Water-Use Efficiency for Alternative Cooling Technologies in Arid Climates

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Abstract

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 indirect evaporative and hybrid evaporative/compressor systems that significantly reduce peak electricity demand and annual energy consumption need not consume any more water than conventional systems.

Nomenclature

Variable	Description	Metric Unit	English Unit
COP	Coefficient of performance		
C_p	Specific heat capacity of air at constant pressure	J/gm·K	Btu/lbm·°F
EER	Energy efficiency ratio		Btu/Wh
H_{total}	Total sensible cooling	MJ_c	kBtu
ΔH_{vap}	Heat of vaporization of water	MJ_c/l	kBtu/gal
$\dot{m}_{condenser}$	Mass flow rate across condenser	gm/s	lbm/min
$\dot{m}_{supply-air}$	Mass flow rate of supply air	gm/s	lbm/hr
$m_{supply-air}$	Mass of supply air	gm	lbm
n	Water-use efficiency	-	-
P	Fan Power	W	W
$Q/\Delta T$	Capacity required to pre-cool condenser air	J/s·K	kbtu/h·°F
T_{out}	Temperature of outside air	°C	°F
T_{room}	Temperature of room air	°C	°F

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T_{supply}	Temperature of supply air	°C	°F
$V_{on-site}$	Volume of water-use on-site for delivered cooling	l	gal/kBtu
w_e	Water-use rate for electricity generation	l/MJ_e	gal/kWh
$w_{off-site}$	Water-use rate off-site per unit on-site cooling	l/MJ_c	gal/kBtu
$w_{on-site}$	Water-use rate on-site	l/MJ_c	gal/kBtu
w_{total}	Total water-use rate for cooling equipment	l/MJ_c	gal/kBtu

1.0 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. 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 effectiveness 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 come up with a common yardstick for measuring and normalizing that consumption. The chosen metric for this paper is the gallons of water consumed per kBtu of indoor cooling capacity delivered, including both on-site water consumption and the off-site water consumption associated with on-site electricity consumption. In metric units, this metric will be expressed in liters per MJ_c, where MJ_c is the cooling delivered. 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 [3, 4].

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 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 [3]. 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 from 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) [5]. 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 University of California Santa Barbara (UCSB) provided a second source for data specifically on California (Row 3 in Table 1) [4]. The thermoelectric power consumption reported by the UCSB excludes nuclear power, which consumes sea water 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 [6]. This is a more accurate assessment for California because the analysis includes 100 hydroelectric facilities in California compared to 120 nationwide (the fraction of the 120 dams located in California is not stated).

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

	Thermoelectric Water Consumption	Hydroelectric Water Consumption	2008 Electricity Generation Mix	Weighted Average Water Consumption (w_e)
Arizona[3, 5]	0.32 gal/kWh (0.34 l/MJ_e)	64.9 gal/kWh (68.2 l/MJ_e)	94% thermo, 6% hydro	4.2 gal/kWh (4.4 l/MJ_e)
California [3, 5]	0.05 gal/kWh (0.05 l/MJ_e)	20.9 gal/kWh (21.9 l/MJ_e)	84% thermo, 13% hydro, 3% wind and solar	2.8 gal/kWh (2.9 l/MJ_e)
California [4, 5]	0.44 gal/kWh (0.46 l/MJ_e)	7.5 gal/kWh (7.9 l/MJ_e)	67% thermo, 17% nuclear, 13% hydro, 3% wind and solar	1.3 gal/kWh (1.4 l/MJ_e)
New Mexico[3, 5]	0.63 gal/kWh (0.66 l/MJ_e)	94.0 gal/kWh (98.8 l/MJ_e)	95% thermo, 1% hydro, 4% wind	1.3 gal/kWh (1.4 l/MJ_e)

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 of 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 either coefficient of performance (COP) or energy efficiency ratio (EER) and the water consumption for electricity generation (w_e) (Equation [1]).

$$w_{off-site} = w_e/COP \text{ (metric units)}$$
$$w_{off-site} = w_e/EER \text{ (English units)} \quad [1]$$

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 only give credit for cooling the required building ventilation, and not any excess ventilation. The ventilation required is expressed as the ratio of ventilation air to the total supply air, r_{vent}. The results are calculated for $r_{vent} = 1/3$, but this variable can be changed to generate results for any ratio of ventilation. In this case, the delivered sensible cooling for evaporative equipment is calculated from Equation [2] and the efficiency for evaporative equipment, required for Equation [1], is obtained using a similar methodology (Equation 3]).

$$H_{total} = m_{supply-air} \times C_p \times \left[r_{vent}\left[T_{out} - T_{supply}\right] + [1 - r_{vent}] \times \left[T_{room} - T_{supply}\right]\right] \quad [2]$$

$$COP = \dot{m}_{supply-air} \times C_p \times \left[r_{vent}\left[T_{out} - T_{supply}\right] + [1 - r_{vent}] \times \left[T_{room} - T_{supply}\right]\right]$$
$$EER = \dot{m}_{supply-air} \times C_p \times \left[r_{vent}\left[T_{out} - T_{supply}\right] + [1 - r_{vent}] \times \left[T_{room} - T_{supply}\right]\right]/P \quad 3]$$

