A Balanced System Approach to the Water–Energy Nexus

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Water conservation has become an increasingly important aspect of commercial building design strategies, with several factors driving this movement. As water resources become threatened in a significant portion of the United States, many states are implementing regulations and incentives aimed at reducing water usage. In addition, a growing number of organizations are making sustainability—including water conservation—a priority in building design and business operations.

With the increased focus on the relationship between water and energy resources, there is a demand for technologies that support water-efficient energy systems. However, current HVAC design trends often favor the consumption of water in order to achieve energy savings. For example, site water consumption associated with water-cooled HVAC equipment is often overlooked when considering system options. Many times there are other system choices available that can optimize multiple environmental and cost objectives.

Previous *ASHRAE Journal* articles have demonstrated that efficient water-cooled HVAC systems consume less total electricity than comparable air-cooled systems, and that power plants use a large volume of water to generate power.[1] What is less understood is the total site and source impact of HVAC operation on the water supply that society depends on. As recognized as recently as September 2017 in *ASHRAE Journal*,[1] humans are moving into the era where energy and water are expensive, in limited supply, and are deserving of conservation strategies.

This article explores chilled-water systems that seek to optimize water conservation and electrical costs, while recognizing a key distinction between water use and water consumption.

Driving Factors in Water Conservation

While efforts to reduce on-site energy consumption in building systems have pushed more commercial buildings toward evaporative water-cooled chiller systems, this technology increases the building consumption of potable water supplies.

Water consumption is a growing local municipal issue as cities must maintain consistent supply to buildings, and there is an increasing effort to find energy efficient solutions while also supporting water conservation. This is a growing challenge as fresh water supplies dwindle, and groundwater levels are slow to replenish.

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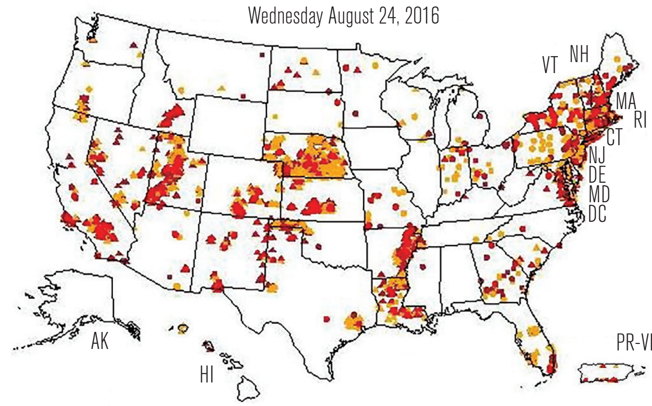
California, in particular, has placed significant emphasis on water conservation, but threatened freshwater supply is a reality in many other states where groundwater levels are declining, as the U.S. Geological Survey (USGS) map of stressed water wells shows (*Figure 1*).

FIGURE 1 U.S. Geological Survey of wells in the active management program, which were below normal for groundwater levels in August 2016. Credit: USGS.



Explanation – Percentile Classes (Symbol Color Based on Most Recent Measurement)								
Low	<10 Much Below Normal	10 – 24 Below Normal	25 – 75 Normal	76 – 90 Above Normal	>90 Much Above Normal	High	Not Ranked	○ Real Time □ Continuous △ Periodic Measurements

Below Normal Groundwater Levels Well Count: 4,391

When considering water conservation, it is important to distinguish between water *withdrawal* and water *consumption*. According to the USGS, water withdrawal refers to applications that use water, and return it back to its source, without reducing the water supply downstream. Often in these cases, the returned water is degraded in some way, such as at a warmer temperature, but is still available for continued societal benefit. Water consumption refers to water that is used and completely removed from the system, such as through evaporation or consumption by plants or humans. Water *usage* is the combination of withdrawal and consumption. Many have based energy–water analysis on the total water usage per unit of electricity generated that can arrive at a different conclusion.

This article focuses on air conditioning system choices that help reduce total water consumption as this draws from potable water supplies that conservation efforts are meant to protect. Changes in water withdrawal, by contrast, do not change the overall volume of river water flow, lake levels, ground water, or general accessibility of water by humans.

