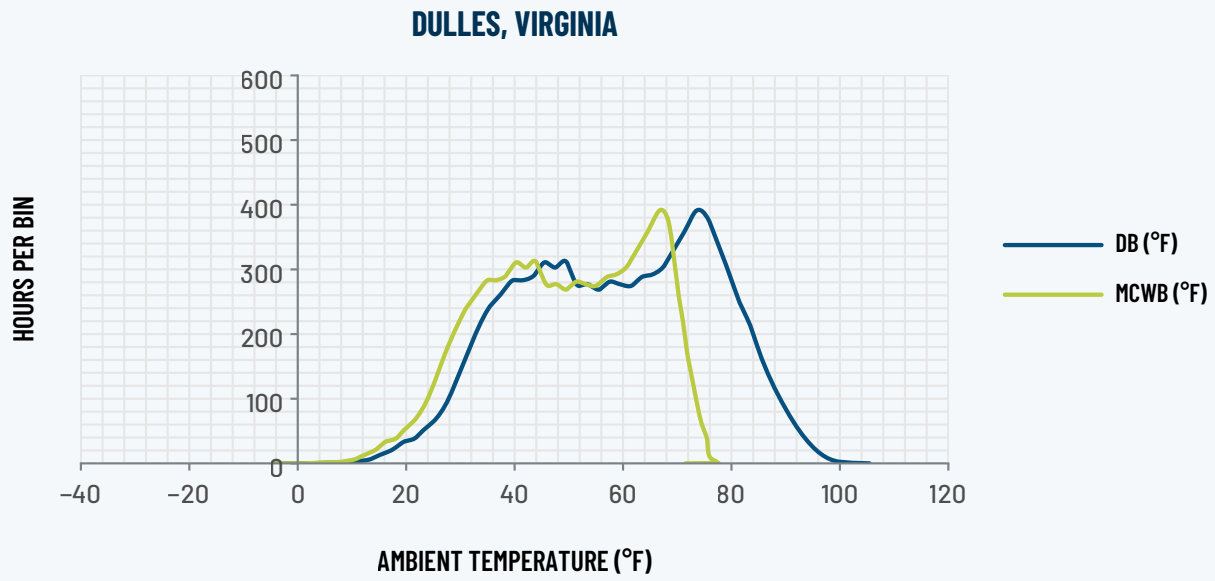


Figure 7: DB and MCWB temperature distributions for Dulles, Virginia, USA, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

HOT DRY CLIMATE

2.5 Amarillo, Texas, USA

Amarillo exhibits a **wide dry-bulb range with a pronounced spread between DB and MCWB,** indicating a **dry climate with strong evaporative cooling potential.** A large portion of operating hours falls in the moderate to warm temperature range, with relatively low wet-bulb temperatures.

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
■ Hot summers with low humidity ■ Significant DB–WB separation across most bins ■ Moderate winter conditions with some hours below freezing ■ Strong distribution across mid to high temperatures	■ **Highly favorable for adiabatic and evaporative systems** ■ Meaningful hours of reduced WCC condenser fluid temperatures, allowing for more free cooling potential ■ Strong opportunity to **trade water use for large energy savings**

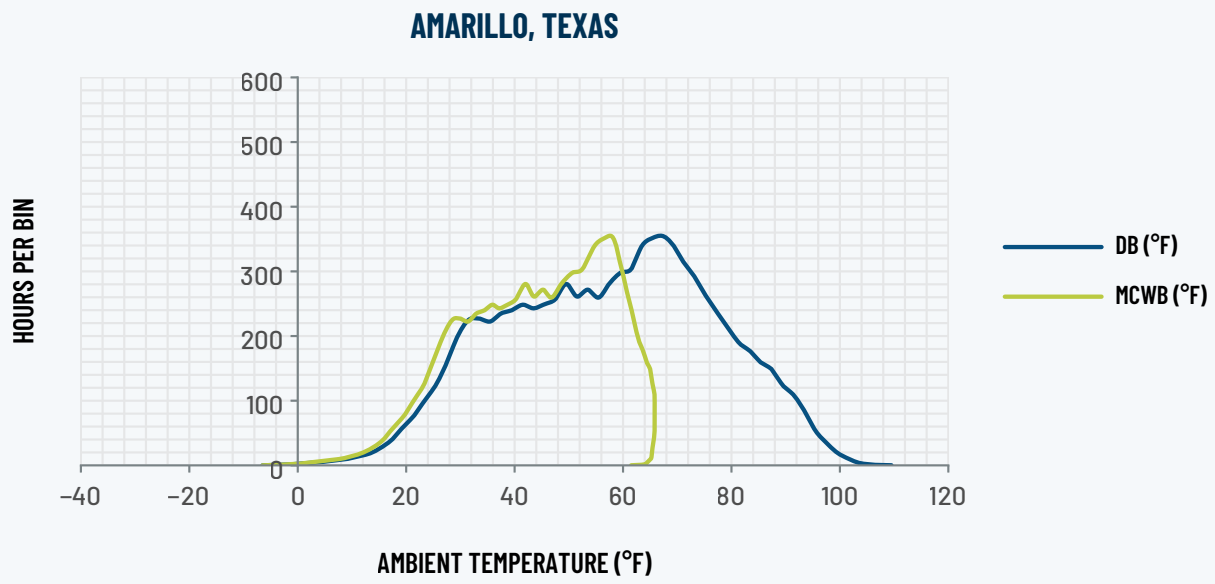


Figure 8: DB and MCWB temperature distributions for Amarillo, Texas, USA, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

COLD CONTINENTAL CLIMATE

2.6 Chicago, Illinois, USA

Chicago displays a **bimodal distribution,** with a large number of hours at low ambient temperatures and a secondary peak in warm summer conditions. The DB curve extends well below freezing, while the MCWB curve tracks closely in colder bins but diverges modestly in summer.

KEY CHARACTERISTICS:	IMPLICATIONS FOR HEAT REJECTION:
■ Cold winters with extended sub-zero operation ■ Warm, moderately humid summers ■ Large portion of the year in low ambient conditions (<50°F) ■ Majority of evaporative benefit is in summer due to the wet-bulb depression	■ **Excellent free cooling potential for a majority of the year** ■ Extended opportunity for dry operation without mechanical cooling ■ Seasonal transition to hybrid or mechanical cooling in summer ■ Particular attention must be paid to **freeze protection and glycol impacts**

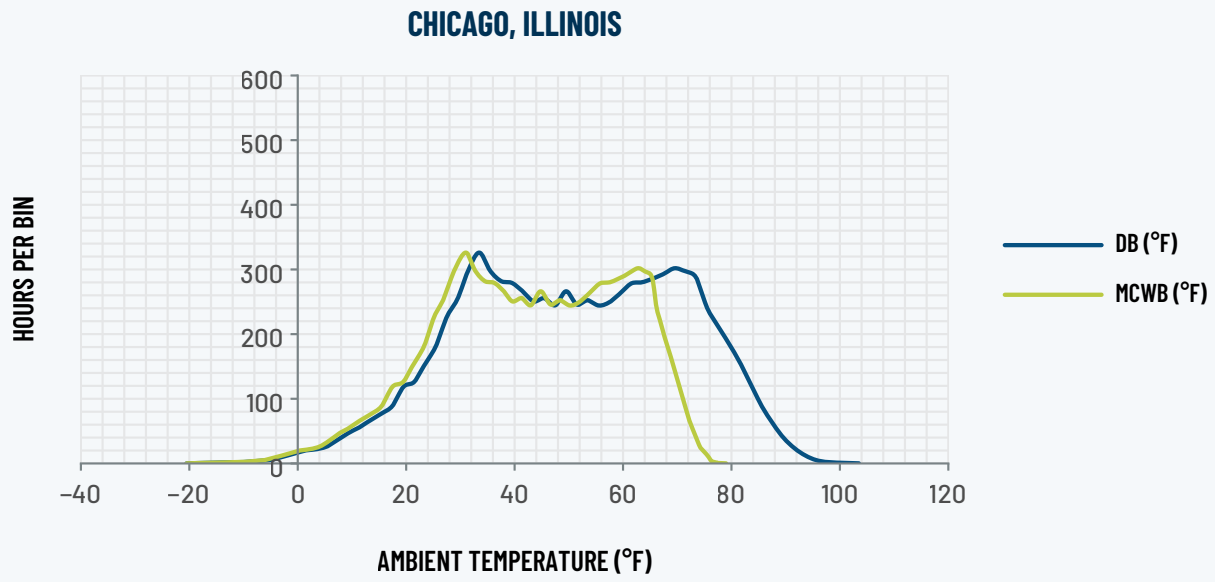


Figure 9: DB and MCWB temperature distributions for Chicago, Illinois, USA, based on ASHRAE 2025 bin weather data, showing annual hours of occurrence. These distributions form the basis for evaluating heat rejection system performance across varying climates.

