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Water-use efficiency for alternative cooling technologies in arid climates

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ABSTRACT

In arid climates, evaporative cooling technologies are generally valued for their reduced energy consumption in comparison to compressor-based air conditioning systems. However, two concerns that are often raised with respect to evaporative cooling equipment are their on-site water use and the impact of poor water quality on their performance. While compressor-based systems do not use water on-site, they do consume water through their use of electricity, which consumes water through evaporation at hydroelectric power plants and cooling at thermal power plants. This paper defines a water-use efficiency metric and a methodology for assessing the water use of various cooling technologies. The water-use efficiencies of several example cooling technologies are compared, including direct evaporative, indirect evaporative in two different configurations, compressor-based systems, compressor-based systems with evaporative pre-cooling of condenser inlet air, and hybrid systems that consist of an indirect evaporative module combined with a compressor-based module. Designing cooling systems for arid climates is entwined in the close relationship between water and energy and the scarcity of both resources. The analyses presented in this paper suggest that evaporative systems that significantly reduce peak electricity demand and annual energy consumption need not consume any more water than conventional systems.

1. Introduction

Residential and commercial cooling are the top two contributors to peak electricity demand for many electric utilities in the US, particularly in the more-arid western states. In California, these two end uses comprise 30% of the summer peak electricity demand [1]. The vast majority of the systems used to provide this cooling are small compressor-based air conditioners. For example, the California Residential Appliance Survey of 2004 found that 94% of homes with air conditioning had compressor-based systems [2]. Only 6% of homes employed evaporation of water for cooling, despite the fact that the various evaporative systems have a large potential to reduce both the peak electricity demand and the energy use associated with both residential and light-commercial cooling.

Evaporative cooling is an alternative or augmentation to compressor-based air conditioning that utilizes the cooling potential of evaporating water to reduce electricity consumption [3,4]. Because these systems consume water, when evaluating the energy savings potential of evaporative cooling systems, it is imperative to consider not just their impacts on electricity use, but also their impacts on water consumption as well. However, it is also necessary to consider the water use associated with the electricity consumed by these systems, and the higher electricity consumption associated with compressor-based cooling systems [3,4]. The objectives of this paper are: (1) to explore the overall water-use impacts of various small-scale cooling systems, (2) to develop an appropriate metric for water-use efficiency and (3) to use that metric to compare, through simplified models, compressor-based air conditioning and various evaporative technologies that are applicable to arid and semi-arid climates.

1.1. Defining water-use efficiency

In order to compare water consumption for different cooling alternatives, it is first necessary to define a common yardstick for measuring and normalizing that consumption. The chosen metric for this paper is liters of water consumed per megajoule of indoor cooling capacity delivered, including both on-site water consumption and the off-site water consumption associated with on-site electricity use. In evaluating the total water use of cooling equipment, it important to recognize that there is water consumption associated with the off-site electricity generation and transmission required to power the fans and compressors used for residential and commercial cooling, and that that off-site water consumption is strongly dependent on the means by which the electricity was generated [5,6].

1.1.1. Off-site water consumption for electricity generation

Two sources that analyzed the water consumption associated with electricity production in the Southwest United States

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Nomenclature

COP	coefficient of performance (–)
C_p	specific heat capacity of air at constant pressure (J/g K)
EER	energy efficiency ratio (–)
H_{total}	total sensible cooling (MJ_c)
ΔH_{vap}	heat of vaporization of water (MJ_c/l)
$\dot{m}_{condenser}$	mass flow rate across condenser (g/s)
$\dot{m}_{supply\text{-}air}$	mass flow rate of supply air (g/s)
$m_{supply\text{-}air}$	mass of supply air (g)
n	water-use efficiency (–)
P	fan power (W)
Q	capacity required to pre-cool condenser air (W)
T_{out}	temperature of outside air (°C)
T_{room}	temperature of room air (°C)
T_{supply}	temperature of supply air (°C)
$V_{on\text{-}site}$	volume of water-use on-site for delivered cooling (l)
w_e	water-use rate for electricity generation (l/MJ_e)
$w_{off\text{-}site}$	water-use rate off-site per unit on-site cooling (l/MJ_c)
$w_{on\text{-}site}$	water-use rate on-site (l/MJ_c)
w_{total}	total water-use rate for cooling equipment (l/MJ_c)

