WHITEPAPER

Optimizing Data Center Cooling with Economizer and Free Cooling Strategies

Data centers are mission-critical facilities with significant energy and cooling demands. As data centers grow in importance, demand, and size, industry sustainability goals continue to intensify, and energy costs continue to rise.

Free cooling allows the utilization of outdoor air to reduce mechanical cooling demand during favorable ambient conditions. This paper outlines the principles of economizer-free cooling, explores common methodologies relevant to data centers, and describes system architectures and practical considerations.

Although airside economizing and thermosiphon technology are addressed briefly, the paper primarily focuses on the more widely applied waterside economizing approach.

Data centers operate continually, driving significant cooling loads to maintain optimal performance and reliability of critical IT equipment. To support these needs, cooling systems are sized for a worst-case "design point," which accounts for peak load and the hottest expected outdoor conditions. In practice, both IT loads and outdoor conditions fluctuate, creating opportunities to reduce cooling energy use by leveraging outside air when conditions allow. Implementing a free cooling strategy as part of a thermal management system design can help operators achieve significant savings and meet sustainability targets.

As server densities and heat loads rise, many modern data center system designs utilize liquid cooling solutions, shifting cooling load away from air and raising acceptable fluid temperatures. The warmer fluid temperatures of these solutions can increase the effective range of some economizer strategies. The reduction of air-cooled IT equipment loads further limits the usefulness of some strategies, such as airside economizing.

Free Cooling Methodologies

An economizer is a strategy or system option that leverages favorable outdoor conditions to minimize or eliminate mechanical cooling (chillers or compressor-based systems). "Free cooling" utilizes an economizer along with naturally cool outdoor air to dissipate heat from the data center, rather than mechanical cooling, resulting in dramatic energy savings.

Without leveraging some type of free cooling, mechanical cooling can easily account for up to 40% of a data center's total energy consumption. Economizer designs vary, but all share the common goal of substituting as much energy-intensive mechanical cooling as possible with more passive cooling assisted by cool outside air.

Application of any economizer strategy in a data center environment is more complex than its use in a typical commercial building. Careful analysis of the infrastructure design and control is essential for effective implementation.

Airside Economizer

Most air-handling systems recirculate the majority of indoor air after cooling it to a specific setpoint to maintain the desired space temperature. Airside economizers directly draw in cool outdoor air, when conditions allow, to replace the air in the space. When the outdoor air is colder than the desired space temperature, the mechanical cooling required to cool the space is reduced or eliminated.

While airside economizing can deliver substantial energy savings in more traditional commercial buildings, the following section outlines the complexities and challenges to consider before turning to more suitable alternatives for data centers.

Challenges to Airside Economizing

Humidity Control
Data centers require precise control of space humidity to prevent electrostatic discharge or condensation, both of which can damage IT equipment. Most guidelines recommend maintaining humidity levels between 40 and 60%. Outdoor air humidity varies widely by location and season, often unpredictably, requiring precise and reliable monitoring and control to maintain safe operating conditions. Outdoor air must be humidified or dehumidified when it falls outside the recommended range, which further increases system cost and operating complexity.

Without humidity control, the high rate of air turnover during airside economizing quickly equalizes space humidity to outside air conditions. To remove the need for outside air humidity treatment, economizing could be allowed only when outside humidity levels are already within the desired limits. This greatly reduces the number of hours economizing is possible and complicates system control and measurement.

Consider the four locations shown below from various U.S. climate zones. Using Typical Meteorological Year (TMY) weather data for each location, the expectation of relative humidity conditions over a typical year is reflected (shown in blue). The number of hours within the desired humidity range varies considerably, but in all locations represents a small portion of the year where economizing could be accomplished with untreated outdoor air.

Additional Filtration Requirements
Dirt, dust, and pollutants from outdoor air can jeopardize sensitive electronics within data centers. Extensive filtration is required, which increases maintenance needs and raises fan energy consumption. Unexpected events, like wildfire smoke, can necessitate a manual economizer lockout.

Challenges to Airside Economizing

Pressure Control Risk
Data center white space should be maintained in positive pressure to limit the risk of dust, contaminants, or unconditioned air from entering the space. The large quantity of outdoor air entering the space during airside economizing makes space pressurization control more difficult.

Limited Support for Liquid Cooled Components
By nature, airside economizing only helps in cooling air-cooled components in the white space. More modern power-dense data centers utilize liquid cooling as much as possible, limiting the energy reduction potential even in ideal airside economizing situations.