The on-site water-use rate is the volume of water evaporated on-site divided by the sensible cooling delivered (Equation [4]).

$$w_{on-site} = \frac{V_{on-site}}{H_{total}} \quad [4]$$

The total water-use rate for evaporative equipment is the sum of the off-site water-use rate from electricity generation and the on-site water-use rate (Equation [5]).

$$w_{total} = w_{off-site} + w_{on-site} \quad [5]$$

The water-use efficiency, n, is defined as the actual sensible cooling delivered, divided by the maximum cooling that can be obtained from evaporating a given mass of water (equal to the heat of vaporization, ΔH_{vap}) (Equation [6]).

$$n = \frac{1/w_{total}}{\Delta H_{vap}} \quad [6]$$

For direct evaporative systems, using Equation [2] as the yardstick for delivered cooling, water-use efficiency is always below one. Because outdoor air is required to produce the cooling, at least some of the heat of vaporization goes into cooling the outdoor air from outdoor temperature to room temperature. Moreover, the fans in these systems all consume electricity, which adds off-site water consumption. Conventional indirect evaporative systems, which utilize only outdoor air, are also limited to efficiencies less than one when utilizing Equation [2]. However some indirect evaporative systems use return indoor air on one or both sides of the heat exchanger, which allows the equipment to re-capture a portion of the temperature difference between indoor and outdoor air. This distinguishes these systems from direct evaporative systems, for which indoor air cannot be re-circulated, as they introduce humidity as well as sensible cooling to the indoor air. For compressor-based air conditioning systems, the water-use efficiency can be greater than one and is based solely on the water consumption needed to generate electricity. An extreme example would be when a solar photovoltaic system, which consumes no water[1], powers a compressor-based air conditioner. In this case, the water-use efficiency would be infinite, regardless of the energy efficiency of the compressor system.

2.0 Methodology and Results

The cooling methods evaluated in this paper for water-use efficiency are:

1. direct evaporative cooling for supply air;
2. indirect evaporative cooling for supply air;
3. compressor-based air conditioning;
4. direct evaporative pre-cooling of condenser air for compressor-based air conditioning; and
5. hybrid systems that combine indirect evaporative and compressor-based systems.

For numerical analyses, all cooling approaches are evaluated using outdoor air with 100°F dry bulb (DB)/69.2°F wet bulb (WB) (37.8°C DB/20.7°C WB) temperatures, and indoor air with 78°F DB/64°F WB (25.6°C DB/17.8°C WB) temperatures.

2.1 Direct evaporative cooling

In direct evaporative cooling equipment, a fan pulls outdoor air through a wet media, which is generally a corrugated cellulose-based structure that distributes the water to the air (Figure 1, left), and blows that cooler, wetter air into the conditioned space. The performance of these systems is generally quantified by the evaporative effectiveness (Equation [7]).

$$\varepsilon = \frac{T_{Dry\ bulb,outdoor} - T_{Dry\ bulb,supply}}{T_{Dry\ bulb,outdoor} - T_{Wet\ bulb,outdoor}} \qquad [7]$$

Referring to the right side of Figure 1, as water is evaporated, the air originally in state (A) increases in humidity and decreases in dry-bulb temperature, while the wet-bulb temperature remains constant, until point (B) is reached. To analyze water-use efficiency, we used a system modeled after a commercially available direct evaporative cooler that had been independently tested by a laboratory [7] with the following results:

1. Intake Air: 99.8°F DB/69.9 WB (37.7°C DB/21.1°C WB), Airflow = 2,047 ft³/min (966 l/s)

[1] Although some water was most certainly used in the process of manufacturing the system, a photovoltaic system does not consume any water on an ongoing basis, which is the metric being used for this paper (i.e. we are not calculating "embedded-water").

2. Supply Air: 73.3°F DB/70.1 WB (22.9°C DB/21.2°C WB), Airflow = 1,964 ft³/min (927 l/s)
3. Wet Bulb Evaporative Effectiveness = 89%
4. External Static Pressure = 0.3”wc (75 Pa), Fan Power = 321 W
5. EER (r_{vent}=1/3) = 79.5 (COP=23.3)

The inputs for the water-use efficiency (Equation 5) are determined by 1) calculating the sensible cooling delivered (Equation 2) using the supply air temperature from the test results, 2) calculating the on-site water use from the humidity ratio increase of the supply air stream using the psychometric chart (Figure 1, right), and 3) calculating the off-site water use from the calculated EER or COP (Equation **3**]). The resulting water-use efficiency of the tested indirect evaporative cooler is 0.37-0.42 (range attributed to water consumption for electricity generation range of 1.28-4.15 gal/kWh (1.35-4.36 l/MJ_e)). Additional water for maintenance of the evaporative media is not included[2]. While direct evaporative cooling systems may be suitable for environments where sensible cooling is required and higher humidity is desirable (e.g. wineries, agriculture), it is often considered a lower-performance solution for residential and commercial environments (these systems do not reduce the enthalpy of the supply air, but rather trade off sensible enthalpy for latent enthalpy).