2.7 Summary of Climate Diversity

Collectively, these six locations span a wide spectrum of operating conditions:

CLIMATE TYPE	LOCATIONS	KEY BEHAVIOR
COOL MARITIME	London; Amsterdam	Free-cooling dominant, low extremes
HOT ARID	Dubai	Peak-driven, minimal free cooling
MIXED HUMID	Dulles	Balanced performance, seasonal switching
HOT DRY	Amarillo	Strong evaporative advantage
COLD CONTINENTAL	Chicago	Free-cooling dominant, freeze constraints

This diversity ensures that the study captures the **full range of conditions under which modern data centers are deployed,** and highlights how **heat rejection system performance is inherently climate-dependent** rather than universally defined by technology selection.

3. Assumptions, Selection Methodology, and Operating Logic

3.1 System Boundary and Load Assumptions

As mentioned in Section 1.3, this analysis considers an **18 MW liquid-cooled data center module,** with the study boundary limited to **external heat rejection systems upstream of the coolant distribution unit (CDU).**

The outdoor cooling loop is defined by:

- **Supply temperature:** 69.8°F
- **Return temperature:** 87.8°F

These values reflect current industry practice for direct-to-chip cooling applications and provide a representative baseline for comparison.

To isolate system performance and ensure consistent comparison across technologies, a **constant 100% load profile** was applied across all **8,760 hours of operation per year.** While real-world facilities may experience load variability, this approach ensures that all systems are evaluated under identical and conservative conditions, fully exposing differences in thermal performance and energy behavior.

3.2 Technology Selection Approach

The study evaluates four primary heat rejection configurations:

- Air-Cooled Chillers with Integrated Air-Cooled Condensers (ACC)
- Water-Cooled Chillers with Dry Coolers (WCC + DAC)
- Water-Cooled Chillers with Adiabatic Dry Coolers (WCC + ADAC)
- Water-Cooled Chillers with Closed Circuit Cooling Towers (WCC + CCCT)

Air-Cooled Chiller (ACC) Selection

A **variable-speed magnetic-bearing air-cooled chiller** was selected as the representative ACC technology. This decision reflects the significantly improved efficiency and part-load performance of modern magnetic-bearing compressors.

Free-cooling air-cooled chillers were not considered in this study due to well-documented tradeoffs associated with the addition of free-cooling coils in line with the condenser coils, including:

- Approximately **15% reduction in cooling capacity per unit**
- Increased airflow requirements
- Up to **50% higher fan energy consumption**

These factors can materially reduce overall system efficiency and increase footprint, particularly at higher load densities. As a result, high-efficiency magnetic-bearing chillers were selected to represent best-in-class air-cooled performance.

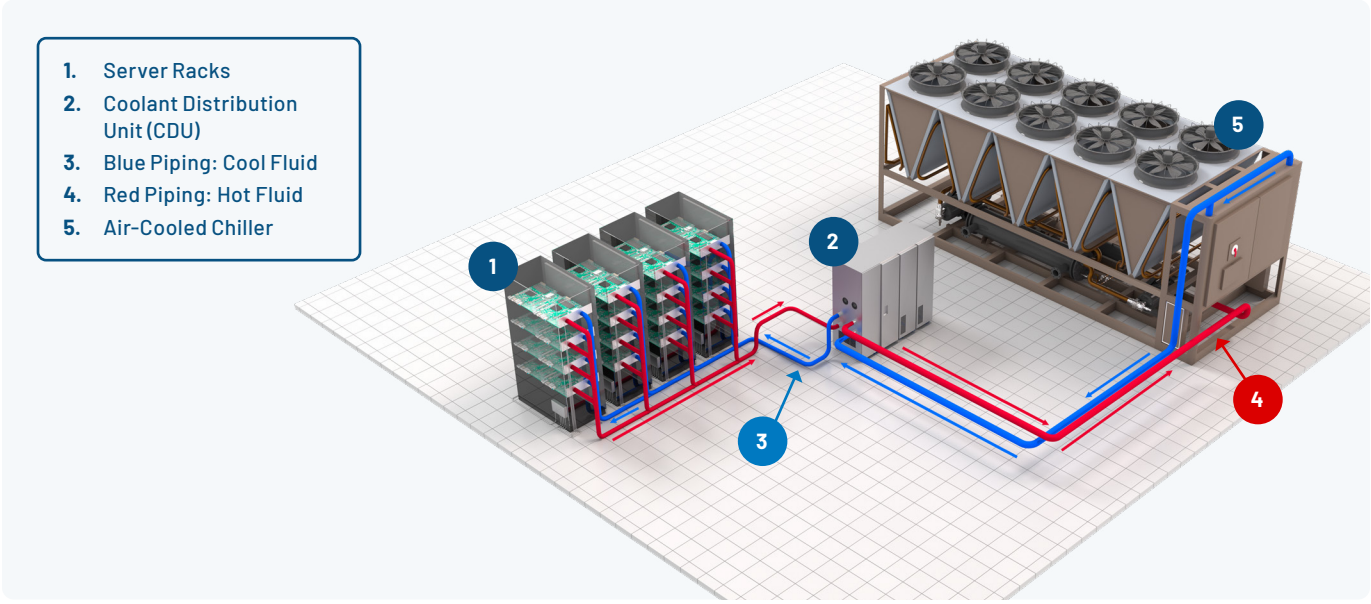


Figure 10: System layout illustrating a typical air-cooled chiller configuration, as used in this study.

3.3 Water-Cooled System Design Assumptions

For all water-cooled configurations, the following baseline assumptions were applied:

- **Condenser water ΔT: 14.4°F**
- **Initial approach temperature:** ~14.4°F (iteratively adjusted during selection)
- **Condenser water pump efficiency:** 70%
- **No trim cooling systems include:**
  - Variable-speed WCC compressor
  - Variable-speed fans on all heat rejection devices

Approach temperatures were not fixed across all scenarios, but instead **optimized during equipment selection to balance:**

- Energy consumption
- System footprint
- Capital cost

This approach reflects real-world design practice, where approach temperature is a key optimization variable rather than a fixed design point.

While the layout shown depicts an adiabatic system, the same piping and connection principles apply to the dry cooler and closed circuit cooling technologies also compared in this study.

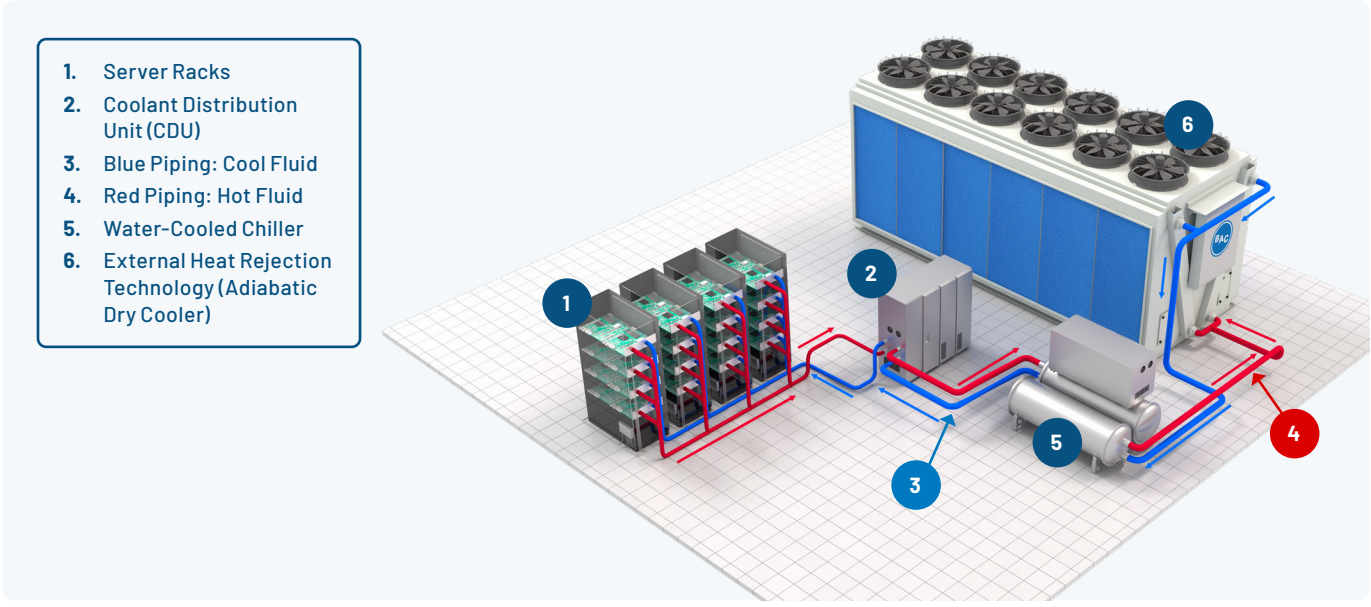


Figure 11: System layout illustrating a typical water-cooled configuration with external heat rejection, as used in this study (adiabatic dry cooler shown).

