This article was published in ASHRAE Journal, November 2022. Copyright 2022 ASHRAE. Posted at www.ashrae.org. This article may not be copied and/or distributed electronically or in paper form without permission of ASHRAE. For more information about ASHRAE Journal, visit www.ashrae.org.

A Review of Evaporative Cooling's Efficiency and Environmental Value

BY KEN MORTENSEN

Global populations depend on cooling and refrigeration to support many manufacturing and energy production processes. Evaporative cooling has been a transformative technology, enabling innovative mass production, and is substantially more energy efficient than alternatives. What may not be obvious is that evaporative cooling may also be the most water efficient option in some applications. Air conditioning is the third-largest category of commercial building energy use, after refrigeration and ventilation.[1] Of the available methods, evaporative cooling requires the lowest energy input per unit cooling output, effectively minimizing fossil fuel use, carbon dioxide (CO_2) production and related environmental impacts. This article examines the environmental, energy and water resource realities of providing modern cooling needs and discusses resource utilization.

The Evaporative Cooling Process: Energy and Environment

Many essential processes have been realized through the use of evaporative cooling. Process improvements are enabled by evaporative cooling technology. The impact is driven by the physics of phase change. Evaporation of a small portion of the total heat-contact water results in sub-ambient cooling of the remaining water stream. Evaporation, i.e., liquid-to-gas phase change, allows the process heat sink to drive toward the immediate environment's wet-bulb temperature, rather than the ambient temperature, resulting in lower bulk water temperature and greater process efficiency.

By definition, "(t)he wet-bulb temperature is the adiabatic saturation temperature."[2] It is the lowest temperature an object, water stream or the air can reach via the evaporation process with "the air at a constant pressure."[3] This means one can cool a surface—or in the case of cooling towers, the bulk recirculating water stream—to below the ambient temperature and approach the wet-bulb temperature.

The word approach here is a term of art. In theory, the water stream could reach the wet-bulb temperature, given unlimited resources, such as an infinitely large cooling tower. In reality, however, the water

Ken Mortensen is senior manager, research and development, at SPX Cooling Technologies, Inc.

temperature only "approaches" the wet-bulb temperature. How closely it approaches depends on tower size. Evaporative cooling provides a substantially lower heat sink via the cooled water stream and a better heat transfer medium to remove heat from surfaces, such as the heat exchangers, than air-cooled alternatives.

Use of this advantageous property is evident in many industries including mass food production, grain milling, metals extraction, oil refining, plastic synthesis and chemical processing. Additionally, refrigeration for food preservation has allowed life-sustaining expansion in food production and most particularly food storage.

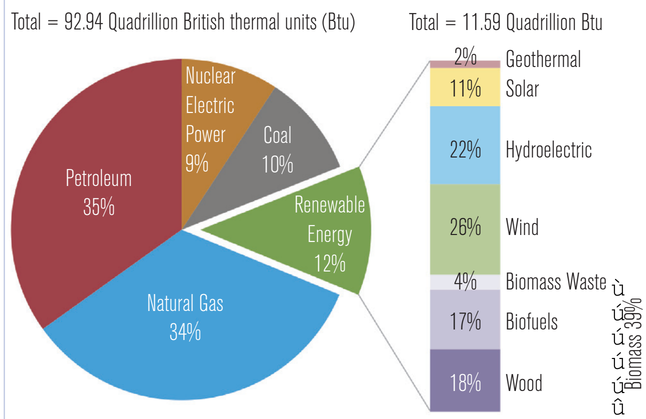
Power generation has also been enhanced by water's unique cooling capability. The efficiency improvements are dramatic and have allowed for the creation of mass electrification. The survival of populations enduring increasing temperatures and climate change may depend on such advantages.

More recent developments in data and information management are also facilitated by evaporative cooling. Case studies detailed in this article show evaporative cooling provides the most energy- and water-efficient delivery of value in comfort cooling, power generation and information server management.

Energy. Cooling in commercial buildings is the largest category of consumer energy use, constituting more than 30% of the U.S. electrical total. Commercial cooling, at 14.8%, and refrigeration, at 15.7%, make up this combined category of energy consumption in businesses.[1] Cooling of commercial buildings during peak load periods is likely an even higher percentage of electrical demand than cited above. This further stresses already overburdened power grids. Energy efficiency achieved in cooling processes via evaporative mechanisms, detailed in the "Specifics of Resource Utilization in Cooling" section of this article, will most likely translate directly into fossil fuel use reduction because coal, oil and natural gas energy production still constitutes 79% of the U.S. total.[4]

From an environmental point of view, marginal energy demand reductions would be expected to subtract from the least environmentally friendly generation method, typically derived from fossil fuel. For the few locations that largely use renewable sources, energy demand reduction would allow a smaller overall energy production infrastructure, providing flexibility in capacity utilization and investment choice. Evaporative cooling

FIGURE 1 Types and amounts of primary energy sources consumed in the U.S., 2020.