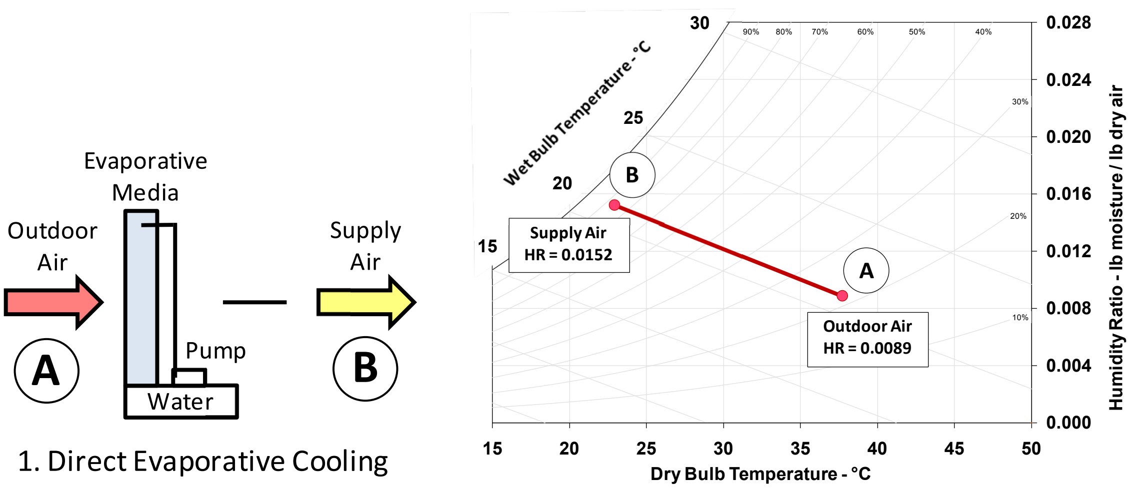

Figure 1 – Direct evaporative cooling of supply air schematic (left) and path on psychometric chart (right).

2.2 Indirect evaporative cooling

Indirect evaporative cooling utilizes a heat exchanger in which one side is a wet-air passage and the other side is a dry-air passage (Figure 2, left). In the conventional configuration, all of the air entering the equipment is outdoor air. The outdoor air enters the dry side of the heat exchanger at (A), exchanges heat with the wet side air, and exits the heat exchanger at (B) without changing its humidity (Figure 2, right). A portion of the air at (B) is delivered to the building as the supply air, while the rest of the air is directed through the wet-side of the heat exchanger. On the wet-side, the air stream increases in enthalpy as it absorbs heat from the dry-side air and evaporates water from the water supply. As for direct evaporative coolers, the metric typically used to quantify the performance of the indirect evaporative heat exchanger is its evaporative effectiveness (Equation [7]).

[2] Note that these calculations do not include water used to maintain the usable lifetime of the evaporative media. In regions with good water quality, this water use can be modest (~5%), however in regions with hard water, maintenance water use can increase on-site water use by 50%.

An evaporative effectiveness greater than one is achievable in an indirect evaporative unit. The physical limitation for the supply air temperature is the dew-point temperature of the incoming outdoor air. Increasing heat exchanger surface area increases effectiveness, however this generally results in additional fan power, and/or increased size and materials requirements. Reducing air flow rates increases effectiveness, but reduces capacity. To analyze water-use efficiency, we used a system modeled after a commercially available indirect evaporative cooler that had been independently tested by a laboratory [8] with the following results:

1. Intake Air: 100°F DB/69.2 WB (37.8°C DB/20.7°C WB), Airflow = 2,770 ft³/min (1,307 l/s)
2. Supply Air: 72.4°F DB/60°F WB (22.4°C DB/15.6°C WB), Airflow = 1,490 ft³/min (703 l/s)
3. Exhaust Air: 78.3°F DB/78°F WB (25.7°C DB/25.6°C WB), Airflow = 1,280 ft³/min (604 l/s)
4. Wet Bulb Evaporative Effectiveness = 90%
5. External static pressure = 0.3”wc (75 Pa), Fan Power = 1,260 W
6. EER (r_{vent}=1/3) = 16.8 (COP=4.9)

The inputs for the water-use efficiency (Equation 5) are determined by 1) calculating the sensible cooling delivered (Equation 2) using the supply air temperature from the test results, 2) calculating the on-site water use from the humidity ratio increase of the exhaust air stream using the psychometric chart (Figure 2, right), and 3) calculating the off-site water use from the measured energy efficiency. The resulting water-use efficiency of the tested indirect evaporative cooler is 0.17-0.23 (range attributed to water consumption for electricity generation range of 1.28-4.15 gal/kWh (1.35-4.36 l/MJ_e)). The on-site water-use calculation includes all water evaporated for cooling, of which ~95% cools the supply air stream and ~5% removes the additional heat generated by the fan. Additional water for maintenance of the evaporative media is not included.