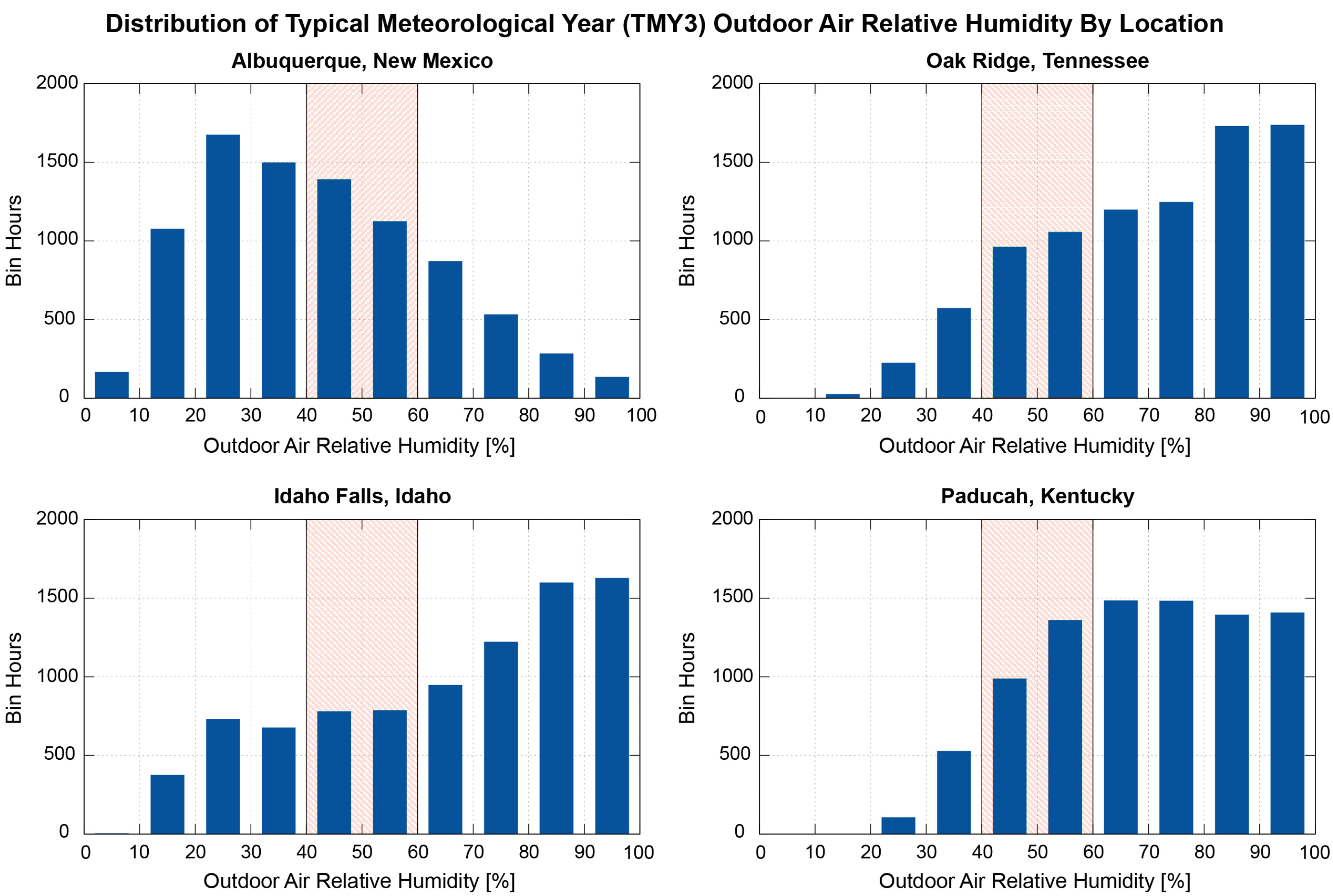


Figure 1: Distribution of TMY outside air relative humidity at four locations over one year.

Waterside Economizer

Waterside economizing can be a viable method of free cooling in any data center with a chilled water plant, whether using air-cooled or water-cooled chillers.

Waterside economizers redirect a portion, or the entirety, of the cooling load to outdoor air via heat exchangers when the ambient temperature is suitably lower than the required return water temperature in the cooling loop. The mechanical cooling provided by chillers can be reduced, or even eliminated, during periods of cooler outdoor air conditions.

The largest driver of economizer free cooling capacity is the temperature delta between the outdoor air and the return fluid temperature of the facility water system (FWS). A larger temperature difference delivers greater cooling capacity — whether achieved through colder outdoor air or warmer return fluid temperatures. Warmer fluid used in liquid-cooled data centers is a benefit, allowing effective free cooling at much warmer outdoor temperatures.

Challenges to Waterside Economizing

Complex System Control
To realize the full energy reduction possible without sacrificing performance, the system-level controls must be able to monitor a wide range of conditions, reliably implement complex control sequences, and stage equipment quickly in response to dynamically shifting loads.

Air-cooled chillers with integrated water side economizers may include a built-in controls strategy. Comparing the return fluid with outdoor temperatures, fluid will either be directed through or bypass the economizer exchangers to maximize free cooling.

Water-cooled chiller plants, or air-cooled chiller plants without integrated water side economizers, typically implement a switchover between full free cooling and full mechanical cooling without allowing hybrid operation. While simple switchover control eliminates hybrid operation, this configuration may not reduce the possible annual energy savings if the dry cooler design capacity is large enough to allow substantial free cooling at warmer outdoor air temperatures.

Increased Piping and Components
Additional piping, heat exchangers, and other components will be needed to support waterside economizing. This will increase the cost and complexity of the design.

Increased First Cost
Because of the additional components and design work required, waterside economizing will likely increase the first cost of the project. In most locations, this increased cost can be quickly recovered through the resulting energy savings.

Thermosiphon or Refrigerant Migration

Thermosiphon cycles exploit two-phase refrigerant cooling without the need for compressor operation, relying instead on natural pressure and temperature differentials. As refrigerant is boiled in the evaporator, a positive pressure differential is created to move the newly created vapor to the condenser, pushing more refrigerant back into the evaporator for continuous cooling. The refrigerant migrates passively between the evaporator and condenser, removing heat from the cooling loop as long as a sufficient temperature gradient exists.

