WATER TREATMENT TECHNOLOGIES IN WHOLE BUILDING ENERGY AND WATER MODELS

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ABSTRACT

Whole building water modeling is gaining traction in the marketplace with the adoption of the LEED Whole Project Water Use Reduction alternative compliance path and ASHRAE 191P Standard for the Efficient Use of Water in Building Mechanical Systems. As project teams explore various means of reducing water consumption; water treatment technologies have come into focus as a means of saving water in mechanical systems. This paper focuses on the procedures for quantifying both energy and water consumption, savings for treatment systems such as reverse osmosis and softening, and their impact on water use in cooling towers, boilers, and humidification systems.

Finally, this paper addresses variable water quality from potable and non-potable systems, and how that impacts energy and water performance in mechanical systems. The drive towards greater water savings introduced the use of non-potable water systems coming either from municipal sources or from on-site sources such as cooling coil condensate, roof rainwater, and reject water from process systems. These sources can be a great way to reduce water purchases, but treatment approaches may need to vary to account for new water chemistries, which impact water and energy use in mechanical systems.

INTRODUCTION

There are numerous economic studies that demonstrate the rising cost of water and sewer throughout the US (PNNL 2017) as well as increasing scarcity of water (UNL 2019). Municipal water consumption accounts for approximately 13% of total U.S. water withdrawals (USGS 2010). Furthermore, environmental organizations and trade associations such as U.S. Green Building Council and ASHRAE have been advancing water efficiency as a means of enhancing the environment and the economic sustainability of civilization.

Numerous papers and guides have been published that articulate how to quantify water consumption in the built environment that include plumbing fixtures, irrigation, HVAC, process equipment as well water reuse systems (Betz 2014, NRDC 2019).

An often overlooked, but potentially critical water user is water treatment systems within buildings. Much of this water is “out of sight, out of mind”, and in certain applications can amount to a large fraction of the water consumption in a building. To date, no modeling tool identified by prior authors includes the following components.

As building designs look to reuse water and/or make use of non-potable water supplies, water quality is of paramount importance. This paper will address basic water chemistry to inform the subsequent analysis, discuss a few water quality technologies, and review two common HVAC applications that are impacted by water quality and treatment technologies. The scope of this paper is by no means comprehensive as water quality is an industry unto itself. The intent is to demonstrate the value of quantifying water quality and its impact on building system performance.

This paper does not address water quality issues such as pathogens like legionella, lead, etc. that may lead to health issues.

BASIC WATER CHEMISTRY

This paper is going to focus on two water quality issues: hardness and total dissolved solids, as these are the two most common factors addressed by water treatment systems for the purpose of functioning in water reuse and mechanical systems.

Hard water contains dissolved minerals such as calcium and magnesium. When these minerals become separated in the water, they form cations and can adhere to the inside of the piping or equipment and can cause scale. Scale impacts the performance of the system by reducing heat transfer coefficients among other adverse effects.

Water hardness varies throughout the world. The map shown in Figure 1 demonstrates the range of hardness expressed in grains per gallon. Project specific hardness values may deviate from these ranges and should be referenced when available.

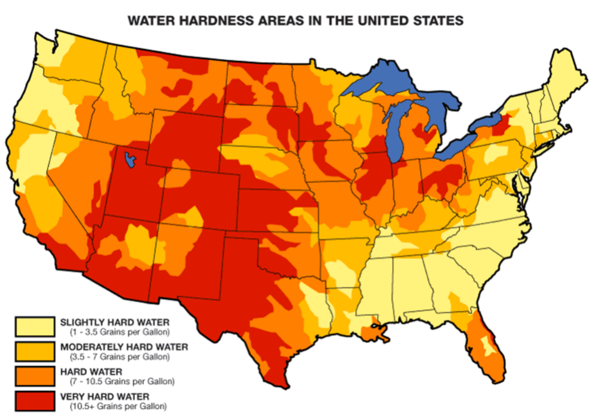

Figure 1. U.S. Water Hardness Map (H2O 2020)

Total dissolved solids, TDS, is a general category of solids that refer to any minerals, salts, metals, cations or anions dissolved in water (WRC 2020). TDS is measured by measuring the conductivity of the water and correlating to TDS, which is typically within 10% accuracy of a laboratory test. TDS is typically expressed in milligrams per liter and conductivity is measured in microsiemens. The correlation factor varies between 0.55 and 0.8 (Atekwanaa, et al 2004).