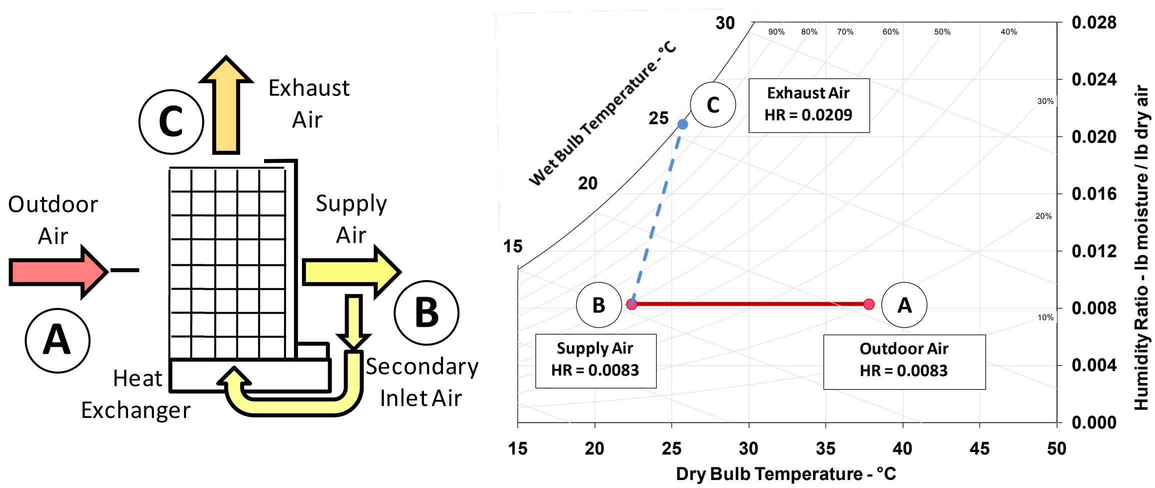

Figure 2 - Indirect evaporative cooling using outdoor air only for intake air schematic (left) and path on psychometric chart (right)

2.3 Indirect evaporative cooling using exhaust air

In order to reduce unnecessary pressurization (above that needed to eliminate infiltration), indoor air can be returned and mixed with outdoor air at the entry to the heat exchanger (Figure 3, left). The other advantage of this configuration is that it incorporates the ability to capture the cooling embodied in the indoor air (i.e. if there weren’t any water evaporation, it would act like an air-to-air heat exchanger). This strategy was recently employed by a manufacturer in designing their hybrid indirect/vapor-compression rooftop unit for the Western Cooling Challenge initiated by the Western Cooling Efficiency Center [9].

In order to investigate the impact of utilizing indoor air on water-use efficiency, the indirect evaporative cooler (without any use of compressor-based cooling) is analyzed again assuming that the outdoor air intake flow exceeds the exhaust air flow by 270 ft³/min (127 l/s) to avoid any infiltration load, and that the return air from the building is mixed with the outdoor intake air to create a mixed-air stream that is used in both the wet and dry passages of the cooler:

1. Outdoor Air: 100°F DB/69.2 WB (37.8°C DB/20.7°C WB), Airflow = 1,580 ft³/min (746 l/s)
2. Return Indoor Air: 78°F DB/64°F WB (25.6°C DB/17.8°C WB), Airflow = 1,240 ft³/min (585 l/s)
3. Mixed Intake Air: 90.3°F DB/66.9°F (32.4°C DB/19.4°C WB), Airflow = 2,820 ft³/min (1,331 l/s)

In order to assess the performance and water-use efficiency implications associated with utilizing mixed outdoor and indoor air, the lab study results [8] for the closest available intake-air test point are used: 90.1°F DB/64.5°F WB. The results for this test point were:

1. Intake Air: 90.1°F DB/64.5°F WB (32.3°C DB/18.1°C WB), Airflow = 2,820 ft³/min (1,331 l/s)
2. Supply Air: 68.8°F DB/56.7°F WB (20.4°C DB/13.7°C WB), Airflow = 1,510 ft³/min (713 l/s)
3. Exhaust Air: 73.6°F DB/72.7°F WB (23.1°C DB/22.6°C WB), Airflow = 1,310 ft³/min (618 l/s)
4. Wet Bulb Evaporative Effectiveness = 83%
5. External static pressure = 0.3"wc (75 Pa), Fan Power = 1,357 W
6. EER (r_{vent}=1/3) = 20.2 (COP=5.9)

The inputs for the water-use efficiency (Equation 5) are determined by 1) calculating the sensible cooling delivered (Equation 2) using the supply air temperature from the test results and the actual outdoor air temperature (100°F (37.8°C)), 2) calculating the on-site water use from the humidity ratio increase of the exhaust air stream using the psychometric chart (Figure 3, right), and 3) calculating the off-site water use from the measured energy efficiency. The resulting water-use efficiency of the tested indirect evaporative cooler is 0.25-0.35 (range attributed to water consumption for electricity generation range of 1.28-4.15 gal/kWh (1.35-4.36 l/MJ_e)). The on-site water-use calculation includes all water evaporated for cooling, of which ~91% cools the supply air stream and ~9% removes the additional heat generated by the fan. Additional water for maintenance of the evaporative media is not included.