3.4 Heat Rejection Equipment Selection Philosophy

Outdoor heat rejection systems for each location were selected based on:

- Manufacturer performance data
- ASHRAE 2025 bin weather conditions
- Reasonable and achievable approach temperatures
- Variable-speed fan
- Industry-standard design practices for airflow, maintenance spacing, and layout

Equipment selections reflect a balance between energy consumption, system footprint, and capital cost, with selection priorities varying by location. The adiabatic configurations for London and Amsterdam illustrate this tradeoff: London prioritizes a more constrained footprint, while Amsterdam prioritizes lower annual operating costs.

3.5 Operating Logic and Control Strategy

A consistent operating logic was applied across all water-cooled systems to reflect practical control strategies.

The system logic prioritizes maximizing free cooling operation whenever ambient conditions allow and minimizing chiller compressor use. Once free cooling is achieved, the chiller compressors are shut down, and the condenser water pumps are de-energized. The heat rejection then continues to maintain the required temperatures independently. This approach ensures that mechanical cooling is minimized and system efficiency is maximized during favorable ambient conditions. It should be noted that for the ACC solution, the air-cooled chiller operates all the time with no economizer mode but will utilize its variable-speed compressor and condenser fan capabilities.

During periods when free cooling is not available, heat rejection systems are operated to achieve the **lowest practical condenser water temperature.** However, once free cooling conditions are met, further reduction in condenser water temperature is not prioritized, and system operation shifts to maintaining stable supply conditions. This control philosophy reflects a **realistic operational balance,** avoiding excessive energy use in pursuit of marginal performance gains once chiller operation is eliminated. In an optimized system, variable-flow condenser loops could be considered to further reduce energy consumption, but this is outside of the scope of this study.

For all water-cooled systems, condenser water pumps operate only during chiller operation. When free cooling is enabled, the condenser pumps are turned off and the system transitions to fixed-flow evaporator water pump circulation for the complete system, reducing parasitic energy consumption and simplifying operation during economizer conditions.

For the purpose of this study, trim cooling (or integrated economizer operation) has not been considered, as it has minimal benefit in the fixed-load operation assumed here. The study instead prioritizes efficiency gains in the chiller with a lower condenser water temperature. Future studies may incorporate integrated economizer operation.

3.6 Performance Modeling Approach

System performance is calculated using manufacturer-provided performance curves for chillers, combined with ambient temperature bin analysis based on the following inputs:

- Dry-bulb (DB) and mean coincident wet-bulb (MCWB)
- Wet-bulb (WB) and mean coincident dry-bulb (MCDB) for CCCT simulations

Chiller compressor power is determined as a function of entering air temperature for ACC systems and entering condenser water temperature for WCC systems. Heat rejection equipment performance is evaluated across all temperature bins to determine achievable condenser temperatures and transition points into free cooling operation.

3.7 Economic Assumptions

Capital cost estimates are based on **industry-standard budget pricing** with an accuracy of ±15%. Operating costs incorporate location-specific electricity, water supply, and wastewater discharge rates, allowing the study to reflect **regional variability in operating economics** rather than relying on generic cost assumptions.

3.8 Key Modeling Exclusions

The assumptions and operating logic applied in this study are intended to reflect realistic design and operational practices, while maintaining a consistent and controlled framework for comparing heat rejection technologies across multiple climates.

To maintain focus and clarity, the following were not included in this phase of the study:

- Trim cooling systems
- Maintenance and lifecycle costs
- Electrical infrastructure costs (generators, switchgear, etc.)
- Heat reuse integration
- Site-specific airflow recirculation effects

These factors are acknowledged as important and will be addressed as **future study considerations.**

4. Findings by Evaluation Metric

The comparative analysis of heat rejection technologies across six global climate zones reveals that **system performance is highly dependent on environmental conditions,** with no single technology consistently outperforming others across all metrics. Instead, each solution demonstrates strengths and limitations depending on the balance between **ambient temperature, humidity, and seasonal temperature distribution as seen below.**

PERFORMANCE SUMMARY MATRIX				
CRITERION	**ACC**	**WCC + DAC**	**WCC + ADAC**	**WCC + CCCT**
CAPEX	High	Medium	Low–Medium	Low
OPEX (Cool Climate)	High	Medium	Medium	Low
OPEX (Hot Climate)	High	Very High	Medium–High	Low
Peak Power	High	Very High	Medium	Low
Footprint	Very High	Low	Medium–High	Low
Water Use	None	None	Low–Moderate	High
Free Cooling Potential	Limited	Moderate	High	High
Climate Sensitivity	High	Very High	Medium	Low–Medium
System Complexity	Low	Medium	Medium–High	Medium
Future Flexibility	Low	Medium	High	Medium

4.1 Capital Cost (CAPEX) Trends[1]

Across all locations, a clear hierarchy in capital cost is observed:

- **Lowest CAPEX:** WCC + CCCT and WCC + ADAC (typically)
- **Mid-range CAPEX:** WCC + DAC
- **Highest CAPEX:** ACC

Water-cooled systems—particularly those utilizing **closed circuit cooling towers**—typically represent the lowest capital cost, benefiting from lower chiller lift, reduced compressor sizing, and more compact heat rejection equipment.

Air-cooled chiller systems consistently exhibit the **highest capital investment,** driven primarily by larger installed equipment requirements, integrated condenser systems, and increased airflow and footprint requirements.

In extreme climates such as Dubai, the spread between technologies becomes more pronounced, with **WCC + CCCT systems showing the lowest overall CAPEX** due to reduced reliance on oversized mechanical systems.

[1] Appendix A: Table A-1 Capital Cost

4.2 Operating Cost (OPEX) Trends[2]

Operating cost results show the **strongest climate dependence of the metrics evaluated in this study.**

Key drivers include:

- Free cooling availability
- Wet-bulb temperature profiles
- Compressor lift requirements

WCC + CCCT systems deliver the lowest OPEX across most locations, while ACC systems consistently show the highest OPEX due to continuous compressor operation. Climate-specific patterns are notable, as illustrated in the figures below.



Cool Climates (London; Amsterdam; Chicago)

The lowest OPEX is observed for WCC + CCCT systems, while ACC systems show significantly higher OPEX due to continuous compressor operation. Dry systems show moderate performance but are less efficient than evaporative options.