Water–Energy Nexus: A Chilled Water System Perspective

As discussions around water and energy conservation become more prevalent, the concept of the water-energy nexus is receiving more attention. The concept refers to the idea that the flow of energy and water are intrinsically connected; the generation of electricity requires water for cooling, and the movement and treatment of water requires energy. As such, the total environmental impact must be considered when consuming both energy and water.

Thermoelectric power plants—which generally include those using coal, natural gas, and nuclear as generation sources—often rely on freshwater from a nearby river or lake to reject heat. Some of this water is evaporated, and thus consumed, while the majority is withdrawn and returned to the source. At the building site water-cooled HVAC systems consume water for heat energy rejection, most of which is via evaporation.

When promoting energy efficiency in buildings that implement chilled water systems, water-cooled chillers are generally preferred over air-cooled. For example, California Title 24 restricts the use of air-cooled chiller for projects 300 tons or larger, unless incorporated with thermal energy storage. At the same time, evolving electrical utility rate structures have become more complex, and many customers are charged substantially higher rates for on-peak usage than for off-peak usage, depending on the time of day. As concerns grow about water availability, there is a greater push toward using different technologies that can be optimized for both water and energy consumption and accompanying utility rates.

Assessing Water Consumption From Chilled Water System Operation

Calculating the site water consumption of a water-cooled chiller system is relatively straightforward. Evaporative conversion rates, and software tools, can provide an accurate assessment. Determining the water consumption at the electricity generation source is less clear. The most recent analysis of water use for electricity generation comes from the Union of Concerned Scientists report *2008 Freshwater Use by Power Plants*, which estimates that, in 2008, 50 trillion gallons of water was withdrawn by power plants, and 1.6 trillion gallons was consumed.

According to the U.S. Energy Information Administration, in 2008 thermoelectric type power plants in the United States generated 3,733,000 MWh of electricity.[2] This, combined with the water consumption rate provided by the Union of Concerned Scientists report, provides the basis to calculate a key conversion factor to relate average thermoelectric type power generation to changes in freshwater supply:

$$1.6E+12 \text{ gallons water consumed} \div 3.733E+6 \text{ MWh electricity generated} = 429 \text{ gal/MWh}$$

In the Union of Concerned Scientists report, water usage is reported in a range of values. The average value is used for this article, which at the time of writing is the best figure available; the reporting range from the report does not change this article's conclusions. Also, while the water consumption factor of thermoelectric power generation will not change significantly over the next decade, the proportion of U.S. electricity generated from thermoelectric power plants will change by region and as renewable energy sources continue to grow. The 429 gallons/MWh conversion factor can be used in estimating the water consumed for just that portion of power usage of a local utility service sourced from thermoelectric plants. Surface water evaporation rates in lakes/reservoirs are ignored for this discussion because no matter what system is chosen for a building, it is not likely that this evaporation rate will change since there will be no change in the surface area of lakes or reservoirs.

Comparing Air-Cooled and Water-Cooled Chillers

Since a detailed evaluation of total water consumption from chillers is new, we will walk through a step-by-step analysis to compare evaporation rates at the site (consumption by the cooling tower) and source (consumption at the power plant). In the *Table 1* analysis we compare the compressor and heat-of-rejection energy of actual vendor selections of a high-efficiency VFD water-cooled centrifugal chiller system, rated at 0.65 kW/ton [0.53chiller+0.05cond pump+0.07tower], and an efficient air-cooled VFD chiller, rated at 1.10 kW/ton at AHRI standard conditions

TABLE 1 Water-Cooled vs. Air-Cooled snapshot comparison.