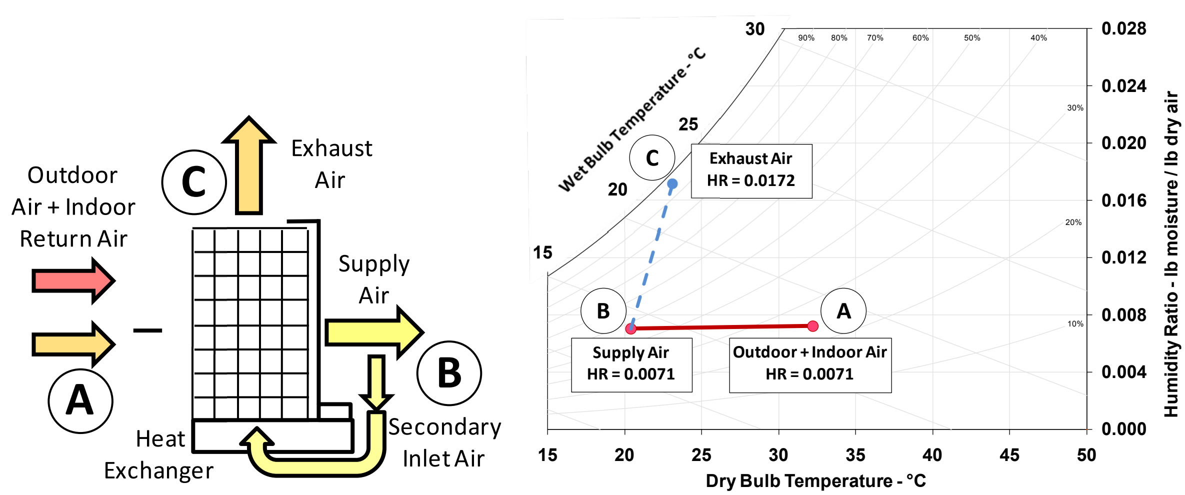

Figure 3 – Indirect evaporative cooling using mixed outdoor air and building return air as intake air schematic (left) and path on psychometric chart (right)

2.4 Compressor-based air conditioning

Compressor-based air conditioning systems do not consume any water on-site. However, the electricity needed to run these systems is generated at power plants that consume water. The efficiency of the equipment can be used to calculate off-site water use. For this analysis, the efficiency is the total cooling capacity delivered when the outdoor air temperature is 100°F (37.8°C) divided by the total electricity consumption for compressors, condenser fans, and blower motor at an external static pressure of 0.5”wc (125 Pa). While a wide variety of compressor-based systems are available, two “representative” systems were selected for this analysis. The first is a “standard-efficiency” unit with refrigerant R-22, which has been utilized in the United States for several decades. The second is a higher-efficiency unit utilizing refrigerant R-410A, which is replacing R-22 as it is phased out of new equipment in the United States by January 1st, 2010 to meet environmental standards[10]. While the choice of refrigerant is not the reason for increased efficiency, new high efficiency designs developed in recent years used R410A early on in anticipation of the phase out of R-22.

In arid climates, compressor-based systems often produce unnecessary dehumidification, and therefore a better yardstick is often the sensible cooling delivered for these regions. For the units described, delivered sensible cooling for indoor air conditions of 78°F DB/64° WB (25.6^{o}C DB/17.8^{o}C WB) is approximately 75% of the total cooling for the R-22 system and 85% of total cooling for the higher efficiency R-410A system.

A nominal 20 ton (240 kBtu/h, 70.3 $kW_{cooling}$) commercial compressor-based air conditioning system utilizing refrigerant R-22 with a sensible EER of 5.6 Btu/Watt·h (COP=1.6) (calculated from the manufacturer’s published data at 100°F (37.8°C))[11] yields a water-use efficiency of 0.16-0.50 (range attributed to water consumption for electricity generation range of 1.28-4.15 gal/kWh (1.35-4.36 l/MJ_e)). Similarly, a nominal 20-ton (240 kBtu/h, 70.3 $kW_{cooling}$) higher-efficiency system utilizing refrigerant R-410A with a sensible EER of 9.4 Btu/Watt·h (COP=2.7) (calculated from the manufacturer’s published data at 100°F (37.8°C) outdoor air temperature)[12] yields a water-use efficiency of 0.26-0.85 (range attributed to water consumption for electricity generation range of 1.28-4.15 gal/kWh (1.35-4.36 l/MJ_e)).