were identified. The first source, a 2003 report by National Energy Renewable Laboratory (NREL), separately analyzed water consumption for thermoelectric power generation and for hydroelectric power generation, the two main types of electricity generation [5]. The water consumption for thermoelectric power generation was based on water withdrawal data from the United States Geological Survey (USGS) and a coefficient of water loss by evaporation approximated by the power plant cooling design. The water consumption for hydroelectric power generation was based on the free-water-surface evaporation map reported by the National Weather Service. Evaporation rates for 120 of the largest damns in the United States were analyzed. The analysis also takes into account 5% generation losses for thermoelectric plants and 9% transmission and distribution losses for all plant types. The thermoelectric and hydroelectric water consumption rates were then applied to recent electricity generation mix data for 2007 from the Energy Information Administration (EIA) [7]. It is assumed that solar and wind power sources do not consume fresh water. The results calculated from the NREL study are summarized for Arizona, California, and New Mexico (Table 1). The weighted average water consumption result is different than reported in the NREL study, which used 1999 EIA data for the electricity generation mix. Between 1999 and 2007, the percentage of electricity generated by hydroelectric power has decreased from 12% to 6% in Arizona, 21% to 13% for California, and remained flat at 1% for New Mexico.

The University of California Santa Barbara (UCSB) provided a second source for data specifically on California (Row 3 in Table 1) [6]. The thermoelectric power consumption reported by the UCSB study excludes nuclear power, which consumes seawater and not fresh water in California. The main difference from the NREL study is that the UCSB study referenced a report by the Pacific Institute for Studies in Development that analyzed annual evaporative losses from 100 California hydroelectric facilities [8]. This should be a more accurate assessment for California because the analysis includes 100 hydroelectric facilities in California compared to 120 nationwide in the NREL study (the fraction of the 120 dams located in California is not stated).

The water consumption for electricity generation differs significantly by state, with water consumption in Arizona being three times greater than that in New Mexico, two adjacent states in the arid southwestern United States. This result is driven by hydroelectric water consumption due to evaporation. Accurately quantifying this evaporation is crucial to the result, as shown by the two separate analyses for California, which yield results that differ by a factor of two. Authors of both sources agree that the water consumption for hydroelectric electricity generation is difficult to quantify and that the result may be inflated, as dams provide benefits other than electricity generation, such as flood control and recreation. In the two studies described, all evaporation is attributed to electricity generation. In evaluating cooling technologies, total water use will be calculated using both the low end and high end water consumption estimates for electricity generation in the southwestern United States.

The off-site water consumption per unit of cooling for both compressor-based air conditioning and evaporative cooling can be calculated from the efficiency of the cooling equipment, in units of coefficient of performance (COP), combined with the water consumption for electricity generation (w_e) (Eq. (1)).

$$w_{off-site} = \frac{w_e}{COP} \text{ (metric units)} \quad (1)$$

1.1.2. On-site water consumption

In order to calculate water-use efficiency, the sensible cooling delivered for the water evaporated needs to be defined. One of the trickiest parts of these calculations is the choice of an appropriate cooling metric for evaporative cooling equipment so that the result can be directly compared to compressor-based systems. The relevant difference between evaporative systems and compressor-based systems is that all evaporative systems are required to use at least some outdoor air to provide cooling, while compressor systems can run on recirculation only. Because evaporative systems use significant amounts of outdoor air, they can over-ventilate the space. The result is that an evaporative cooler system may have to provide more total cooling (to cool excess ventilation air) as compared to a compressor-based system meeting the same indoor load. In order to compare the two side-by-side, the equation for evaporative cooling should take credit for the temperature difference

Table 1
Weighted average water consumption for electricity generation in the southwestern United States.

	Thermoelectric water consumption	Hydroelectric water consumption	2007 electricity generation mix	Weighted average water consumption (w_e)
Arizona [5,7]	0.34 l/MJ_e	68.2 l/MJ_e	94% thermo, 6% hydro	4.4 l/MJ_e
California [5,7]	0.05 l/MJ_e	21.9 l/MJ_e	84% thermo, 13% hydro, 3% wind and solar	2.9 l/MJ_e
California [6,7]	0.46 l/MJ_e	7.9 l/MJ_e	67% thermo, 17% nuclear, 13% hydro, 3% wind and solar	1.4 l/MJ_e
New Mexico [5,7]	0.66 l/MJ_e	98.8 l/MJ_e	95% thermo, 1% hydro, 4% wind	1.4 l/MJ_e