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2021, preliminary data.

Note: Sum of components may not equal 100% because of independent rounding.

is an excellent resource choice, providing energy conservation.

To show how power is actually generated today, sources of primary energy in the U.S. as of 2020 are still primarily fossil fuel, with petroleum comprising 35% of sources, natural gas 34% and coal 10% (*Figure 1*). Nuclear and renewables—"non-greenhouse gas" sources—make up about 21%, which includes the 9% nuclear portion of the total.[4]

CO_2 emissions. Significant CO_2 emissions result from the 79% of U.S. energy production that is provided by fossil fuel (*Figure 1*). Energy reductions provided by evaporative cooling have a substantial positive environmental impact. Fossil fuels, of various types, produce CO_2 at levels shown in *Table 1*.[5] These amounts of CO_2 can be reduced by energy-efficient cooling and refrigeration process choices.

Water. Total water consumption can also be lowered by using evaporative cooling. This is not intuitive. Alternatives often use little to no water at the cooling process delivery site, giving the illusion of a substantial water use advantage. The hidden reality is that air-cooled or alternative systems consume more energy on-site and use substantially more water at the power generation site to produce the required energy premium. The result is that the combined water use for evaporative cooling on-site and at the point of power generation is often lower than that of the cooling alternatives. This concept is explored in depth in the studies detailed in the next section.

Specifics of Resource Utilization in Cooling

This section details studies comparing the resource efficiency of air and evaporative (wet) cooling processes. This is a resource comparison, not a cost-based evaluation. Other cooling processes are available, but are not the subject of this article or the case studies cited here. The method of heat rejection and the predominant energy production system supplying the electrical power vary widely from state to state and region to region. The following case studies are presented to illustrate total grid resource evaluation methods for energy and water, with some surprising results.

TABLE 1 Pounds CO_2 emitted per million British thermal units (Btu) for various fuels.

FOSSIL FUELS	lb CO_2/MMBtu
Coal (Anthracite)	228.6
Coal (Bituminous)	205.7
Coal (Lignite)	215.4
Coal (Subbituminous)	214.3
Diesel Fuel and Heating Oil	161.3
Gasoline (Without Ethanol)	157.2
Propane	139.0
Natural Gas	117.0

TABLE 2 Energy, emissions and water use for air-cooled vs. water-cooled (evaporative) systems.

	AIR COOLED	WATER COOLED (EVAPORATIVE)	REDUCTION
ANNUAL ENERGY CONSUMPTION, MWH	440	190	56.8%
ANNUAL EMISSION,[a] lb CO_2	682,000	294,500	56.8%
ANNUAL WATER USE, GALLONS (ON-SITE[b] + POWER PLANT[c])	1,944,000	1,530,000	21.3%

[a]Average U.S. energy plant emits 1.55 lb of CO_2 for each kWh generated.
[b]Site water includes water for makeup, assuming six cycles of concentration.
[c]In California and many western states, each kWh produced consumes 4.42 gallons of water. On average in the U.S., each kWh produced consumes 2 gallons of water.[7]

Case Study: Comfort Cooling

For comfort cooling, a highly relevant study was published in 2008 by environmental consultant Jerry Ackerman. The study used data from Pacific Gas & Electric and the National Renewable Energy Laboratory (NREL) to evaluate a typical 400 ton (1407 kW) cooling system for a building in California.[6] It is not surprising that significant energy and CO_2 reductions exist for the evaporative system compared to air cooling. But the study also compared water use, including the water consumption for energy generation. In this case, total water use for evaporative cooling was lower than that for air cooling. Findings included:

- Annual energy consumption for evaporative cooling is 190 MWh vs. 440 MWh for air cooling, a reduction of 56.8%.
- Greenhouse gas emission, measured in lb of CO_2, for evaporative cooling is 294,500 vs. 682,000 for air cooling, a parallel reduction of 56.8%, based on average U.S. plant emissions of 1.55 lb of CO_2/kWh generated.
- Total water use in gallons for evaporative cooling was 1,530,000 vs. 1,944,000 for air cooling, which represents a reduction of 21.3%. Site water use for evaporative cooling included water for makeup, assuming six cycles of concentration. Power plant water use is average for California; each kWh produced consumes 4.4 gallons of water. The study notes that water consumption per kWh varies by state and region.

Evaporative cooling systems also provide additional benefits, including lower operating noise, fewer fans, smaller site area and use of sustainable recycled plastic materials.