2.5 Compressor-based air conditioning with evaporative pre-cooling of condenser air

Another type of evaporative cooling uses direct evaporative cooling to decrease the temperature of the outdoor air delivered to the condenser coil of a compressor-based air conditioning system (Figure 4, left). The energy required to pre-cool the condenser air is a function of the mass flow rate of air across the condenser and the specific heat capacity of air (Equation [8]).

$$Q/\Delta T = \dot{m}_{condenser} \times C_p \qquad [8]$$

For a nominal 20 ton (240 kBtu/h, 70.3 $kW_{cooling}$) system moving 1,120 lbm/min (8490 g/s) across the condenser coil, 16.2 kBtu/h (4.7 $kW_{cooling}$) is needed to pre-cool the condenser air by 1°F (0.6°C). Using manufacturer’s literature for the two “representative” systems, the efficiency of the system with refrigerant R-22 improves approximately 0.9% per 1°F (0.6°C) of pre-cooling provided (Figure 4, right) [11] and the efficiency of a system with refrigerant R-410A improves approximately 1.5% per °F (0.6°C) of pre-cooling provided (Figure 4, right) [12]. The steeper slope of the R-410A system is related to the performance of the refrigerant, as it is more sensitive to outdoor air temperature as compared to R-22. Even though the higher efficiency R-410A system uses less energy, the performance degrades more quickly as outdoor air temperature increases. Therefore, condenser air pre-cooling provides a greater benefit for R-410A systems than for R-22 systems.

For the R-22 system, the 0.9% improvement equals an increase in sensible capacity of 1.4 kbtu/h (0.4 $kW_{cooling}$). For the R-410A system, the 1.5% improvement equals an increase in sensible capacity of 2.9 kbtu/h (0.8 $kW_{cooling}$). The additional indoor cooling capacity provided to the building divided by the condenser pre-cooling required yields a water-use efficiency for the evaporative pre-cooling component of 0.09 for the R-22 system and 0.18 for the R-410A system.

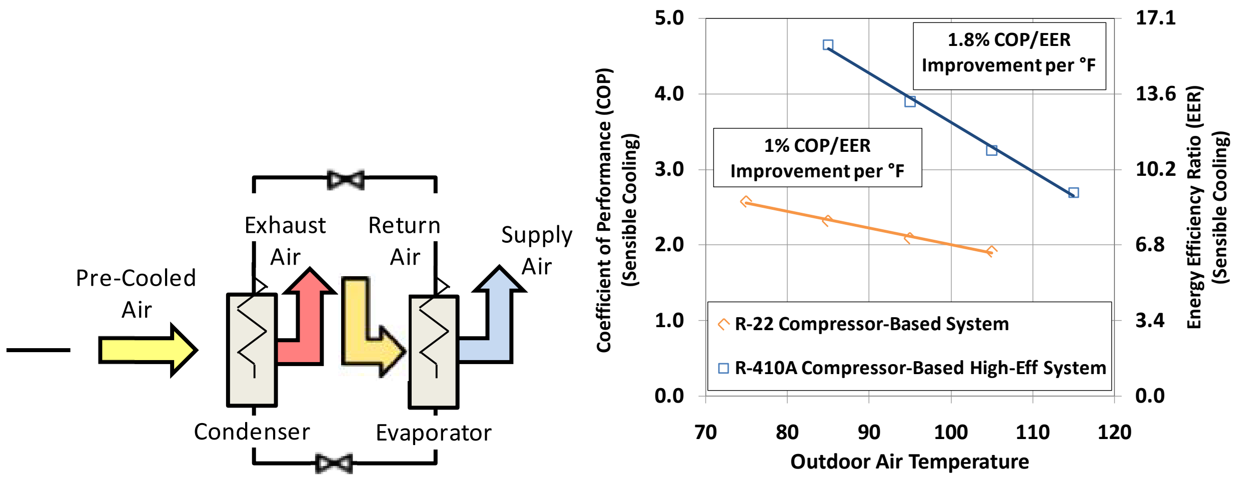

Figure 4 – Pre-cooled air to condenser of a compressor-based system (left) and relationship between condenser air temperature and efficiency for R-22 and higher efficiency R-410A compressor based systems [11, 12]

2.6 Hybrid vapor-compression/indirect-evaporative systems

Although it can prove to be a cost-effective retrofit to improve the efficiency and capacity of existing compressor-based air conditioners, evaporating water directly for the purpose of pre-cooling condenser intake air is shown in section 2.5 to be one of the least efficient ways to use water for cooling. However, for a multiple component system where the wet-side exhaust of an indirect evaporative system (Figure 2 and Figure 3, flow C) is used as the intake air flow for the condenser (Figure 4, left), condenser-air pre-cooling can be more efficient. The exhaust air from an indirect evaporative system generally has a dry bulb temperature that is cooler than outdoor air temperature because it is impractical to utilize all the cooling available from the exhaust air stream in the indirect heat exchanger (doing so would require an impractically large heat exchanger or an impractically slow air flow rate). The cool, wet exhaust can thus be used to improve the efficiency of the compressor-based air conditioner. To calculate the water-use efficiency for this configuration, the additional cooling provided by the exhaust air is added to the cooling provided by the indirect evaporative unit. The major benefit of this hybrid system is that the cooler wet-side air being exhausted from the indirect heat exchanger is being re-used for condenser pre-cooling instead of being wasted. The specific efficiency improvement obtainable for the hybrid system described depends on the design of the indirect evaporative system, the water used off-site for electricity generation, and the refrigerant used in the compressor-based system (Table 2). In addition, the sizing of the compressor-based system relative to the indirect evaporative system is important. If the exhaust air flow from the indirect module is larger than the flow rate across the condenser of the compressor-based system, then some of the cooled exhaust air is wasted. Increasing the size of the compressor-based system such that the flow across its condenser exceeds the exhaust flow from the indirect module does not impact the overall water use efficiency.