TECHNOLOGIES

There are a multitude of water treatment technologies available to improve water quality. Each technology serves a specific function(s) when improving water quality such as reducing hardness or removing TDS. These functions can range from treating drinking water to providing clean washing of sterile products.

The intent of many of these technologies is to improve water quality in order to reduce energy or water consumption. However, in order to treat water, many technologies consume water and energy in the process.

The following sections provide an overview of how each treatment technology works, and how to define how much water and/or energy is consumed.

Softening

Water softening is a chemical ion-exchange process to soften the water by removing the hardness. Water softening replaces the calcium and magnesium in the water stream with another mineral like sodium or potassium. These minerals are much more soluble in water than calcium and magnesium, resulting in new ions that are not scale forming. Water softening does not address TDS.

Water softening uses a mineral bed charged with sodium or potassium chloride ions. As the hardwater passes through the mineral beds, the ions are exchanged, and the beds become depleted. When the bed is depleted of its anions, the beds need to be regenerated. The regeneration process uses a salt brine to recharge the anion beds. During the recharging process, the calcium and magnesium ions are backflushed out of the softener mineral beds and down the drain. This backflush water is often overlooked in the water model.

The amount of water used for the regeneration process can depend on the type of softener used. Older softener technology uses a time clock to regenerate the softener beds on a timed cycle regardless if the beds needed recharging or not. The amount of water consumed in the regeneration cycle is included in a typical softener specification sheet.

More advanced water softeners regenerate based on demand for softened water. The demand is determined based on the hardness of the water and a flow meter to measure production of softened water. This demand control can substantially reduce the amount of regeneration water versus a time clock-based control.

Demand based softener regeneration is based on the consumed volume of soft water and the extracted grains of hardness. The softener calculates this based on data from a flow meter and an estimate of the incoming water hardness, for example, 23 grains per gallon. If the target hardness is zero grains per gallon, then 23 grains are extracted per gallon.

The water model or metered data will then define how many gallons are softened to determine a total quantity of grains removed. Per NSF/ANSI Standard 44, softeners shall consume less than five gallons [18.9 liters] per 1,000 grains of hardness removed. Softener manufacturers may have more efficient systems, which should be considered as a water savings measure.

Returning to the example of extracting 23 grains of hardness per gallon [6.1 grain/l]. At this rate; 43.5 gallons [164.7 liters] of water will be softened before regeneration is required due to the removal of 1,000 grains of hardness. Therefore, approximately 48.5 gallons [183.6 liters] of water is required to create 43.5 gallons [164.7 liters] of soft water.

It should be noted that the size of the softener is not arbitrary. Oversized softeners may suffer from channeling, which occurs in low flow and not utilizing the entire softener bed resulting in hard water leakage. A softener is typically sized for regeneration every three days.

Per NSF/ANSI Standard 44; the softeners must have a rated efficiency of 3,350 grains removed per pounds [7,370 grains/kg] of salt used for regeneration. The state of California requires an efficiency of at least 4,000 grains removed per pound of salt added (Applied, 2007)

Another technology is salt brine recovery. This process flushes the brine used in the start of the regeneration process down the drain. The beginning of the regeneration cycle flushes the harder water down the drain. As the regeneration process continues, the hardness of the wasted water decreases. The water at the end of the regeneration cycle is softer and is returned to the brine tank for a future regeneration. Brine recovery can save a large amount of the water used for softener regeneration and should be based on manufacturer specifications.

Reverse Osmosis

Reverse Osmosis (RO) uses a semipermeable membrane technology to filter out TDS among other contaminants, however the focus here is on TDS.

The RO unit uses a pump to create a high-pressure zone on one side of the filter and a low-pressure zone on the other. This pressure differential creates osmotic pressure to force the pure water (permeate) molecule through the membrane and leaves the TDS behind in the concentrate as shown in Figure 2.