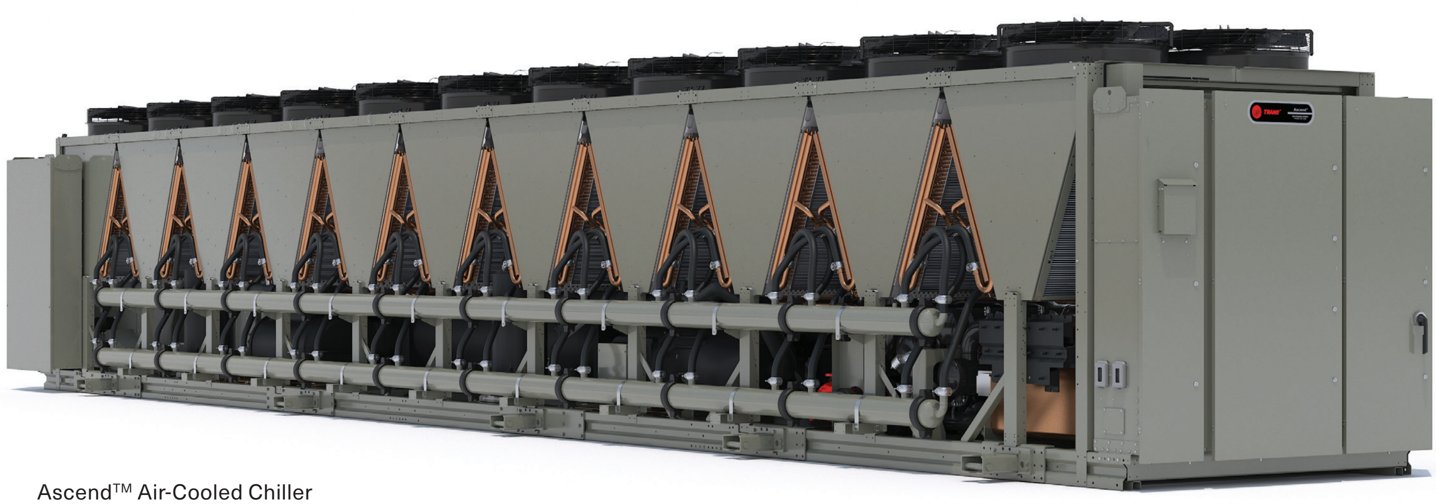
The refrigerant migration can be assisted by a refrigerant pump to achieve higher cooling capacity by overcoming internal pressure losses through the refrigeration system. This pump differs from a compressor in that the pressure change is relatively small.

As with the waterside economizer, the warmer data center return fluid temperatures make the thermosiphon attractive across a broader range of outdoor temperatures. Warmer return fluid temperatures expand the operating window for thermosiphon cooling, increasing low-energy cooling hours and reducing annual cost, power consumption, and compressor dependence.

Challenges to Thermosiphon Economizing

High Volume Refrigerant Requirements
Thermosiphon system designs vary greatly. To achieve adequate capacity, a large volume of refrigerant is often required. This is especially true for distributed systems.

Scaling Limitations for Large Cooling Plants
Thermosiphon systems can be challenging to scale to the capacities required for large data center cooling plants. This limitation can be reduced when pump assisted thermosiphon economizer functionality is integrated into mechanical cooling packaged equipment.



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Waterside Economizer System Architectures

Air-Cooled Chillers

Packaged air-cooled chillers offer an efficient, scalable solution for cooling data centers of varying sizes while delivering high-efficiency mechanical cooling. Adding waterside economizing to allow free cooling can further reduce the annual cooling energy consumption in most climates.

Waterside economizer exchangers can often be factory integrated into the chiller to avoid mounting additional components on site. This approach requires no additional footprint, reduces installation labor and total equipment cost, and helps reduce risk to project timelines. Economizer exchangers mounted to the face of the condenser coils allow the condenser fans to serve the economizer exchangers as well. This adds air pressure drop to the condenser fans, but the energy impact is minimal.

While operating in full free cooling or full mechanical cooling, the condenser and economizer coils function independently. When in hybrid operation, the economizer coils warm the air entering the condenser coils as the fluid is cooled. However, since the required mechanical cooling is also reduced, the resulting chiller lift will still be lower than if the equipment were operating solely in mechanical cooling mode.

The waterside economizer exchanger capacity is limited by the outdoor air temperature. To increase economizer capacity, adiabatic cooling devices could be added upstream to pre-cool air entering the economizer. Adiabatic cooling does introduce water consumption, which may be problematic in many locations. To limit water consumption, adiabatic cooling could be limited to periods of particularly high outside air temperatures or high cooling demand.