The indirect module used in this analysis is the same as that analyzed in the previous section where the exhaust air is 22-26°F (12-15°C) cooler than the outdoor air temperature. For a correctly-sized compressor-based system, the improvement in water-use efficiency over the standalone indirect module is significant, between 16%-45% in Table 2. This increase in water-use efficiency for the hybrid system is greatest for compressor systems using the refrigerant R-410A, for which the performance is more strongly related to condenser air temperature as compared to refrigerant R-22. It should be noted that there exist a multitude of alternative hybrid system designs other than the one analyzed in this paper, and there may exist designs that have even higher water use efficiencies.

Table 2 - Water-use efficiency improvement of using the exhaust of an indirect evaporative system for condenser-air pre-cooling

	Water-use Efficiency		
Indirect system and water-use rate for electricity generation	Indirect Only	+Indirect Exhaust to R-22 Compressor System	+Indirect Exhaust to R-410A Compressor System
Outdoor Air Only w_e= 1.28 gal/kWh (1.35 l/MJ_e)	0.23	0.27 (+16%)	0.30 (+31%)
Outdoor Air Only w_e= 4.15 gal/kWh (4.36 l/MJ_e)	0.17	0.21 (+21%)	0.24 (+42%)
Outdoor Air + Return Indoor Air w_e= 1.28 gal/kWh (1.35 l/MJ_e)	0.35	0.41 (+16%)	0.46 (+31%)
Outdoor Air + Return Indoor Air w_e= 4.15 gal/kWh (4.36 l/MJ_e)	0.25	0.30 (+22%)	0.36 (+45%)

3.0 Discussion

The water-use efficiencies for all types of cooling equipment analyzed are summarized for side-by-side comparison in Figure 5. This comparison indicates that direct evaporative cooling has a competitive water-use efficiency, especially when water needs to generate electricity are high. However, the value of this efficiency is offset by the fact that the applicability of this technology is limited due to the elevated indoor humidity that it produces. On the other end of evaporative technologies, evaporative pre-cooling of condenser air is one of the least efficient options, with a water-use efficiency of 0.09-0.18. This strategy is shown to be more advantageous for R-410A systems than for R-22 systems as R-410A performance is more strongly related to condenser air temperature. Even though pre-cooling condenser air is not the most efficient water-use option, it has several advantages, namely that it is a relatively inexpensive retrofit that provides significant electricity savings and increased cooling capacity without impacting indoor humidity levels.

The most interesting results in Figure 5 involve indirect evaporative cooling, as it does not add any indoor moisture, yet its water use efficiency can be elevated above that of direct evaporative cooling by appropriate equipment design (i.e. incorporating this equipment with a compressor-based system). For the options that were analyzed, the water-use efficiency of indirect evaporative cooling is maximized when indoor return air is incorporated into the intake air stream and the indirect-section exhaust is used as pre-cooled condenser inlet air for a properly-sized compressor-based system. When the water requirements for electricity generation are high, 4.15 gal/kWh (4.36 l/MJ_e), an indirect evaporative cooler that recycles indoor air and recovers exhaust for a compressor-based system has a water-use efficiency of n=0.30, which is actually more efficient than the standard-efficiency compressor-based system (n =0.16) and high efficiency R-410A compressor-based system (n=0.26). When the water requirements for electricity generation are low, 1.28 gal/kWh (1.35 l/MJ_e), the high efficiency R-410A system has a water-use efficiency nearly two times greater than the most water-efficient evaporative system analyzed. In either case, the evaporative system significantly reduces peak electricity demand and annual energy consumption. It is clear that pinpointing the quantitative water-use efficiency results relies very heavily on the water use for hydroelectric electricity generation, which varies by state. Without knowing the "exact" answer, it is clear that evaporative technologies that are superior from an energy efficiency standpoint can be competitive from a water-use efficiency standpoint as well.

The comparative results shown assume that the required ventilation for the building is 33% of the total supply air. However, the direct and indirect systems with no recovery of indoor air actually provide 100% ventilation air. The indirect system with recovery of indoor air analyzed provides a supply air stream that is 56% ventilation air. The sensible cooling provided by the evaporative cooler (Equation [2]) only receives credit for the required 33% ventilation. If the required ventilation is higher, the water-use efficiencies for the evaporative cooling systems will increase. If the required ventilation is lower, the water-use efficiencies for the evaporative cooling systems will decrease. The water-use efficiency for compressor-based systems is not a function of ventilation rate. Therefore, evaporative systems are even more attractive for buildings with high ventilation requirements, or in buildings with multiple cooling units, where particular units can be dedicated to providing additional ventilation.