	WATER-COOLED	AIR-COOLED
Onsite Cooling Load (tons)	1.0	1.0
Chiller Efficiency (kW/ton)	0.53	1.00
Chiller Condenser Heat Rejection (kW/tons)	0.12	0.10
Subtotal of Compressor and Rejection Energy (kW/ton)	0.65	1.10
Site Water Evaporation (gal/Cooling ton-Hour)	1.69	0.00
Site Electricity Consumption (kWh/ton)	0.65	1.10
Utility T&D Losses	9%	9%
Electricity Generation Required (kWh/ton)	0.7085	1.20
Proportion of Thermoelectric Generation*	83.4%	83.4%
Thermoelectric Generation Required (kWh/ton)	0.591	1.00
Thermoelectric Water Consumption Rate (gal/MWh)	429	429
Power Plant Water Evaporation (gal/Cooling ton-Hour)	0.253	0.429
Combined Consumption (gal/Cooling ton-Hour)	1.95	0.43

*From U.S. Energy Information Administration, Electricity Annual 2016, 2015 net generation by source: 86.4% thermoelectric, 6.1% solar & hydroelectric, 7.5% other renewable and pumped hydro. To account for increase in renewable electricity generation, 83.4% thermoelectric generation is assumed in 2020.

To determine cooling tower water consumption, in gallons/cooling ton-hours, we rely on a water usage calculator tool to develop typical water usage rates. Note that blow-down (0.0092 gpm/ton) discharged as waste water is ignored,† as it is a form of water withdraw and not consumption:

(0.0281 gpm/ton [evaporation] + 0.0001 gpm/ton [drift]‡ = water consumption [gpm/cooling ton])‡

This figure is multiplied by 60 to convert cooling tower water consumption to gallons/cooling ton-hours, and is equal to the site water consumption of the cooling tower.

To calculate source water consumption, we use electricity transmission and distribution losses and the proportion of daytime electricity served by thermoelectric generation to determine the total generation output needed in MWh. This figure is multiplied by the 429 gallons/MWh factor discussed earlier to determine water evaporation.

The snapshot comparison between the two chiller systems operating on a hot afternoon (95°F [35°C] outdoor

†While blow down is ignored in the *Table 1* analysis, if blow down is from potable supply and discharged to the ocean, a case could be made to include it as part of the chiller site water consumption, and would make the site consumption that much greater.
‡Inputs of a 100 ton system, 250 gpm, 11.1 ΔT, 80 cold temp, 73 wb, 0.005% drift, four concentrations (values per ton).

ambient temperature) is shown on the previous page for a ton-hour of cooling.

When considering the water or energy consumption associated with power generation to provide cooling, as expected, air-cooled chillers are responsible for nearly double the source water consumption compared to water-cooled chillers. However, while the site water consumption of water-cooled chillers is commonly an afterthought, it is, by far, the driving factor in determining the total water consumption for cooling. When looking at both site and source water consumption, the real opportunity to save water is presented by air-cooled chillers, consuming roughly one quarter of the total water as water-cooled chillers to provide the same amount of cooling.

At this point, the typical evaluation of water-cooled and air-cooled chillers demonstrates that an air-cooled chilled water plant uses more power and less water than a water-cooled chilled water plant. Most of the time, the total installed cost of an air-cooled system is significantly less than a high-efficiency water cooled-system, and thus the stage is set for a classic life cycle cost analysis. But are there other options to further optimize chilled water plants for multiple objectives?

Additional Considerations Due to Complex Electricity Rates

Most commercial buildings in the United States are serviced by continually evolving, complex time-of-use (TOU) electricity rates. TOU electricity rates are any combination of rate and demand cost structures that require users to pay more for per kWh during high "peak" hours, and have the effect of more expensive electrical rates during the day (peak) than at "low peak" periods such as at night. A recent NREL analysis[3] shows that in most of the heavily populated areas in the United States, commercial and industrial customers have maximum monthly peak demand charges of at least$10/kW, and they can be as high as $51/kW. Additionally, many of these utilities use time-of-use rates that lowerthe cost of nighttime "off peak" electricity consumption by as much as half of daytime rates. As a result, the total cost differential between consuming incremental units of electricity in the mid-afternoon versus night can be a factor of two to four times.

The imbalance of demand on the electric grid, and accompanying rate volatility, creates more value for energy storage technologies. While often overlooked, thermal energy storage (TES) is a readily available and reliable technology that can be directly integrated into chilled water system designs. TES-integrated chilled water systems rely on the chiller to generate cooling (ton-hours) at night – when electricity demand and rates are low – which is stored in the form of ice and melted to produce cooling energy during peak demand periods the next day.