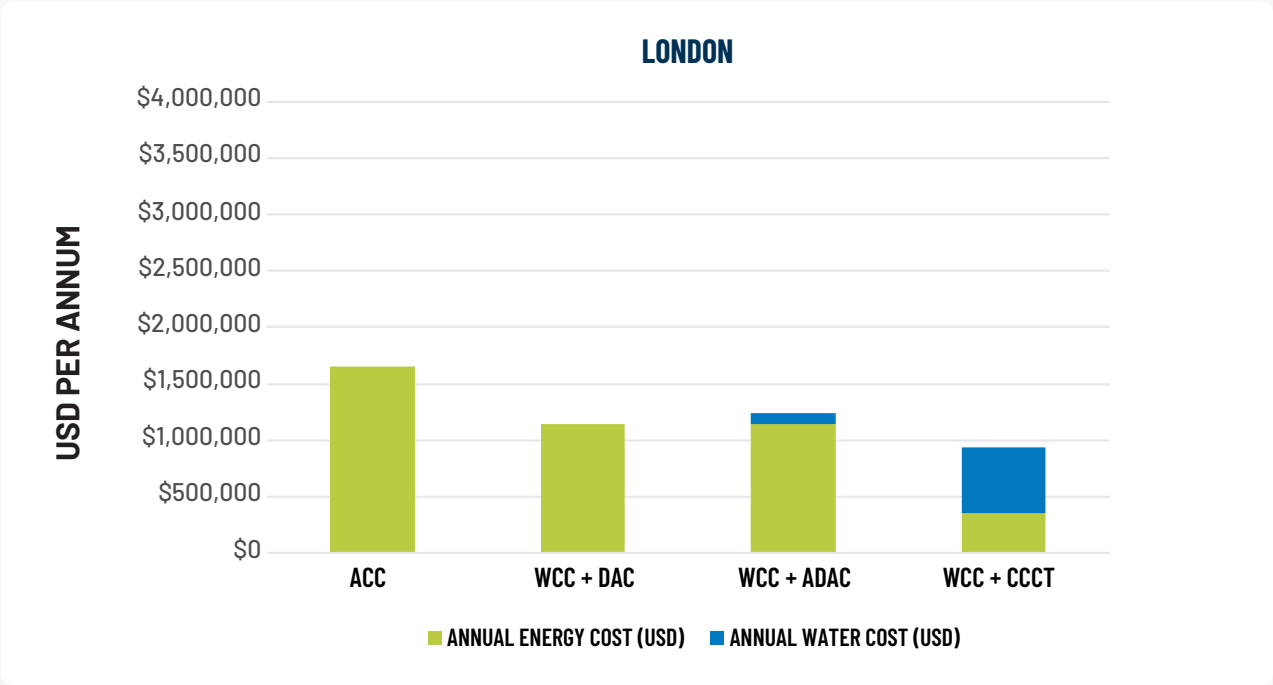


Figure 12: Operating costs for London

Note: London's modeled adiabatic configuration was selected for a more constrained footprint.

[2] Appendix A: Table A-2 Operating Cost

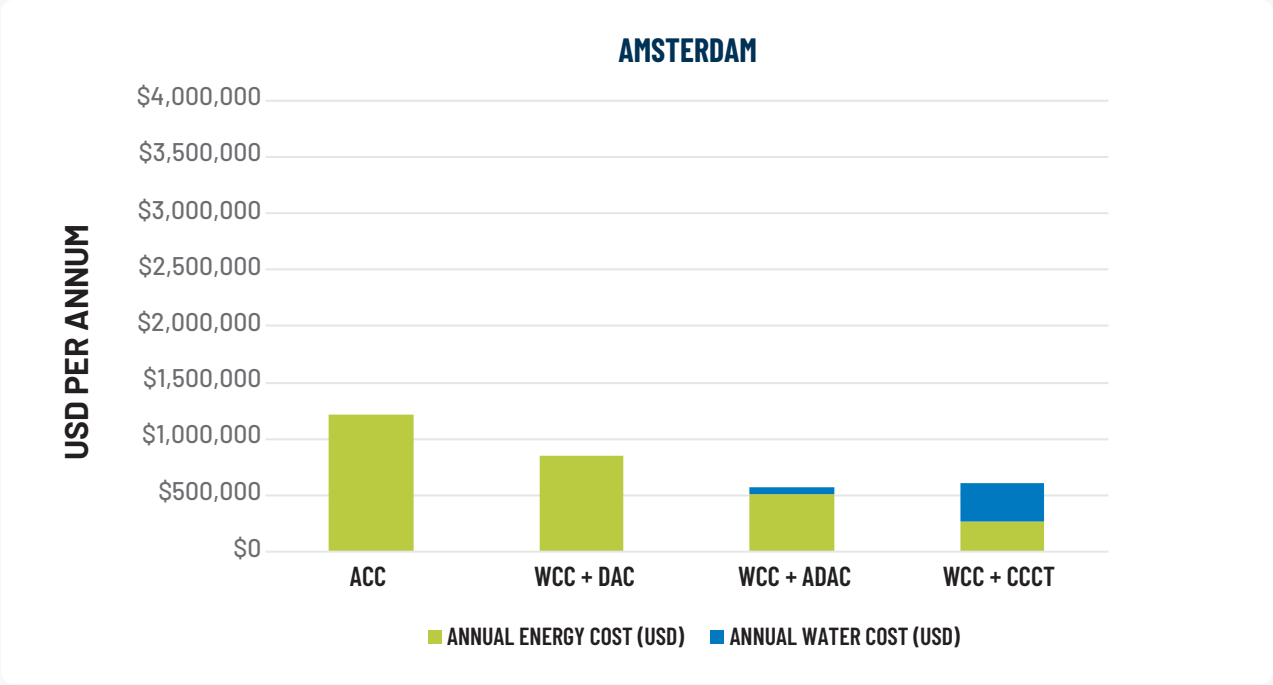


Figure 13: Operating costs for Amsterdam

Note: Amsterdam's modeled adiabatic configuration prioritizes lower annual operating costs.

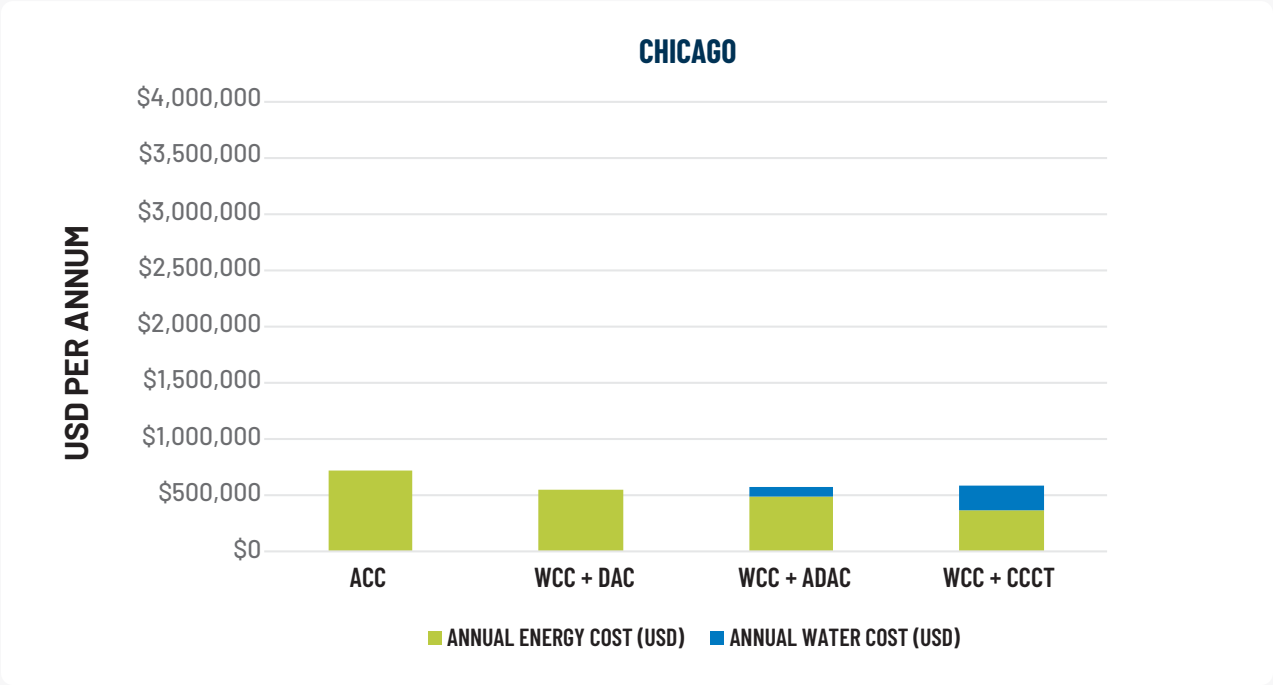
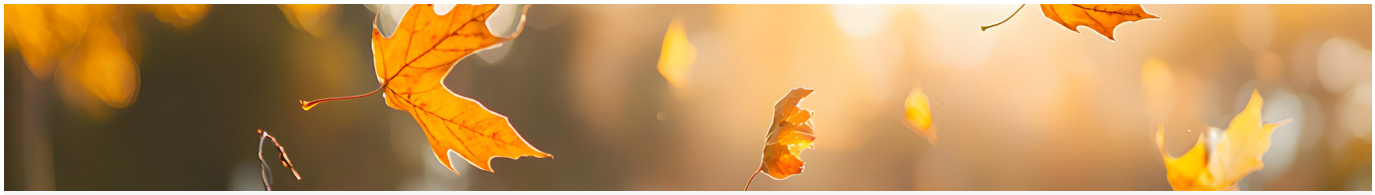


Figure 14: Operating costs for Chicago



Mixed Climates (Dulles)

All systems show similar OPEX ranges, though WCC + CCCT systems maintain a consistent OPEX advantage. Seasonal switching between chiller and economizer operation plays a key role in overall system efficiency.