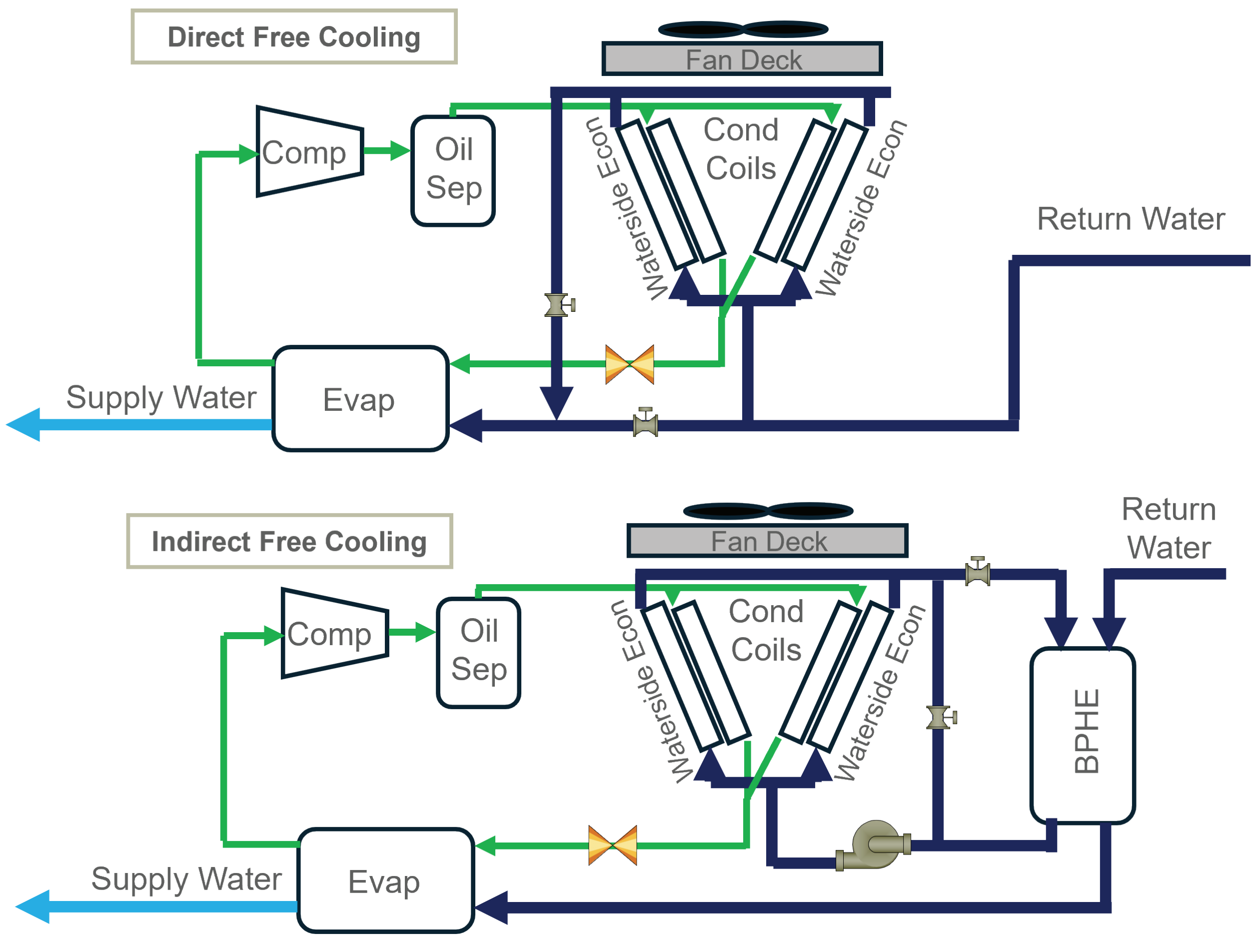

Figure 2: Air-cooled chiller with waterside economizing coils installed on the face of the condenser coils.

Direct Free Cooling

In a direct free cooling configuration, the FWS fluid is used directly in the waterside economizers. The waterside economizers are piped in series with the evaporator.

Fluid can bypass the waterside economizers when not in use. The system is capable of operating in free cooling only, mechanical cooling only, or hybrid free cooling utilizing waterside economizing and mechanical cooling simultaneously.

This approach is simple to implement but may require glycol to be used throughout the entire system. Compared to traditional water use, glycol increases the power required by pumps, chillers, dry coolers, etc., versus water and usually requires additional equipment to meet capacity.

Indirect Free Cooling

While similar to the direct free cooling configuration, in an indirect free cooling configuration, the FWS fluid is isolated from the waterside economizers via a brazed plate heat exchanger (BPHE). The waterside economizers are piped in series with the evaporator.

Fluid can bypass the waterside economizers, and the system is capable of operating in free cooling only, mechanical cooling only, or hybrid free cooling utilizing waterside economizing and mechanical cooling.

Isolating the waterside economizer into its own loop allows glycol to be used for freeze protection in the economizer coils even when water is used as the primary fluid. To support this isolation, a dedicated pump is needed for the waterside economizer loop.

Due to the inefficiencies of the BPHE and the additional pump required, the free cooling potential in an indirect configuration can be reduced. However, the benefits of isolation may still make this a viable option. This is especially true when this isolation can reduce or eliminate glycol in the primary facility loop.

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Water-Cooled Chillers

Water-cooled chillers are part of a distributed system of one-to-many chillers and one-to-many dry coolers. Waterside economizing leverages the existing dry coolers to indirectly cool the FWS as conditions allow taking advantage of the existing components as much as possible.

While the waterside economizer could be connected for direct or indirect free cooling in this arrangement, direct connected is not typical as it requires the same fluid to be used in the condenser and cooling distribution loops. Indirect free cooling, using the BPHE, prevents mixing of the condenser and cooling distribution loops.

Dry cooler design capacity is typically sized for the chiller condenser load alone. This provides enough heat rejection capacity for full free cooling or full mechanical cooling but may limit the free cooling available in hybrid operation where the free cooler and chiller condenser both have heat rejection needs. Dry cooler design capacity should be optimized, as space allows, to provide sufficient capacity for hybrid operation.