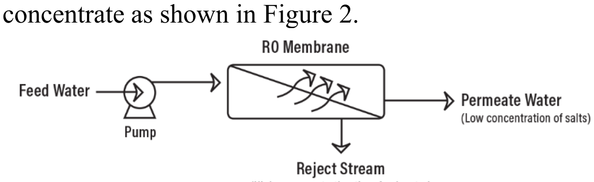

Figure 2: RO System Diagram. (Purtec 2012)

RO effectiveness ranges between 50% and 80%. In other words; a 50% effective RO system has a 2 gallon input and a 1 gallon output of permeate and a 1 gallon output of concentrate (Purtec, 2012). In a 75% effective system; if two gallons of water enter the RO system, then 1.5 gallons of permeate is generated and 0.5 gallons of concentrate is rejected.

The power consumption of RO systems vary by manufacturer but can range between 4 and 12 kWh/m3 (0.016- 0.045 kWh/gallon) (Meefog, 2014).

Furthermore, a softener is frequently used to remove the hardness in the water before it passes through a RO unit. Hard water decreases the life expectancy of the RO membrane requiring it to be replaced more often.

APPLICATIONS

The next two sections apply concepts from the water treatment section in two common systems found in the built environment.

The water accounting practices defined in the examples facilitate the creation of accurate water balances when treatment is required for the efficient operation of the systems.

Softened water for cooling towers

Cooling towers are one of the most intense water consuming technologies found in the built environment consuming water through evaporation, blowdown, and drift. The evaporation rate is a function of how much heat is rejected, and the blowdown rate is a function of water quality. As water is evaporated minerals are left behind that become concentrated. The process of removing these minerals is defined as blowdown. A small amount of water is also lost through drift or windage which is an uncontrolled water loss, primarily a function of wind velocity. Water quality can be improved via softening to decrease the blowdown volume in cases where calcium and/or magnesium levels are high.

A key metric in cooling tower water quality is cycles of concentration. Cycles of Concentration (COC) are defined as the ratio of the makeup rate to the sum of the blowdown and drift rate. The number of COCs is dependent on the composition of the makeup water, particularly minerals and their quantity contained in the makeup water supply (ASHRAE 189.1-2017).

ASHRAE 189.1-2017 regulates cycles of concentration based on maximum thresholds of certain chemical constituents, which include calcium and magnesium as defined in Table 1. Both calcium and magnesium are addressed by a water softener, providing the potential to improve the cycles of concentration.

Table 1: ASHRAE 189.1-2017 Table 6.3.2.3 Recirculating Water Properties for Open Circuit Cooling Tower Materials of Construction

Properties of Recirculating Water*	Maximum Values of Limiting Parameters
Conductivity (micro-ohms)	3,300
Total Dissolved Solids (ppm)	2,050
Total Alkalinity as CaCO3 (ppm)	500
Calcium Hardness as CaCO3 (ppm)	500
Chlorides as Cl (ppm)	300
Sulfates (ppm)	250
Silica (ppm)	150
LSI (Langelier Saturation Index)	+2.8

The values in Table 1 are maximum thresholds for the concentration of certain parameters within the water. For example; calcium harness as CaCO3 is limited to 500 ppm. If makeup water to the cooling tower is 14 grains per gallon or 239 ppm, then the maximum cycles of concentration as a function of CaCO3 is 500 divided by 239 or 2.1.

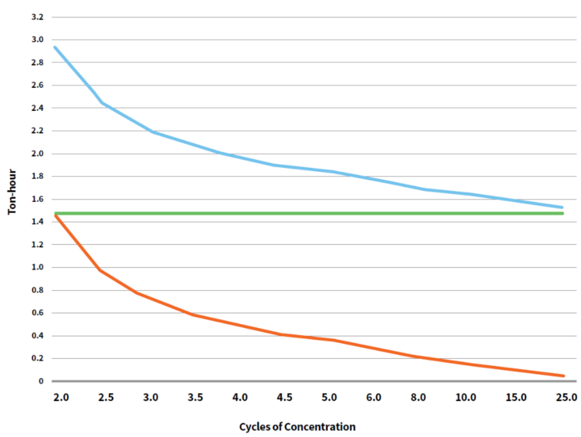

Figure 3: Cooling tower makeup, evaporation, and blowdown rates (H.W. Hoffman 2017).