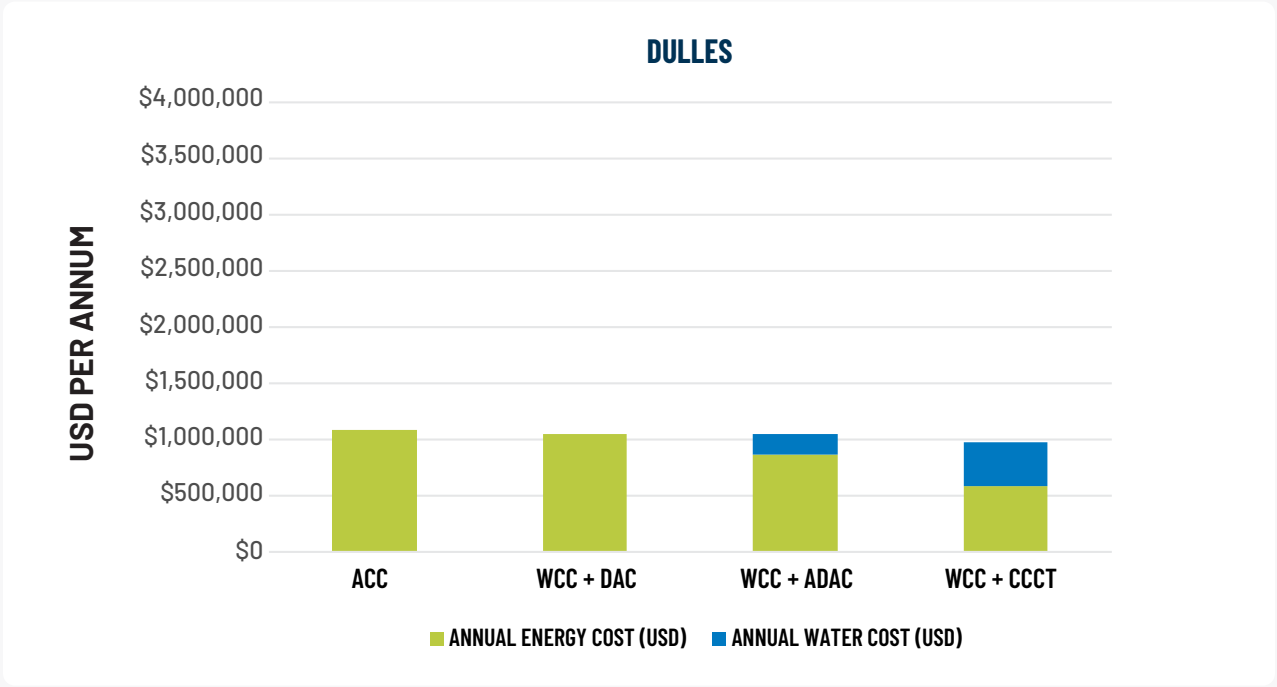


Figure 15: Operating costs for Dulles

Hot Arid Climates (Dubai)

The divergence between technologies is most pronounced. WCC + DAC systems exhibit the highest OPEX due to elevated condenser temperatures, while WCC + CCCT systems benefit from evaporative performance for significantly lower OPEX. WCC + ADAC systems offer a more balanced position between water use and energy savings.

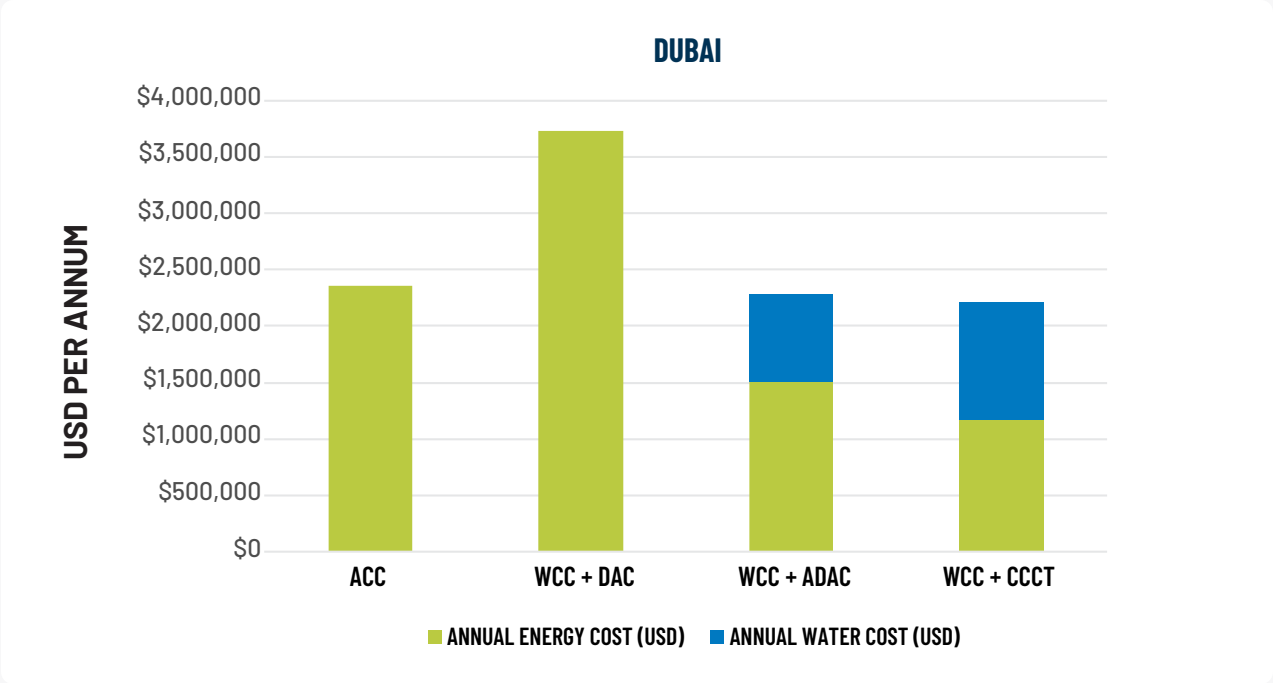


Figure 16: Operating costs for Dubai



Dry Climates (Amarillo)

WCC + ADAC systems demonstrate strong performance due to effective use of adiabatic cooling. WCC + CCCT systems still deliver the lowest OPEX.