Dry cooler capacity is limited by the outdoor air temperature. To increase peak load design and economizer capacity, adiabatic cooling devices could be added upstream to evaporatively pre-cool the dry cooler entering air. Again, adiabatic cooling introduces water consumption, but the overall benefit may still be attractive when limited to periods of particularly high outside air temperatures or cooling demand. The additional free cooling savings may justify the water consumption, depending on location, project goals, and local guidelines.

To minimize water consumption, modern data center designs typically avoid the use of cooling towers. While open-loop evaporative cooling towers can be used in place of dry coolers when water conservation is not a primary concern, and in most climates offer the highest cooling efficiency, their significant water demand makes them a less suitable choice for hyperscale and colocation data centers, where water use, sustainability objectives, and utility constraints are important design considerations.

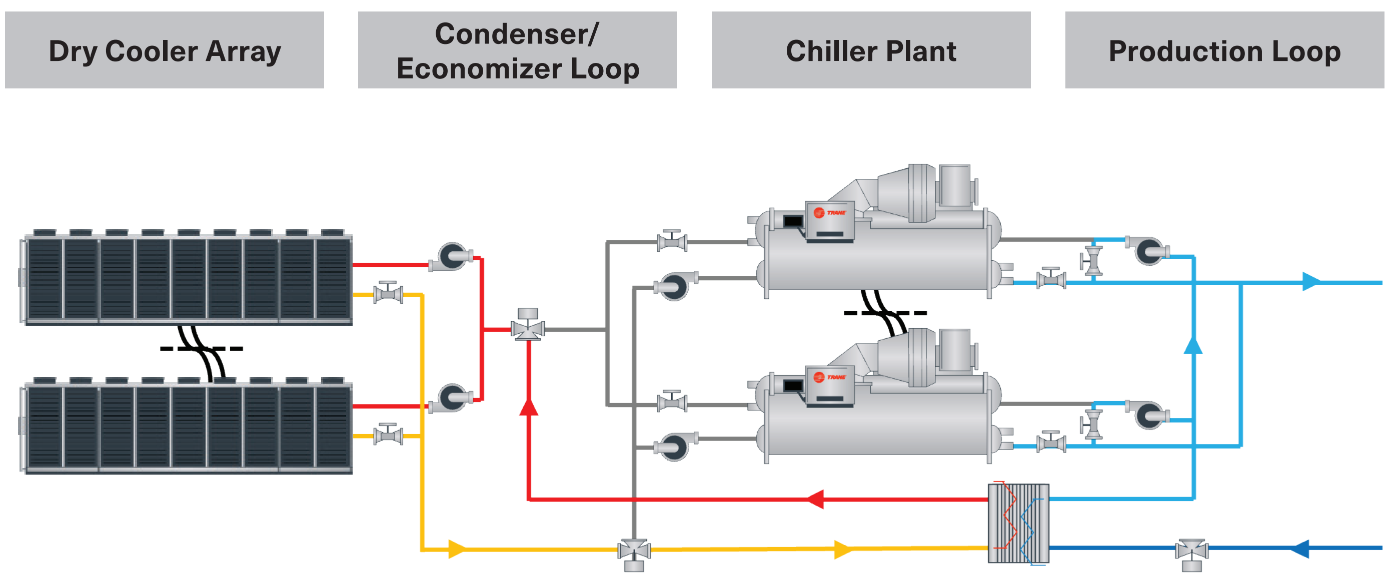


Figure 3: Water-cooled chillers with dry coolers and a waterside economizer heat exchanger.

Waterside Economizer Operation

To clarify the free cooling potential at various outdoor conditions, system operation can be evaluated across three outdoor temperature ranges relative to the return water temperature setpoint. An air-cooled chiller with integrated waterside economizer coils is shown below, but example operation applies similarly to a water-cooled chiller plant using dry coolers for waterside economizing, shown above.

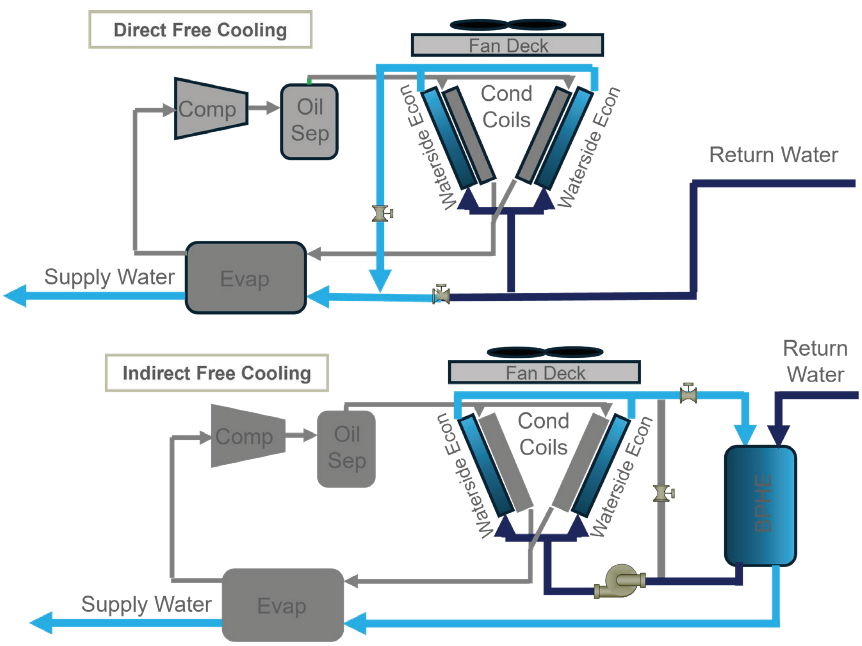


Figure 4: Air-cooled chiller with integrated waterside economizer, highlighting operation at low ambient temperature and full free cooling.