Data from the study by Ackerman are summarized in *Table 2*.

Case Study: Data Center Cooling

In the information infrastructure space, dramatic increases in data generation, storage and digital processes have spawned massive data centers with substantial attendant heat generation. Effective and efficient cooling of data centers to meet these information demands represents important resource and environmental choices. Evaporative cooling has often proven to be the optimum choice, reducing energy, CO_2 emissions and even water use for these facilities when examined on a total system resource basis. Evaluation of data center water use for cooling systems must use this type of holistic analysis, including water used both on-site and by electricity generation.

A 2017 study by Tim Chiddix and Brook Zion works through a resource comparison of air-cooled and water-cooled building systems.[8] The study's authors calculated the energy requirements of these systems and went on to calculate the amount of water used both on-site and at the point of electricity generation for air vs. evaporative (wet) cooling by location for Denver, Phoenix and Los Angeles. Power generation methods and their water use vary across the western U.S. and the country, and those differences by state are factored into the analysis for the three locations studied. Data are specific to the locations cited.

In this study, the water resource requirement for the generated power is expressed in gallons/kWh for the three locations analyzed. Data from NREL, technical report TP-550-33905, defined the regional differences in water use, as shown in *Table 3*.[7]

TABLE 3 Power plant water consumption.

	POWER PLANT WATER CONSUMPTION, gallon/kWh
COLORADO	1.20
ARIZONA	7.85
CALIFORNIA	4.64

Energy. This study looked at the power requirement for a 1,500 kW cooling load using a standard efficiency water-cooled chiller, including chiller pumps and cooling tower, vs. an air-cooled chiller system at full load. The facility cooling systems' energy use for wet vs. dry is calculated as Wet Chiller Energy plus Tower Energy vs. Air-Cooled Chiller Energy for a given climate and is listed in *Table 4*.

Water. Water consumption at the power plant equals energy use of the system multiplied by power plant water consumption per unit energy. For the evaporative system, "on-site" water consumption is then added back to get the total water requirement. Results are shown in *Tables 5* and *6*.

Overall, it is not surprising that energy use for the evaporative system is substantially lower than for the air-cooled system. The energy reduction is 65% to 66% for each of the three cases. It is surprising that the total water use, when power generation is considered, is higher for the air-cooled system than for the evaporative system in all cases. The reduction for evaporative cooling is 23% to 59% in varying climates in the western U.S. Even in the cooler Colorado climate, air-cooled water consumption exceeds evaporative system consumption.

Owners of data centers must weigh multiple cooling options and consider comprehensive operating costs as key factors in design choices. Water-cooled chiller, air-cooled chiller, direct evaporative, adiabatic and other types of cooling systems are all in play.

Regarding such choices, Chiddix stated, "Municipalities requiring data centers to use less energy and water on-site may not have considered the full implications of these requirements." The results of such requirements may actually result in use of higher amounts of both energy and water.

Additional operating methods for evaporative cooling technologies that create energy savings are 1) "free cooling" in sufficiently cool climates (with enough cool/cold hours to overcome the added cost of a plate and frame heat exchanger and any other additional equipment) and 2) "variable flow," which involves reducing water flow or fan speed during cool/cold periods.

When considering energy use and generated CO_2, these studies demonstrate why evaporative cooling is the more sustainable system for meeting U.S. building cooling needs.

The Impact of Cooling System Choices

Driving energy efficiency in building cooling and refrigeration can create a significant reduction in U.S. CO_2 emissions and can also have a positive impact on

TABLE 4 Full-load chiller power.

CHILLER TYPE	DENVER (kW/ton)	PHOENIX (kW/ton)	LOS ANGELES (kW/ton)
Air Cooled	1.250	1.340	1.250
Water Cooled	0.431	0.462	0.426

Source: Chiddix and Zion (Reference 8)

TABLE 5 Cooling system energy use for 1,500 kW data center.

CHILLER TYPE	DENVER ANNUAL ENERGY (kWh)	PHOENIX ANNUAL ENERGY (kWh)	LOS ANGELES ANNUAL ENERGY (kWh)
Water Cooled	1,610,748	1,726,603	1,592,062
Air Cooled	4,663,470	4,999,089	4,663,470
DIFFERENCE	3,052,722	3,272,486	3,071,408
ENERGY REDUCTION FOR WATER COOLED	65.5%	65.5%	65.9%

TABLE 6 Cooling system water use for 1,500 kW data center.