The green line (horizontal) in Figure 3 depicts the amount of water evaporated per ton-hr of cooling, or approximately 1.45 gallons [5.49 liters]. The x-axis defines cycles of concentration, which per the previous calculation was 2.1 and would correspond to approximately 1.25 gallons per ton-hr [1.35 liters/kWh]. The combined makeup water is then 2.7 gallons per ton-hr [2.9 liters/kWh]. An example of this analysis is shown in Table 2 for 1,000 ton-hrs [3,517 kWh] of heat rejection.

Table 2: Heat Rejection Water Consumption Example

1,000 ton-hrs [3,517 kWh] of Heat Rejection		
Evaporation Rate	1.45	gallons/ton-hr
	1.56	liters/kWh
Evaporation	1,450	gallons
	5,489	liters
Blowdown Rate	1.25	gallons/ton-hr
	1.35	liters/kWh
Blowdown	1,250	gallons
	4,748	liters
Makeup Water	2,700	gallons
	10,237	liters

Table 3 demonstrates the application of a water softener to 50% of the makeup water to reduce hardness and improve the COC. The softened and unsoftened water will be mixed prior to use in the cooling tower.

Returning to Table 1; if the initial hardness if 14 grains per gallon [3.7 grains/liter], then a 50% softened mixture will be 7 grains per gallon [1.85 grains/liter]. This corresponds to about 4.2 COC or 119.5 ppm. Therefore, a new blowdown rate of 45 gallons per ton-hr [0.48 liter/kWh] per Figure 3. Applying the softener to the example from Table 2 yields Table 3.

Table 3: Heat Rejection Water Consumption Example with 50% Water Softening

1,000 ton-hrs [3,517 kWh] of Heat Rejection		
Evaporation Rate	1.45	gallons/ton-hr
	1.56	liters/kWh
Evaporation	1,450	gallons
	5,489	liters
Blowdown Rate	0.45	gallons/ton-hr
	0.48	liters/kWh
Blowdown	450	gallons
	1,704	liters
Makeup Water	1,900	gallons
	7,193	liters

Based on the results from Tables 2 and 3, a total of 900 gallons [3,607 liters] is saved. However, this does not account for the softener regeneration.

If 50% of the makeup water or 950 gallons [3,596 liters] from Table 3 is softened from 14 grains per gallon [3.7 grains/liter] to zero, then 13,300 grains are removed. The regeneration rate of five gallons per

1,000 grains [18.9 liters/1,000 grain], 66.5 gallons [251.7 liters] will be required for regeneration.

This reduces the savings from 900 gallons [3,607 liters] to 833.5 gallons [3,155 liters] or a 7% reduction. Furthermore, both the additional regeneration water and the cost of the salt should be accounted for in the calculation. Applying NSF/ANSI Standard 44 rate of 3,350 grains removed per pound of salt added would yield 4.0 lbs [1.8 kg] of salt for regeneration per 1,000 ton-hr [3,517 kWh].

It should be noted that the incoming water quality has a major impact on this analysis as COC is not a linear relationship as shown in Figure 3. If the incoming water quality has a hardness of 5 grains per gallon, and the same process is repeated, only 172 gallons (651 liters) is saved.

Finally, in this example, it is assumed hardness is the driving factor for COC, which is the case in many locations. However, if silica, for example, is the driving factor, then softening will have no impact on the COC calculation as softening does not address silica.

Reverse Osmosis for Adiabatic Humidification

Adiabatic humidification is becoming increasingly popular for a variety of building types as a low energy alternative to steam humidification. While the energy benefits of adiabatic humidification are well defined, the water consumption impacts are not.

Steam Boiler Base Case

First a baseline system is established using boiler generated steam serving an air handling unit. Water consumption in direct injection steam systems takes place in both the absorption of the steam into the air as shown in Figure 4 and the generation of steam at the boiler.