The snapshot analysis (*Table 2*) assesses the water and energy consumption associated with an air-cooled chiller with integrated ice storage type of TES [AC_TES] that is capable of shifting the cooling electricity requirement away from midday to nighttime use. It follows the same logic as the previous assessment, but adjusts transmission and distribution losses and power generation mix for nighttime.

Both air-cooled systems still consume over 75% less water than water-cooled chillers, and depending on building needs, climate, and utility rate structures, an AC_TES system can offer an attractive three to seven year payback compared to a water-cooled system. A correctly designed and modeled AC_TES system located in a typical metropolitan utility service area with many cooling-degree days will often have the lowest life-cycle cost when compared to water-cooled and air-cooled chillers, while seeing only a small increase in source water consumption when compared to the air-cooled system.

TABLE 2 Snapshot comparison of *Table 1* Plus AC_TES.

	WATER-COOLED	AIR-COOLED	AIR-COOLED W/TES
Onsite Cooling Load (tons)	1.0	1.0	1.0
Chiller Efficiency (kW/ton)	0.53	1.00	1.00
Chiller Condenser Heat Rejection (kW/ton)	0.12	0.10	0.10
Additional Energy for TES	–	–	0.02
Subtotal of Compressor and Rejection Energy (kW/ton)	0.65	1.10	1.12
Cooling Tower Water Evaporation (gal/Cooling ton-hour)	1.69	0.00	0.00
Site Electricity Consumption (kWh/ton)	0.65	1.10	1.12
Utility T&D Losses*	9%	9%	6%
Electricity Generation Required (kWh/ton)	0.7085	1.20	1.1872
Proportion of Thermoelectric Generation	83.4%	83.4%	90.4%
Thermoelectric Generation Required (kWh/ton)	0.591	1.00	1.112
Thermoelectric Water Consumption Rate (gal/MWh)	429	429	429
Power Plant Water Evaporation (gal/Cooling ton-hour)	0.253	0.429	0.46
Combined Consumption (gal/Cooling ton-hour)	1.95	0.43	0.46

*TES site electricity consumption occurs at night in order to meet the next afternoon's cooling demand, hence variance in transmission and distribution losses, which are lower at night.

Case Study: Modeling a Typical Office Building in Silicon Valley, Calif.

The results of a design analysis study of a typical multistory office building in the Silicon Valley area of California, comparing a high-efficiency water-cooled VFD chiller system, an all air-cooled chiller system, and an air-cooled system with a partial thermal energy storage (AC_TES), is shown in *Figure 2*. The inputs used the chiller and plant efficiencies used in the *Table 2* evaluation and local water and utility rates ($5.50/CCF). The study provides a comparison of energy consumption, operating costs, and total water consumption using the conversion factor derived in this article.

The graphical results from this performance model demonstrates that an AC_TES system is a well-balanced approach of all three performance measures for chilled water systems discussed in this article: site energy consumption, operating cost, and site+source water consumption.

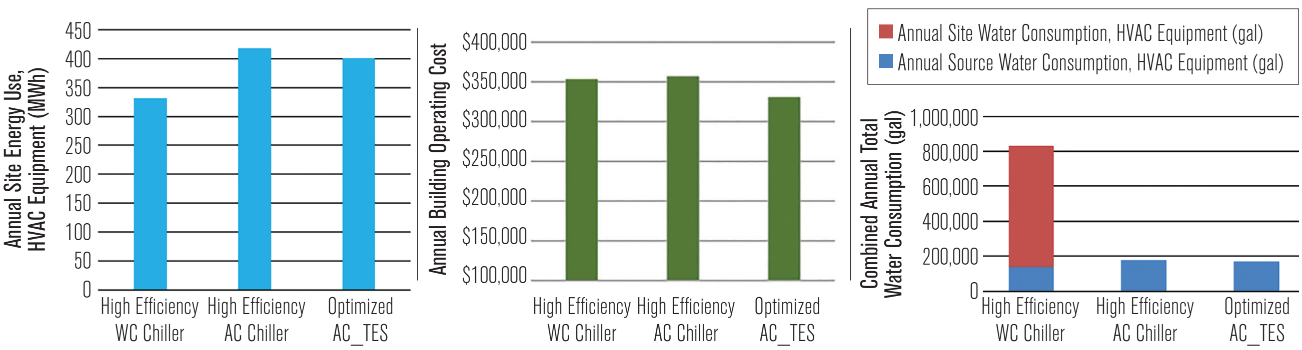
It is worth noting that TES modeling in typical software is more complicated than modeling a typical chiller plant. One key to verify accuracy in TES modeling is to validate the monthly savings of both demand charges and electrical usage consumption charges for each month that there is a cooling load. In electric utility territories that use peak demand as part of its TOU rate, demand costs in properly modeled TES systems should be significantly lower.