Full Free Cooling

(Low Ambient)

When the outdoor air temperature is sufficiently lower than the return fluid temperature, the waterside economizer provides enough cooling to satisfy the full cooling load. No mechanical cooling is used. The condenser (or dry cooler) fans modulate to maintain cooling capacity and consume a relatively small amount of energy.

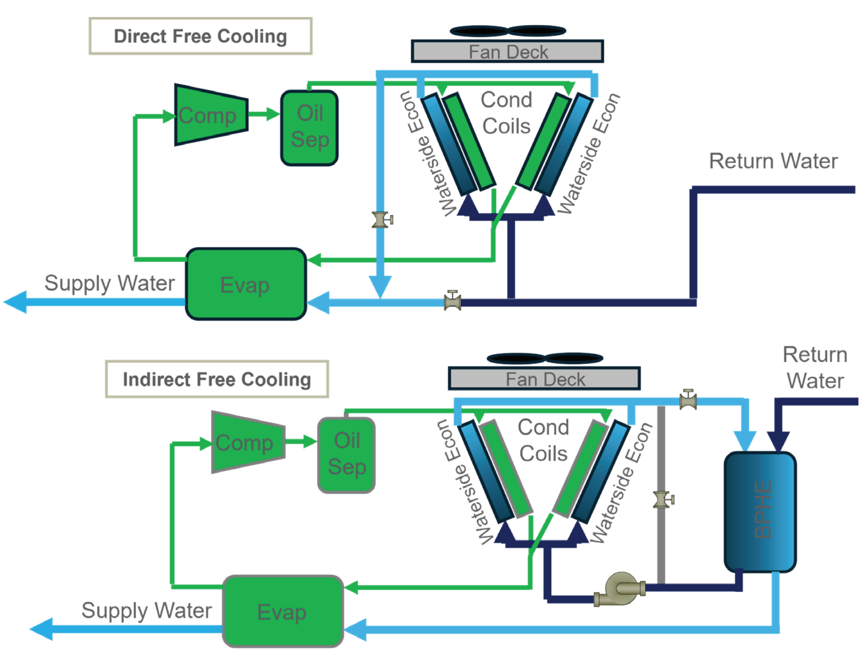


Figure 5: Air-cooled chiller with integrated waterside economizer. This highlights operation at moderate ambient temperature and hybrid free cooling utilizing waterside economizing and mechanical cooling simultaneously.

Hybrid Cooling

(Moderate Ambient)

When the outdoor air temperature is lower than the return fluid temperature, but not low enough to provide the full cooling need, the waterside economizer is still able to provide some cooling. Mechanical cooling is used to supplement and satisfy the remaining cooling at reduced load.

Hybrid operation minimizes the mechanical cooling required and maximizes energy savings and flexibility.