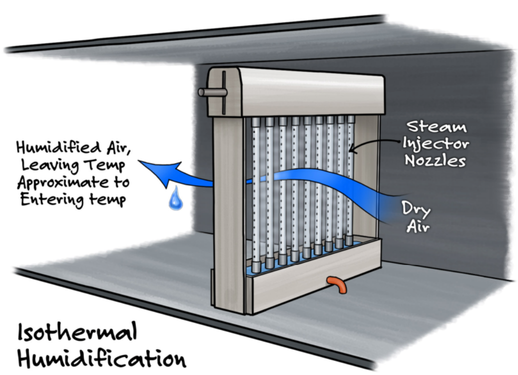

Figure 4: Steam Humidifier in Air Handling Unit (AEI 2020)

For this example; 1,000 cfm [1,699 m3/hr] at ambient conditions of 0°F [-17.8 °C], 50% RH has a humidity ratio of 0.000392 lb of water per lb of air [0.000392 kg per kg of air].

The air is heated to 75°F [23.9 °C], which corresponds to approximately 2% RH. The air is humidified isothermally to 30% RH, or 0.00542 lb of water per lb of air [0.00542 kg per kg of air].

Therefore, to humidify 1,000 cfm [1,699 m3/hr] requires 0.005028 lb of water per lb of dry air (0.005028 kg per kg of air). At 0°F [-17.8 °C], the density of air is approximately 0.0862 lb/ft3 (1.381 kg/m3), therefore 1,000 cfm (1,699 m3/hr) weighs approximately 86.2 lb (39.1 kg).

Combining the humidity ratio and the mass of the air; approximately 0.43 lb/min [0.20 kg/min] of water is injected into the air stream to reach the desired relative humidity level. Scaling the result to an hourly rate yields 26.0 lb/hr [11.8 kg/hr] or 3.1 gal/hr [11.9 l/hr].

In addition to the humidification water, the boiler generating the steam for injection consumes water via blowdown. For this example, it is assumed the boiler is generating steam at 15 psig [103 kPa] with an enthalpy of 945 Btu/lb [2,198 kJ/kg]. Generating steam at a rate of 26 lb/hr [11.8 kg/hr] corresponds to a steam production rate of 24,570 Btu/hr [25,936 kJ/hr].

The blowdown rate of a steam boiler is a function of the steam production rate, the enthalpy of steam, and a blowdown fraction that is a function of the treatment technology applied for the boiler (Betz 2014).

$$\dot{m}_{BD}\left[\frac{lb}{hr}\right] = \dot{Q}_{Steam}\left[\frac{Btu}{hr}\right] \times \frac{1}{h_{Steam}}\left[\frac{lb}{Btu}\right] \times f_{Blowdown}$$

For this example; it is assumed that only a softener is used for treatment and therefore a 5% blowdown rate is estimated. The blowdown rate is calculated to be 1.3 lb/hr [0.59 kg/hr] or 0.16 gallons per hour [0.59 liter/hour].

Finally, the softened water for the boiler will have regeneration water. At 0.16 gallons per hour [0.59 liter/hour] and 14 grains per gallon of hardness [3.7 grains/liter] the removal rate is approximately 2.2 grains per hour. At 5 gallons per 1,000 grains [18.9 liter/1,000 grains] a regeneration rate of 0.011 gallons per hour [0.04 liter/hr]. Table 4 summarizes the steam humidification water consumption per 1,000 cfm [1,699 m3/hr].

Table 4: Summary of Steam Humidification Water Consumption

1,000 CFM [1,699 m3/hr] Humidification from 0F [-18C] to 70F [24C]/30% RH		
Humidification Water	3.1	gal/hr
	11.9	l/hr
Steam boiler blowdown	0.16	gal/hr
	0.59	l/hr
Softener regeneration	0.01	gal/hr
	0.04	l/hr
Total water consumption	3.27	gal/hr
	12.53	l/hr

Atomizing Humidification

The same analysis is completed using adiabatic humidification for a 1,000 cfm [1,699 m3/hr] air flow as an alternate to steam humidification. Specifically, atomizing humidification is investigated, which brings with it numerous water treatment requirements.

Atomizing humidification is the process of injecting RO treated water through nozzles at high pressure into an air stream as shown in Figure 5.