Another issue that will need to be addressed for evaporative coolers in some regions is the effect of hard water on the maintenance of the system. Hard water can cause mineral buildup on wet-side heat exchange surfaces. Initial experiments indicate that the mineral build up does not appear to reduce evaporative effectiveness, but that it does increase flow resistance and, therefore, capacity and efficiency. Typically, manufacturers drain sump water and/or use extra water to wash the media on a regular basis to prevent and remove mineral buildup. Use of extra maintenance water is not considered in the analysis and will reduce water-use efficiency. The amount of maintenance water required based on mineral content is not well understood, but "rule of thumbs" are in the range of 5-50% of the evaporated water. Potential options to reduce maintenance water consumption include pre-treating the water supply to remove minerals or changing evaporative media on a periodic basis when mineral buildup reaches an unacceptable level.

One other consideration when comparing the water use efficiencies of various cooling-equipment alternatives is the difference between localized water use and power-plant water use. On the negative side for evaporative equipment is the fact that it takes energy to transport water to the local cooling equipment. On the positive side for evaporative equipment is that there are localized water sources that are suitable for evaporative cooling purposes, but which currently cannot be used for drinking. These include air-conditioner condensate, captured rainwater, and grey water. Along a similar line, purge water from evaporative coolers can potentially be used for gardens, thereby eliminating maintenance-water use from the equation.

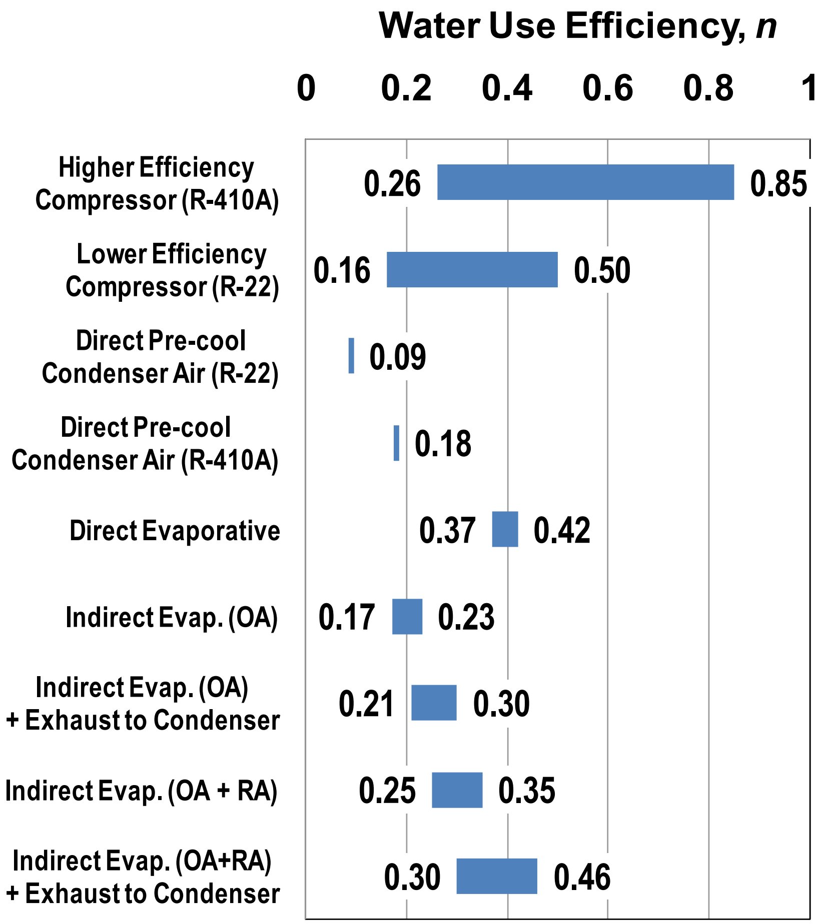

Figure 5 – Summary of water-use efficiencies for various cooling technologies (ranges are based upon high and low values for water consumption for electricity generation in the southwestern United States).

4.0 Conclusions

Designing cooling systems for California's climate is entwined in the close relationship between water and energy and the relative scarcity of both resources on both peak and annual bases. It is clear that a rationale basis is needed for comparing cooling-system alternatives. This paper has presented a possible framework for such comparisons, as well as example applications of that framework to a number of cooling alternatives.

The work presented in this paper suggests that there exist viable alternatives for reducing energy consumption and peak electricity demand that do not significantly increase overall water use. One such solution may be in designing hybrid evaporative-plus-compressor systems that significantly reduce peak and annual electricity demand while making efficient use of on-site water. This paper also suggests that additional research on water quality impacts and local water management strategies could prove to be valuable.

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