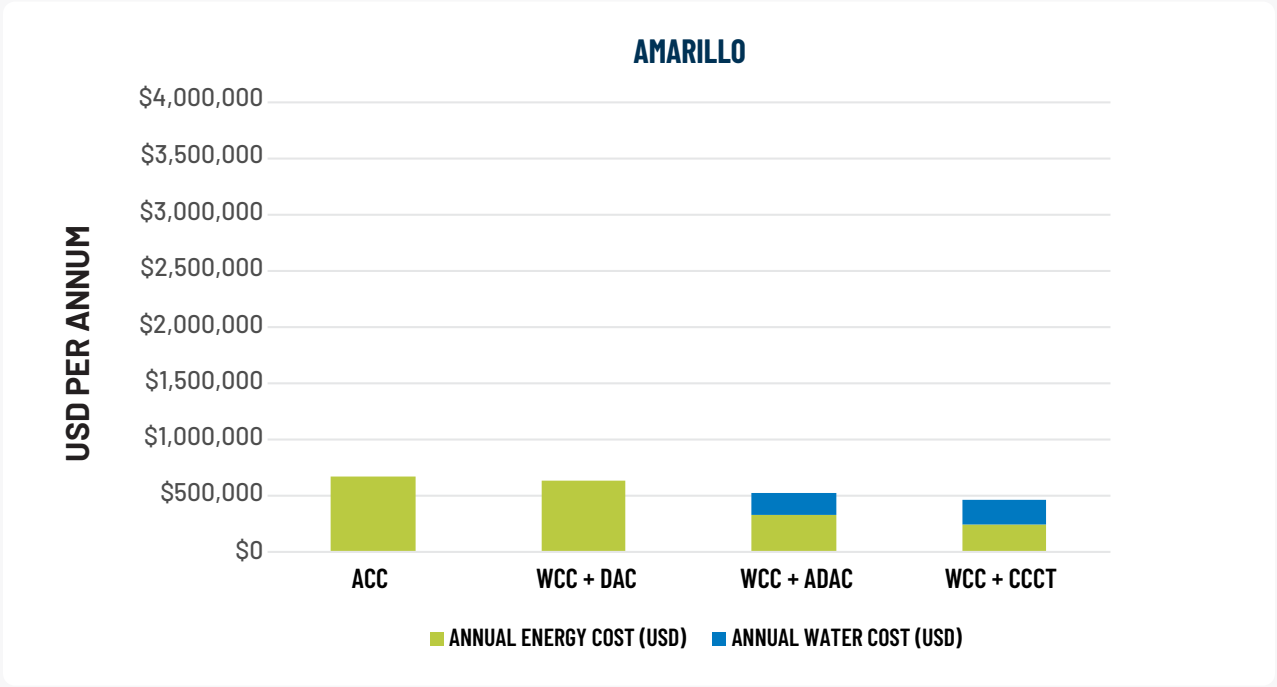


Figure 17: Operating costs for Amarillo

4.3 Peak Electrical Demand[3]

Peak input power is a critical design driver, directly impacting:

- Electrical infrastructure sizing
- Generator capacity
- Grid interconnection requirements
- Data center available capacity

Across all climates, WCC + CCCT systems demonstrate the lowest peak demand, followed by WCC + ADAC systems. WCC + DAC and ACC systems consistently show the highest peak demand. Systems that reduce **condenser temperature via evaporative cooling** significantly reduce compressor lift at peak conditions, resulting in **substantial reductions in peak electrical demand.**

For example, in Dubai, peak demand reduces from ~5200 kW for WCC + DAC systems to ~2300 kW for WCC + CCCT systems. In temperate climates, similar proportional reductions are observed, though absolute values are lower. These differences carry major implications for electrical CAPEX, backup power system sizing, and utility demand charges.

4.4 Water Consumption[4]

- **ACC and WCC + DAC** achieve zero operational water consumption, trading off water use for higher power consumption and peak electrical demand.
- **WCC + ADAC** provides a flexible balance between water use and energy savings, particularly in dry climates.
- **WCC + CCCT** requires the greatest water consumption but consistently delivers the lowest operating costs and peak electrical demand.
- Water use is strongly influenced by **ambient wet-bulb temperature, duration of warm operating conditions, and the availability and type of free cooling.**

The results reinforce that evaluating heat rejection technologies solely on water consumption can be misleading, as reductions in water use may result in higher energy consumption and larger supporting infrastructure requirements. Note also that water cost is a significant percentage of the overall OPEX in many cases, reflecting the greater percentage of economizer operation enabled by the relatively high operating temperatures in today's data centers.

In addition, reducing water use at the site often transfers such water use to the power plant supplying the data center with electricity. The most appropriate solution is therefore dependent on site-specific priorities, including water availability, energy cost, electrical capacity, sustainability objectives, and long-term resiliency requirements.

[3] Appendix A: Table A-3 Peak Electrical Demand
[4] Appendix A: Table A-4 Water Consumption

4.5 Footprint Considerations[5]

Footprint varies significantly across technologies. ACC systems require the largest footprint across all locations, driven by large air volume requirements, the need for significant spacing for proper airflow and maintenance access, and distributed equipment layouts. In contrast, WCC + CCCT systems achieve the smallest footprint **through higher heat transfer efficiency,** compact evaporative design, and reduced airflow requirements per unit of heat rejection. WCC + DAC and WCC + ADAC systems fall in an intermediate range.

Notably, WCC + ADAC systems show an increased footprint compared to WCC + DAC due to the larger coil surface area required for partial dry operation. More compact configurations can be achieved at the expense of increased annual energy and / or water consumption.

4.6 Climate-Driven Technology Performance Summary

The results clearly demonstrate that **climate dictates system suitability** as long as there is water availability.

CLIMATE SUITABILITY MATRIX				
CLIMATE TYPE	**ACC**	**WCC + DAC**	**WCC + ADAC**	**WCC + CCCT**
COOL MARITIME	Acceptable	Good	Good	Good
COLD CONTINENTAL	Good	Good	Good	Good
MIXED HUMID	Acceptable	Acceptable	Good	Good
HOT DRY	Moderate	Moderate	**Strong performer**	**Strong performer**
HOT ARID	Moderate	Lowest	Moderate	Good

[5] Appendix A: Table A-5 Total Footprint

Cool Maritime (London; Amsterdam)

- Strong performance across all WCC technologies
- **WCC + CCCT provides the lowest annual OPEX in London, while WCC + ADAC provides the lowest annual OPEX in Amsterdam. WCC + CCCT provides the lowest peak electrical demand and the highest annual water consumption in both locations.**
- ACC remains penalized on energy and footprint.

LONDON	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	3,813	4,163	2,641	2,375
Total footprint (ft^2)	9,159	6,719	7,738	6,705
Total CAPEX (USD)	$6,420,000.00	$6,098,000.00	$5,498,000.00	$6,380,000.00
Total water cost (USD/year)	$0	$0	$95,770	$580,174
Total energy cost (USD/year)	$1,656,153	$1,146,267	$1,140,917	$351,466
Total OPEX (USD/year)	$1,656,153	$1,146,267	$1,236,687	$931,640

Figure 18: London performance summary

AMSTERDAM	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	2,832	3,818	2,697	2,600
Total footprint (ft^2)	9,159	6,719	9,710	6,705
Total CAPEX (USD)	$6,420,000.00	$5,830,000.00	$6,040,000.00	$5,632,000.00
Total water cost (USD/year)	$0	$0	$50,859.34	$349,143.02
Total energy cost (USD/year)	$1,209,903.77	$848,984.14	$516,260.35	$262,213.63
Total OPEX (USD/year)	$1,209,903.77	$848,984.14	$567,119.70	$611,356.65

Figure 19: Amsterdam performance summary

Note: Lowest or optimum values for each criterion highlighted in the above tables.

Cold Continental (Chicago)

- Extensive free cooling hours
- Strong performance across all technologies
- **Evaporative systems still maintain advantage during summer peaks**
- Particular attention needs to be paid to freeze protection and glycol impacts

	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	3,115	3,663	2,878	2,550
Total footprint (ft^2)	9,159	7,852	9,228	6,433
Total CAPEX (USD)	$7,800,000.00	$6,690,000.00	$5,970,000.00	$5,562,000.00
Total water cost (USD/year)	$0	$0	$91,942.17	$219,646.14
Total energy cost (USD/year)	$718,026.70	$538,809.25	$478,065.50	$355,880.57
Total OPEX (USD/year)	$718,026.70	$538,809.25	$570,007.67	$575,526.71

Figure 20: Chicago performance summary

Mixed Humid (Dulles)

- Balanced performance across all systems
- **Seasonal switch point between chiller and economizer operation drives results**
- No clear winner, but WCC + CCCT maintains consistent overall performance benefits

	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	3,121	3,911	2,725	2,594
Total footprint (ft^2)	9,159	7,852	9,228	6,433
Total CAPEX (USD)	$7,800,000.00	$6,690,000.00	$5,970,000.00	$5,562,000.00
Total water cost (USD/year)	$0	$0	$184,006.84	$390,142.39
Total energy cost (USD/year)	$1,082,401.99	$1,045,337.54	$865,112.73	$579,347.37
Total OPEX (USD/year)	$1,082,401.99	$1,045,337.54	$1,049,119.57	$969,489.76

Figure 21: Dulles performance summary

Note: Lowest or optimum values for each criterion highlighted in the above tables.