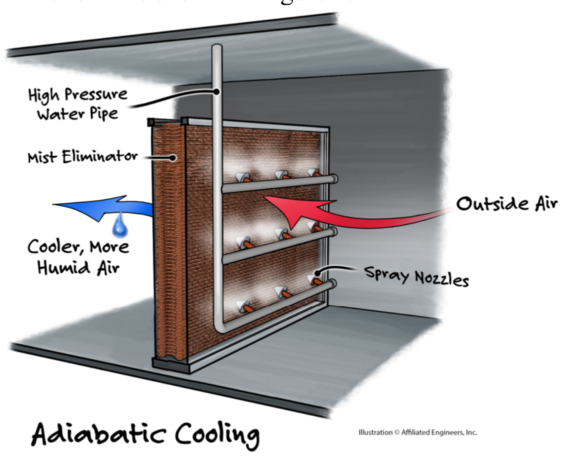

Figure 5: Diagram of adiabatic cooling in Air Handling Unity (AEI, 2020)

In contrast to direct steam injection, atomizing humidification has an absorption effectiveness of 70%, thus requiring more water than a steam injection system (Meefog, Carel, Condair). Therefore, 4.4 gal/hr (16.8 l/hr) of water are required as compared to the 3.1 gal/hr (16.8 l/hr) of steam shown in Table 4.

In order to prevent the atomizing spray nozzles from fouling as well as for air quality purposes, RO water is required in many adiabatic humidification applications (ASHRAE 170-2018).

Applying an RO system recovery effectiveness of the 75% yields a makeup water flow rate of 5.9 gal/hr (22.2 l/hr). Further, the softener is applied to this flow to protect the RO system.

Assuming a hardness of 14 grains per gallon [3.7 grains/liter] is supplied to the softener and a zero grain per gallon hardness is supplied to the RO system; 82.6 grains per hour are extracted from the supply water. Assuming a regeneration rate of five gallons per 1,000 grains (18.9 l/1,000 grains); regeneration water of 0.41 gallons per hour is anticipated [1.6 l/hr]. Table 5 provides a summary of the water flows for the atomizing humidification system.

Table 5: Summary of Atomizing Humidification Water Consumption

1,000 CFM [1,699 m3/hr] Humidification from 0F [-18C] to 70F [24C]/30% RH		
Humidification Water	3.1	gal/hr
	11.9	l/hr
Overspray	1.3	gal/hr
	5.1	l/hr
RO Efficiency	5.9	gal/hr
	22.7	l/hr
Softener regeneration	0.4	gal/hr
	1.5	l/hr
Total water consumption	6.3	gal/hr
	24.2	l/hr

Finally, there is a periodic nozzle purge that is scheduled to occur daily to ensure that the nozzles stay clean and that bacteria do not have a chance to grow in the RO water. RO water contains little to no residual chlorine, so purging is recommended. The purge is based on the volume of water within the RO pipe system so this volume will be dependent on the design of the system.

Humidification Energy

There are potential energy savings by applying atomizing humidification versus steam systems. The energy addition to the air stream is approximately the same, however the equipment efficiency may be different.

Steam boilers are generally 80-85% efficient systems and come with maintenance and safety challenges associated with steam systems.

The RO system requires energy and the evaporative cooling effects of atomizing humidification need to be offset. This typically takes the form of more preheat energy. The addition of preheat energy is approximately equal to the steam energy. For this analysis preheat is coming from heating hot water, which is relatively flexible in its generation.

Condensing boilers provide heat at efficiencies between 90-98%, and options such as solar thermal and other forms of recovered low grade heat are potentially available.

The process of making RO water and injecting it does consume energy, which as stated earlier can range between 4 and 12 kWh/m3 (0.016- 0.045 kWh/gallon).

Humidification Systems Comparison

The unit analysis above is calculated in relatively small quantities and hourly rates that make the values seem trivial for overall water consumption. To provide greater context for the impact this analysis can have on real buildings, four EnergyPlus^{TM} models are considered here that include commonly humidified building types as shown in Table 6.