CHILLER TYPE	DENVER ANNUAL WATER (gallon/yr)	PHOENIX ANNUAL WATER (gallon/yr)	LOS ANGELES ANNUAL WATER (gallon/yr)
Water Cooled	3,593,000	14,844,000	7,732,000
Air Cooled	4,645,000	36,182,000	16,640,000
DIFFERENCE	1,052,000	21,338,000	8,908,000
WATER USE REDUCTION FOR WATER COOLED	22.6%	59.0%	53.5%

water use. In many cases, the more energy-efficient evaporative (wet) cooling system also provides water resource gains.

Building energy consumption is a large contributor to CO_2 emissions. Buildings and their construction together account for 36% of global energy use and 39% of energy-related CO_2 emissions annually, according to the United Nations Environment Program.[9] The U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey estimates that there were 5.6 million commercial buildings in the U.S. in 2012, housing 87 billion ft^2 (8 billion m^2) of floor space. The average building size is about 15,500 ft^2 (1440 m^2).[10]

Data demands are also growing at a significant pace. Thousands of new data centers are planned to be built in the next five years, and this construction has only been accelerated by the "work at home" trend initiated during the COVID-19 pandemic.

The impact of cooling system choices on energy, water and CO_2 emissions will be substantial. Evaporative cooling can contribute positively to energy-efficient resource choices and CO_2 reductions. To improve the environment, one must use holistic thinking to review energy consumption and push toward reducing energy produced from coal and natural gas.

Conclusions

Even in 2022 with the growing emphasis on renewable sources of energy, the majority of the power generated in the U.S. remains nearly 80% fossil-fuel based. That means that for the foreseeable future, cooling energy choices will directly impact CO_2 emissions.

If the U.S. uses evaporative heat rejection efficiently, substantial reductions in CO_2 emissions can be achieved. These choices can also reduce demand on our electricity generation infrastructure and hence the capital projects to provide that energy supply.

The benefits of evaporative (wet) cooling over air cooling include improved quality of life and substantial resource reductions. In some cases, evaporative cooling enables processes that cannot run on air-cooled systems.

1. In the studies discussed in this article, evaporative cooling was the most energy-efficient method for cooling buildings and data centers.

- Energy used for building and data center cooling reduced by 57% to 66% at multiple locations in California, Arizona and Colorado.
- CO_2 generation from building and data center cooling reduced by the same amount (57% to 66%) at multiple locations in California, Arizona and Colorado.

2. In the studies reviewed in this article, evaporative cooling is the most water-efficient cooling method when total water use includes the power plant water consumption.

- Water used for cooling was reduced by 21% to 59% at multiple locations in California, Arizona, and Colorado.

3. Commercial buildings use a significant amount of the generated electricity in the U.S. Buildings and their construction together account for 36% of global energy use and 39% of energy-related CO_2 emissions annually. The choice of building cooling systems will substantially impact the environment.

4. Data center cooling needs in the U.S. are expanding rapidly and cooling choices are being made now that will substantially impact the environment.

References

1. EIA. 2016. "Commercial Buildings Energy Consumption Survey, Table E5, Electricity Consumption (kWh) by End Use, 2012." U.S. Energy Information Administration. https://tinyurl.com/ne45a95f

2. The Engineering Toolbox. 2004. "Dry Bulb, Wet Bulb and Dew Point Temperatures." The Engineering Toolbox. https://tinyurl.com/328ckttk

3. ScienceDirect. 2014. "Wet Bulb Temperature." ScienceDirect. https://tinyurl.com/2jvck8mz

4. EIA. 2021. "U.S. Energy Facts Explained." U.S. Energy Information Administration. https://tinyurl.com/44h7kmb5

5. EIA. 2021. "Frequently Asked Questions (FAQs): How Much Carbon Dioxide is Produced When Different Fuels are Burned?" U.S. Energy Information Administration. https://tinyurl.com/5xd3yfvh

6. Ackerman, J. 2008. "What a Water-Cooled HVAC System Can Do for Your Building." Buildings.com. https://tinyurl.com/3rsujzsc

7. Torcellini, P., N. Long, R. Judkoff. 2003. "Consumptive Water Use for U.S. Power Production," National Renewable Energy Laboratory. https://tinyurl.com/mtdwcy5p

8. Chiddix, T., B. Zion. Undated. "Data Center Water Usage for Denver, Phoenix and Los Angeles: A Look at the Big Picture." Swanson Rink. https://tinyurl.com/yc8d9zyf

9. UNEP. 2020. "Building Sector Emissions Hit Record High, But Low-Carbon Pandemic Recovery Can Help Transform Sector—UN Report." United Nations Environment Programme. https://tinyurl.com/y9nxbera

10. EIA. 2016. "2012 Commercial Buildings Energy Consumption Survey: Energy Usage Summary." U.S. Energy Information Administration. https://tinyurl.com/2tarr4nt ■