Hot Dry (Amarillo)

- Strong advantage for **adiabatic systems**
- WCC + ADAC closes gap with evaporative systems
- Opportunities for **optimized water use versus energy tradeoff**

	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	3,461	4,232	2,878	2,247
Total footprint (ft^2)	9,159	7,852	9,228	6,433
Total CAPEX (USD)	$7,800,000.00	$6,690,000.00	$5,970,000.00	$5,562,000.00
Total water cost (USD/year)	$0	$0	$195,607.40	$221,761.31
Total energy cost (USD/year)	$663,556.86	$626,796.35	$325,262.69	$234,313.05
Total OPEX (USD/year)	$663,556.86	$626,796.35	$520,870.09	$456,074.36

Figure 22: Amarillo performance summary

Hot Arid (Dubai)

- Most challenging climate, with **close separation between technologies**
- However, magnetic-bearing air-cooled chiller's tend to have competitive energy consumption
- Evaporative systems deliver significant benefits
- WCC + CCCT provides lowest OPEX, peak demand, and overall system stress, with the highest water uses

	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
Peak input power (kW)	4,271	5,209	3,315	2,285
Total footprint (ft^2)	9,159	7,290	8,649	5,645
Total CAPEX (USD)	$7,800,000.00	$5,830,000.00	$4,290,000.00	$3,882,000.00
Total water cost (USD/year)	$0	$0	$783,538.08	$986,636.64
Total energy cost (USD/year)	$2,359,923.85	$3,725,245.41	$1,504,976.63	$1,294,287.14
Total OPEX (USD/year)	$2,359,923.85	$3,725,245.41	$2,288,514.71	$2,280,923.78

Figure 23: Dubai performance summary

Note: Lowest or optimum values for each criterion highlighted in the above tables.

4.7 Core Conclusions

The results confirm that **heat rejection selection cannot be reduced to a single metric or simplified technology preference.** Instead, optimal system selection requires balancing energy consumption, water use, capital cost, and infrastructure constraints within the context of the specific climate.

Across all locations:

- **Evaporative-assisted systems (WCC + CCCT)** consistently minimize energy use and peak demand
- **Dry systems (ACC and WCC + DAC)** provide water savings but often at the cost of increased energy and infrastructure requirements
- **Adiabatic solutions (WCC + ADAC)** offer a flexible middle ground, particularly in drier climates

Water-cooled chillers run more efficiently on average than air-cooled chillers at a given location due to lower chiller lift and reduced compressor sizing.

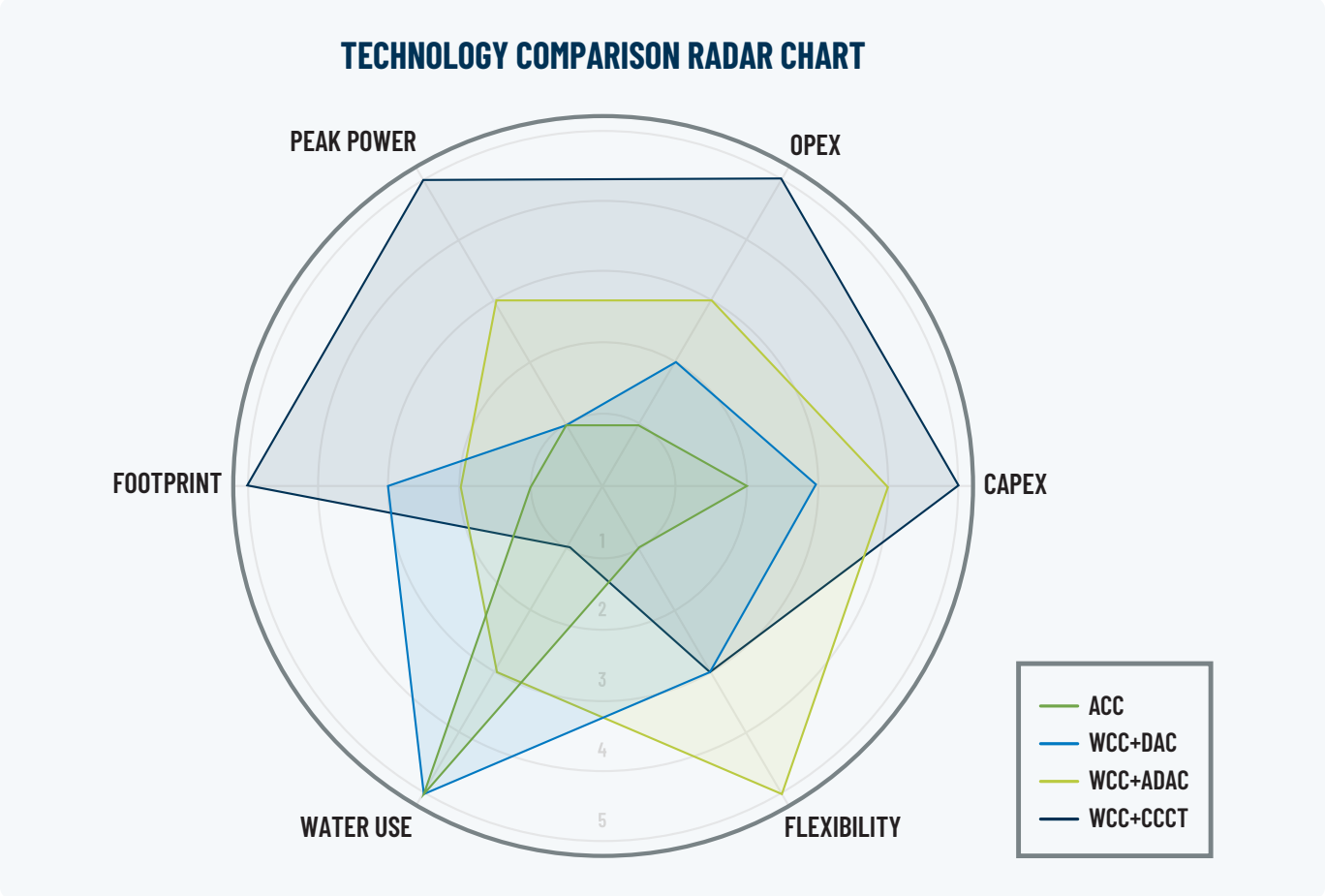


Figure 24: Each axis represents relative performance on a scale of 1 to 5, from the inner ring (1) to the outer ring (5), where a higher score indicates a more favorable outcome for that metric. The shape traced by each technology highlights its relative strengths and tradeoffs. Please note: Water Use scores reflect water efficiency relative to other configurations, not absolute consumption.

5. Application of Results

The results of this study are intended to support **early-stage system selection and concept development,** highlighting the importance of climate-specific optimization and the potential value of hybrid operating strategies. Detailed results, assumptions, and sensitivity analyses are provided in the appendix, allowing the main document to focus on key comparative insights rather than exhaustive data tables.

6. Future Considerations and Expansion of Study Scope

While this study provides a structured comparison of several widely deployed heat rejection strategies, the rapid evolution of data center cooling technologies necessitates ongoing expansion of the analysis framework. The following areas represent key opportunities for extending the study and refining future system selection methodologies.

6.1 Immersion Cooling Architectures

The current study focuses on direct-to-chip liquid cooling with traditional chilled water interfaces upstream of the CDU. However, **immersion cooling represents an increasingly viable alternative for high-density deployments.**

Immersion systems significantly reduce or eliminate the need for chillers by operating at higher fluid temperatures and enabling direct heat rejection to ambient air through dry or hybrid systems.

Key considerations for future study encompassing immersion cooling should include:

- Reduction or elimination of the use of chillers, which have the largest energy consumption in the system, including the use of integrated economizer operation
- Impact on heat rejection system sizing and approach requirements
- Fluid compatibility, containment, and lifecycle considerations
- Integration with facility-level heat reuse strategies

Analyzing immersion cooling would provide valuable insight into **chiller-less architectures and high-temperature operation envelopes,** particularly for next-generation AI deployments.

6.2 Open Circuit Cooling Towers

This study evaluates closed circuit evaporative systems; however, open circuit cooling towers remain widely used in large-scale facilities. Open circuit cooling towers offer higher thermal efficiency due to direct contact heat transfer, lower approach temperatures under favorable conditions, and reduced capital cost in certain configurations.

Future analysis should include:

- Water treatment complexity and operating cost
- Site constraints
- Water consumption relative to closed-loop systems
- Comparative performance versus closed circuit cooling towers under varying climates

A comparative analysis of open circuit cooling towers and closed circuit cooling towers would help quantify the tradeoff between **efficiency and operational complexity.**

6.3 Water Availability, Sourcing, and Treatment

Water consumption is a critical factor in evaluating evaporative and adiabatic systems, but **water source and quality** are equally important considerations.