Table 6: Humidification Example Building Descriptions

	Location	Area (ft2)	Outside Air (cfm)	Humidification (gal/year)	Hardness (grain/gallon)
Hospital	Ann Arbor, MI	690,000	171,600	1,012,000	7
Clinic*	Carmel, IN	84,000	31,000	68,000	11
Laboratory	Madison, WI	255,000	197,000	1,014,000	22
Office**	Madison, WI	130,000	35,000	161,000	22

*This clinic has a total energy wheel that captures and releases moisture.

**This is a class A office building that is humidified.

The humidification water shown for each example is the water calculated within the energy model for moisture added to the air stream. Subsequent analyses following the steam and atomizing methods above are shown in Tables 7 through 10.

Table 7: Summary of System and Utility Assumptions

Device	Assumed Value	Unit
Steam Boiler Eff	0.82	
Cond. Boiler Eff	0.92	
Atomizing Eff	0.7	
RO Eff.	0.75	
RO Energy Rate	0.03	kWh/gal
Nat. Gas Rate	0.50	$/therm
Electric Rate	0.10	$/kWh
Water Rate	4.00	$/kgal
Sewer Rate	5.00	$/kgal

Table 8: Water Consumption per Example Building

	Modeled Humidification (gal/year)	Additional Steam Plant Water (gal/year)	Additional Atomozing Humidification Water (gal/year)
Hospital	1,012,000	52,000	983,000
Clinic	68,000	4,000	69,000
Laboratory	1,014,000	56,000	1,130,000
Office	161,000	9,000	179,000

Table 9: Energy Consumption per Example Building

	Steam Boiler Nat. Gas (therm/year)	Atomizing System Cond. Boiler Nat. Gas (therm/year)	Atomizing System Electricity (kWh/year)
Hospital	52,000	97,000	8,773,000
Clinic	4,000	7,000	589,000
Laboratory	56,000	97,000	8,787,000
Office	9,000	15,000	1,395,000

Table 10: Economic Summary

	Total Steam Utility Cost ($/year)	Total Atomizing System Utility Cost ($/year)
Hospital	53,000	76,000
Clinic	4,000	5,000
Laboratory	53,000	77,000
Office	8,000	12,000

Table 10 demonstrates that under these conditions it costs 20-30% more to operate the atomizing system. However, when recovered heat is introduced to the analysis (assume 50%), then the analysis changes to break even as shown in Table 11.

Table 11: Economic Summary with Recovered Heat

	Total Steam Utility Cost ($/year)	Total Atomizing System Utility Cost ($/year)
Hospital	53,000	54,000
Clinic	4,000	4,000
Laboratory	53,000	56,000
Office	8,000	9,000

This analysis is very sensitive to the various utility rates and water qualities involved so it should be repeated on a case-by-case basis, as well as first and maintenance cost. In one instance, it may be economically favorable to use steam and in the next, atomizing humidification. A complete life cycle cost analysis is recommended when comparing these two system options.

VARIABLE WATER QUALITY CONSIDERATIONS

One of the challenges found in both potable and non-potable water is inconsistent water quality. For example; the city of Phoenix, AZ, has six different municipal water supplies that come from differing sources. Consequently, the water and the treatment will be variable throughout the year.

A similar issue exists in non-potable water systems that are served by multiple sources. For example; cooling coil condensate and rainwater have little to no hardness and may be seasonal, whereas, foundation drain water is effectively ground water with higher levels of hardness. Gray water (water from showers and lavatories) will likely have the same hardness as the inlet water.

Municipal non-potable water systems may have similar challenges if the sources of non-potable water vary. Managing treatment of this water can be a significant challenge especially if the systems using the non-potable water are sensitive to water quality fluctuations.

CONCLUSIONS & NEXT STEPS

Accurate quantification of water and energy consumption of HVAC systems and supporting water treatment is critical to providing informed decisions for project teams. This paper serves as a means of adding knowledge to this domain and as a guide for others to develop calculations and case studies to ensure these analyses are comprehensive in scope.

Hourly and subhourly water use data to fully validate the water models described herein. A future study focusing on individual systems and a comprehensive sensitivity analysis of the variables defined herein would provide a simpler reference for engineers planning these systems.

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