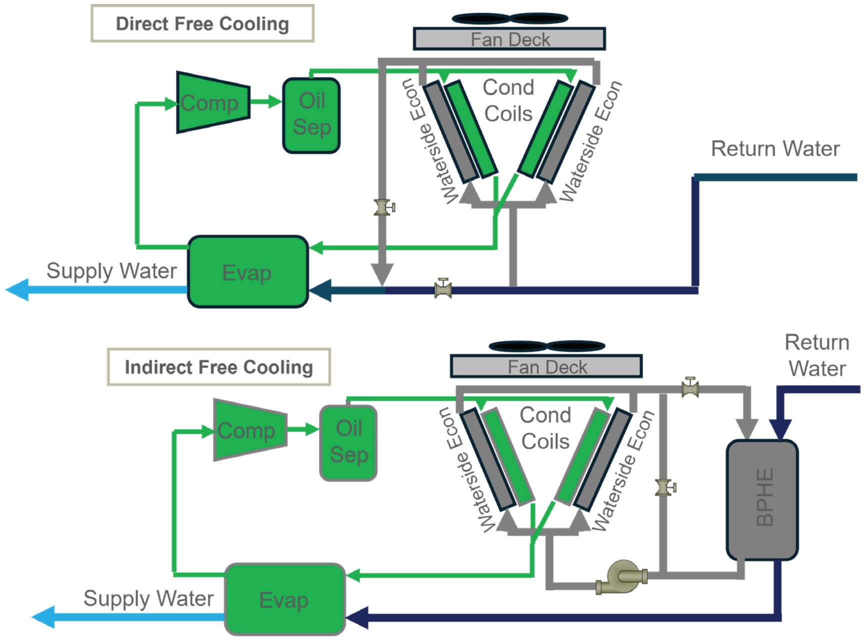


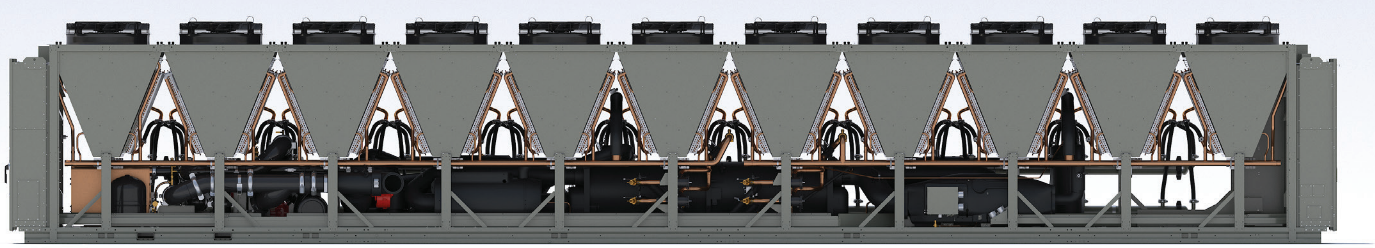
Figure 6: Air-cooled chiller with integrated waterside economizer. This highlights operation at high ambient temperature and full mechanical cooling. Waterside economizer is bypassed to minimize pump power.

Mechanical Only Cooling

(High Ambient)

When the outdoor air temperature exceeds the return fluid temperature, the waterside economizer cannot provide cooling, and mechanical cooling must serve the full load. With no free cooling available, this is the highest cooling energy state.

The waterside economizer loop is completely bypassed not only to minimize pump power but to avoid transferring heat from the hot outside air into the fluid. If not bypassed, the waterside economizer loop would add to the cooling load and increase the mechanical cooling required.



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Benefits of Economizer Free Cooling

Energy and Cost Savings

By reducing mechanical cooling, free cooling can substantially reduce annual cooling energy in many climates. Warmer FWS temperatures can further increase the savings. The term "free cooling" can be a bit misleading, because free cooling is not actually free. The system still needs pump and condenser, dry cooler, or cooling tower fan energy during free cooling. Design decisions — particularly equipment sizing — can impact not only the availability of free cooling but also the fan energy needed when operating in free cooling mode.

Optimized system control and design decisions drive not only how much free cooling is possible in cold weather, but also how much free cooling is practical in warmer hybrid cooling conditions where many operating hours are spent. For example, in moderate temperatures, forcing all free cooling operation can result in higher overall condenser fan energy consumption than running mechanical cooling at partial load.

Reliability and Longevity

Reduced runtime of mechanical cooling components decreases wear on compressors, pumps, and fans, resulting in fewer failures, lower maintenance costs, and improved overall system reliability. Supported by Trane's commissioning expertise, data center qualified technicians, and proactive remote monitoring, systems stay optimized from day one, helping ensure stable performance. By minimizing mechanical stress, equipment lifecycles are extended, and the likelihood of unplanned outages is reduced — an essential benefit in mission-critical data center environments.

- ✓ **By lowering the operating hours of compressors and other mechanical components,** systems experience less mechanical fatigue and fewer service interventions. Combined with rapid support from Trane's skilled technicians, this not only cuts maintenance costs but also enhances uptime and prolongs the useful life of cooling equipment, contributing to long term operational stability for data centers.
- ✓ **Reducing mechanical cooling runtime decreases component degradation,** which improves mean time between failures (MTBF) and reduces the frequency of both scheduled and unscheduled maintenance. When paired with Trane's connected services and predictive maintenance capabilities, data centers gain higher reliability, longer equipment lifespans, and a more predictable operating environment.

Sustainability

Free cooling can reduce energy consumption, improve PUE, and lower carbon emissions, helping data centers meet increasingly stringent regulatory requirements, sustainability goals, and performance standards such as ASHRAE 90.4. Beyond the environmental benefits, greater cooling efficiency can also free up more available power for IT and compute capacity, making energy savings a meaningful operational advantage for data center owners and operators. By reducing overall energy use, these strategies support both business performance and ESG objectives.

Limiting water usage is also an important sustainability priority for data center operations in many locations. With careful management, allowing limited water use through adiabatic precooling during peak conditions can reduce peak energy demand while keeping overall water consumption low. This balanced approach helps operators improve efficiency and manage infrastructure demands while advancing water stewardship and reducing overall environmental impact.

Location-Based Dependency

Regardless of thermal management system design, outdoor air temperature remains a major factor in free cooling potential. Simply said: the cooler the climate, for a given FWS temperature, the greater the ideal free cooling potential.

Unfortunately, relocating to a more favorable free cooling climate zone is not always a practical or desirable solution for data center owners/operators. Peak outdoor temperature is a key driver in every plant and equipment sizing activity. Examining typical temperatures across the year helps to inform sizing and control parameters to maximize free cooling, as well as peak cooling performance.

The plots below show the distribution of outdoor temperatures across the typical meteorological year weather for the four locations examined earlier. All four locations offer substantial free cooling potential but realizing that potential requires careful integration and balancing of economizer and mechanical cooling equipment in the system design.