Observations and Future Considerations

The most direct takeaway from this analysis suggests that water-cooled chillers are the preferred chilled water system type when energy conservation is the primary objective, and air-cooled chillers are preferred choice when water conservation is preferred. However, the actual results of the air-cooled chiller with integrated thermal energy storage analysis suggests that all reasonable chilled water system design alternatives, including those that use TES, should be considered to ensure that the optimum system selection is made. Tools are readily available today that can assess the energy consumption, water consumption, peak demand cost, and volumetric energy cost, associated with a chilled water system in a given location. It is imperative that we model and analyze available system choices to appropriately balance the multiple environmental and cost-reduction benefits that chilled water system technologies can provide. Additionally, the water consumption on site and at the power generating source associated with HVAC technologies should be totaled and reported.

We recognize that the optimal solution for many of these objectives is dependent on the utility rate structures, climate, and power generation mix for a building. Utility incentives, such as those available for load shifting, also significantly impact the cost-effectiveness of available chilled water system designs. Finally, as the power generation mix shifts over time away from thermoelectric and toward renewables, the environmental and cost impacts also change. The source water

FIGURE 2 Analysis comparing chilled water system performance.



consumption factor developed in this study together with the basic table methodology allows for a project analysis to change when appropriate, and is meant to encourage system modeling with the appropriate inputs for each of these factors.

Additionally, this analysis does not consider the impact of returning water withdrawn by a power plant back to its source. As stated previously, this water is still available for continued social benefit, but often returned to the water body at a warmer temperature. A separate ecological impact study may be necessary to fully assess the impact this process has on the environment.

Further, a separate and equally important analysis of the source greenhouse gas (GHG) emissions impacts of each of these systems is reserved for a separate study. At first blush, one might point to the modest increase in energy used by an AC_TES system as a contributor to additional GHG emissions.

However, a proper evaluation that takes into account the improved thermocycle electricity generation efficiency at night, lower distribution losses, and increased grid efficiency in using renewables by having a cold energy battery will make a significant difference versus a simple conversion. For example, in the ISO New England territory in 2016, marginal CO_2 emissions were roughly 9.5% lower for off-peak (weekdays, 12 a.m. to 6 a.m.) than peak (weekdays, 12 p.m. to 6 p.m.) generation periods.[4] Additionally, models that include California time dependent value multipliers help to account for this and AC_TES produce lower annual source energy rates.

This article is not meant to imply that water-cooled systems should not be utilized at all; water-cooled chillers offer improved energy efficiency and large cooling capacity in a manageable footprint over air-cooled chillers, and can also use TES, which will capture much of the cost-related benefit demonstrated by AC_TES. Rather, the intended outcomes of this article are threefold: 1) To expand our understanding of how HVAC affects potable water supplies including a conversion factor to make useful calculations; 2) for owners and engineers to add optimally modeled AC_TES systems as a design concept option with consideration for both energy and total water consumption in its analysis; and 3) for future building regulatory policies to consider the conservation of both water and energy, and encourage solutions which can optimize these two objectives together.

Applications in commercial HVAC place tremendous emphasis on energy efficiency, and rightfully so. However, we must not lose sight of other objectives such as water conservation, both environmental and cost-related, which can be achieved through careful system analysis and optimization. Further, as the ways in which building owners pay for utilities becomes more complex, as do global environmental challenges, optimized chilled water system designs and energy storage become even more valuable. If we adopt a balanced approach to system design, and building policy reinforces it, we will do more to ensure sustainable buildings for today and tomorrow.

References

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