Future expansions could incorporate:



ALTERNATIVE WATER SOURCES

- Reclaimed municipal water
- Greywater systems
- On-site water recovery and reuse



WATER TREATMENT IMPACTS

- Chemical treatment requirements
- Filtration and biological control
- Impact on system reliability and maintenance



REGIONAL CONSTRAINTS

- Water scarcity or regulatory limitations
- Cost variability for water supply and discharge
- Future variations in available water supply

This broader perspective would allow evaluation of not just **water quantity,** but **water sustainability and lifecycle impact.**

6.4 Maintenance and Lifecycle Cost Modeling

The current study measures CAPEX and OPEX (primarily energy and water) but does not explicitly quantify **maintenance costs and system lifecycle impacts.**

Future analysis could include:

- Routine maintenance requirements (cleaning, inspection, component replacement)
- Water treatment and monitoring costs
- Equipment degradation over time (e.g., fouling, scaling, corrosion)
- Downtime risk and associated operational cost

Analyzing these factors would provide a more complete **total cost of ownership (TCO)** comparison across technologies.

6.5 Electrical Infrastructure Implications

Peak power results clearly demonstrate that heat rejection technology significantly impacts electrical infrastructure requirements.

Future analysis could include:

- Generator sizing and redundancy implications
- Switchgear, transformers, and UPS capacity
- Impact on grid interconnection and demand charges
- Capital cost associated with electrical infrastructure scaling
- Water use at the power plant

In many cases, **reductions in peak power may offset higher mechanical system costs,** making this an essential dimension of the analysis.

6.6 Equipment Layout and Recirculation Effects

The current study assumes idealized equipment performance based on manufacturer data and equipment layout guidelines. Recirculation and interference from the heat rejection equipment discharges are assumed to be negligible.

However, real-world system efficiency is often influenced by actual site layout and airflow interaction effects, including prevailing wind direction, location of generator exhausts, and adjacent structures. These effects become especially pronounced when multiple modules, such as the 18 MW modules studied here, are multiplexed together for larger-capacity data centers. The larger the heat load, the more potential for the local air temperatures surrounding the heat rejection equipment to be elevated. This can increase system energy use, especially during peak climate and load conditions.

Practitioner experience and computational fluid dynamics (CFD) analysis can help to anticipate and adjust the layout as necessary to minimize such "heat island" impacts or establish design temperature allowances to assure the necessary performance under all circumstances. Introducing such layout-based adjustments on very large projects would allow for more realistic predictions of effective approach temperatures, possible performance degradation, and site-specific optimization opportunities.

6.7 Expanded Climate Coverage

While the selected locations provide a strong range of climate conditions, further expansion would enhance global applicability.

Additional climates to consider:

- Tropical high-humidity regions (e.g., Southeast Asia)
- Extreme cold climates (e.g., Nordic regions)
- High-altitude environments
- Coastal versus inland variability

A broader dataset would enable more robust conclusions regarding technology sensitivity to humidity versus temperature, regional optimization trends, and global deployment strategies.

6.8 High-Temperature Operation and Reduced Dependence on Chillers

Recent developments in processor technology, including announcements of **higher allowable liquid cooling temperatures (e.g., 104°F to 122°F range),** introduce the potential for **significantly reduced or eliminated chiller use.**

Future analysis could include:

- Operation with elevated supply temperatures (e.g., >86°F)
- Direct heat rejection using dry or adiabatic systems
- Use of **high-temperature air-cooled chillers** with reduced lift
- Impact on free cooling hours and energy savings
- Impact on data center reliability metrics and reduced redundancy requirements

These scenarios represent a major shift toward simplified, low-energy cooling architectures, especially given that chillers are the most complex individual piece of equipment in most data center cooling systems.

6.9 Close Approach CDU Designs

Advancements in CDU design are enabling **lower approach temperatures between the TCS loop and water loop,** which has significant implications for heat rejection.

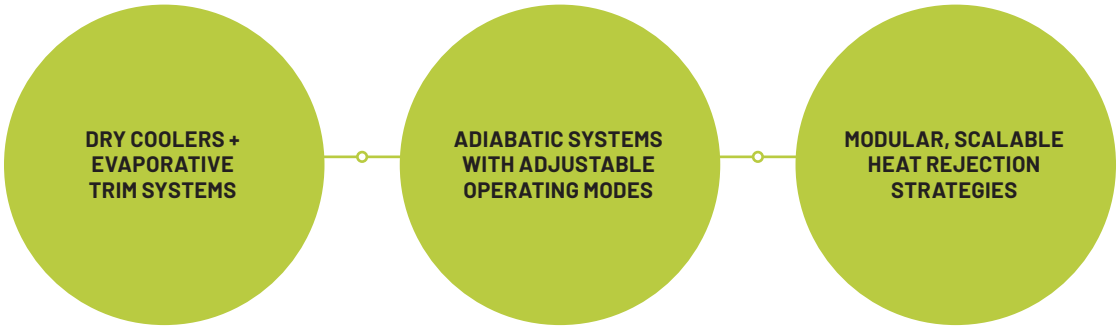
Future analysis could include:

- Increased opportunity for free cooling
- Reduced chiller operating hours
- Lower required condenser temperatures
- Improved system efficiency across all heat rejection technologies
- Impact on OPEX of closer approach CDU designs

Evaluating multiple CDU performance scenarios would help quantify how **improving the internal thermal interface can reduce external system energy demand.**

6.10 Hybrid and Adaptive System Architectures

Future work should explore integrated hybrid systems, combining multiple technologies into a single architecture:



These systems can provide increased resiliency, operational flexibility, and the ability to adapt to changing constraints (water, energy, load growth), warranting future analysis.

Appendix A: Detailed Study Results

Table A-1 Capital Cost (CAPEX) [USD]

LOCATION	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
London	$6,420,000	$6,098,000	$5,498,000	$6,380,000
Amsterdam	$6,420,000	$5,830,000	$6,040,000	$5,632,000
Dubai	$7,800,000	$5,830,000	$4,290,000	$3,882,000
Dulles	$7,800,000	$6,690,000	$5,970,000	$5,562,000
Amarillo	$7,800,000	$6,690,000	$5,970,000	$5,562,000
Chicago	$7,800,000	$6,690,000	$5,970,000	$5,562,000

Table A-2 Operating Cost (OPEX) [USD/year]

LOCATION	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
London	$1,656,153	$1,146,267	$1,236,687	$931,640
Amsterdam	$1,209,904	$848,984	$567,120	$611,357
Dubai	$2,359,924	$3,725,245	$2,288,515	$2,280,924
Dulles	$1,082,402	$1,045,338	$1,049,120	$969,490
Amarillo	$663,557	$626,796	$520,870	$456,074
Chicago	$718,027	$538,809	$570,008	$575,527

Table A-3 Peak Electrical Demand [kW]

LOCATION	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
London	3,813	4,163	2,641	2,375
Amsterdam	2,832	3,818	2,697	2,600
Dubai	4,271	5,209	3,315	2,285
Dulles	3,121	3,911	2,725	2,594
Amarillo	3,461	4,232	2,878	2,247
Chicago	3,115	3,663	2,878	2,550

Table A-4 Water Consumption [gal/year]

LOCATION	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
London	0	0	7,646,196	51,024,832
Amsterdam	0	0	7,101,209	48,749,254
Dubai	0	0	67,865,272	86,880,640
Dulles	0	0	21,925,488	58,894,253
Amarillo	0	0	34,481,586	61,666,475
Chicago	0	0	16,156,499	55,261,359

Table A-5 Total Footprint [ft^2]

LOCATION	ACC	WCC + DAC	WCC + ADAC	WCC + CCCT
London	9,159	6,719	7,738	6,705
Amsterdam	9,159	6,719	9,710	6,705
Dubai	9,159	7,290	8,649	5,645
Dulles	9,159	7,852	9,228	6,433
Amarillo	9,159	7,852	9,228	6,433
Chicago	9,159	7,852	9,228	6,433

WHITE PAPER

Evaluating External Heat Rejection Options for Liquid-Cooled Data Center Applications

To learn more about this white paper and to contact BAC about your next data center project, please visit **baltimoreaircoil.com/data-centers**



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