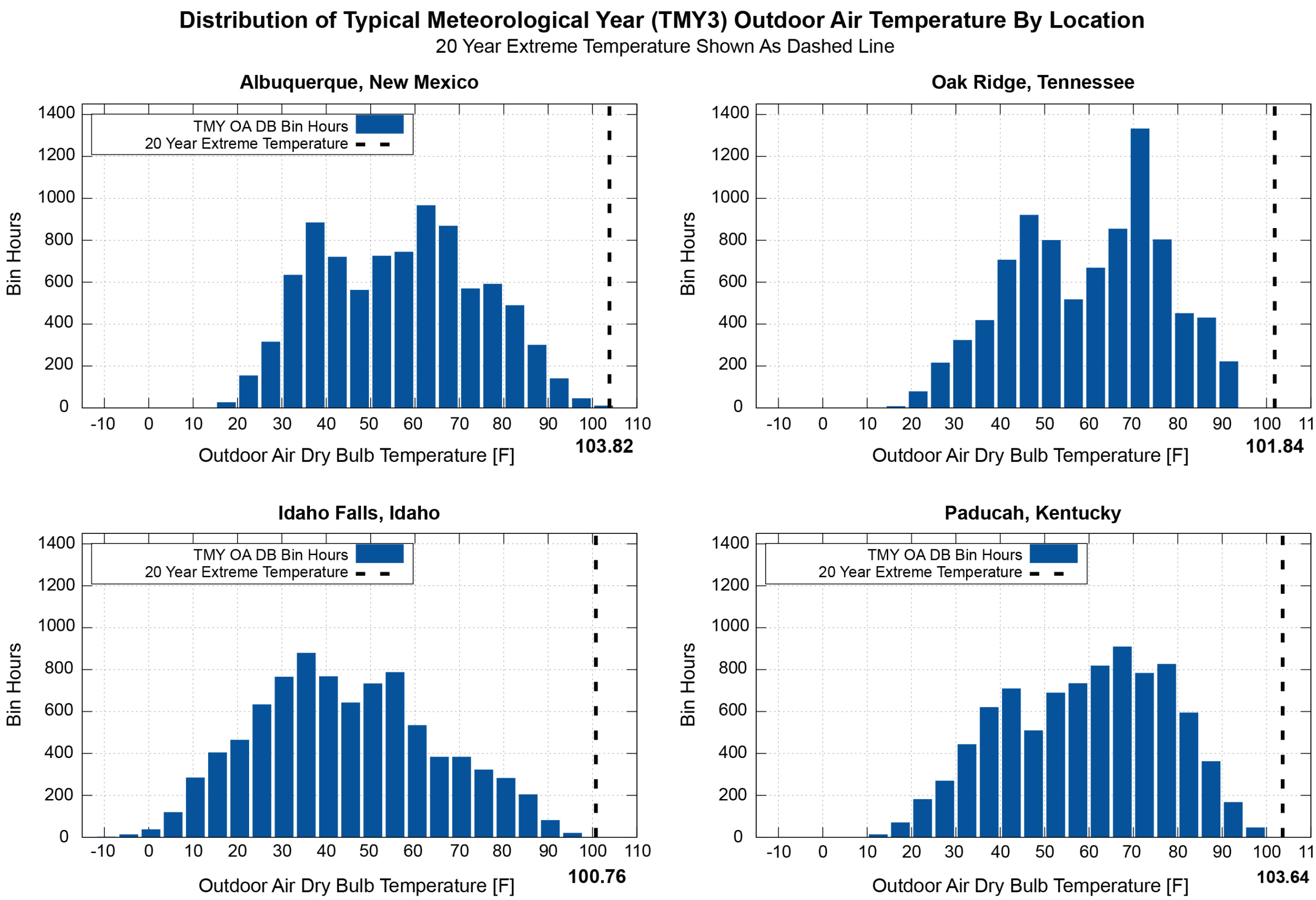

Figure 7: Distribution of TMY outside air dry bulb temperature at four locations over one year.

Conclusion

Modern data centers house thousands of servers and networking devices in tightly controlled environments that operate 24/7 year-round. As server densities and heat loads rise, so does the importance of efficient thermal management systems. Cooling can account for up to 40% of a data center's total energy consumption.

Free cooling is an essential tool for modern data center operational cost management. Leveraging ambient conditions and advanced heat exchange technologies to lower energy costs, extend component lifetime, and support sustainability goals are attractive and manageable strategies for data centers. Well-designed systems dynamically transition between free, hybrid, and mechanical cooling modes, ensuring continuous, reliable operation at the lowest possible energy cost. As data centers continue to scale in capacity and importance, the demand for reliable, efficient, and sustainable cooling solutions will intensify. Free cooling — when properly engineered — provides a proven path to improving energy efficiency, enhancing system longevity, reducing environmental impact, and meeting increasingly stringent industry standards.

However, the effectiveness of any economizer strategy is highly dependent on climate, system integration, and control sophistication. By leveraging the right economizer strategies and aligning them with climate conditions and design priorities, data center operators can substantially improve resilience and sustainability while maintaining the high reliability expected of mission-critical facilities.

About the Author

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Bob Coleman joined Trane in 2000 after receiving a Bachelor of Science degree in Electrical Engineering from the University of Kentucky and rejoined Trane in 2021 after a two-year hiatus exploring the world of building automation and energy services.

His experience includes advanced system modeling and design, product engineering, and technical support across a wide range of HVAC applications. Bob has significant experience in analysis and modeling of data center thermal management systems, including airside and mechanical cooling systems, to support reliability, efficiency, and capacity in mission critical environments.

He is currently involved in ASHRAE as a member of Technical Committee 2.9 Ultraviolet Air and Surface Treatment, and past chair of Technical Committee 1.11 Electric Motors and Motor Control and Standard 222 Standard Method of Test for Electrical Power Drive Systems.

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