Addressing Water Consumption of Evaporative Coolers with Greywater

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ABSTRACT

Evaporative coolers (ECs) provide significant gains in energy efficiency compared to vapor compression air conditioners, but simultaneously have significant onsite water demand. This can be a major barrier to deployment in areas of the world with hot and arid climates. To address this concern, this study estimated where in the world evaporative cooling is suitable, the water consumption of ECs in these cities, and the potential that greywater can be used to reduce the consumption of potable water in ECs. ECs covered 69% of the cities where room air conditioners (ACs) are likely to be deployed, based on comfort conditions. Varying with climate, water consumption due to ECs ranged from 200 to 650 L/household/day, with the potential for greywater to provide 100% to 40% of this amount, respectively, based on conservative cooling load calculations. In the Mediterranean, the Middle East, Northern India, and the Midwestern and Southwestern United States alkalinity levels are high and water used for bleeding will likely contribute significantly to EC water consumption. Upfront costs for household GW systems are variable, however, in many cases the combined cost of an EC and GW system can be lower than comparable vapor compression ACs. Moreover, regions of the world that face problems of water scarcity find that the benefits substantially outweigh the costs.

Introduction

The use and ownership of room air conditioners (ACs) are increasing rapidly across the globe, driven by a worldwide increase of income and urbanization (McNeil & Letschert, 2008). This will lead to increased peak electricity demand and substantial additions of CO_2 to the atmosphere (Lin & Rosenquist, 2008). To mitigate the impacts of growing AC demand, policy makers and utilities turn to increased efficiency as a negative-cost solution. At the moment, efficiency standards in most countries only include vapor compression ACs. They do not address evaporative cooling air conditioners (ECs), which easily have an energy efficiency ratio (EER) an order of magnitude above vapor compression ACs.

The Technology

There are four main types of evaporative cooling technologies: direct, indirect, indirect/direct, and Maisotsenko Cycle (M-Cycle). In a direct EC, outside air is drawn through wetted filter pads, where the hot, dry air is cooled by the latent heat of evaporation. The dry-bulb temperature of the air leaving the wetted pads approaches the wet-bulb temperature of the ambient air. Since the supply air can never be colder than the wet-bulb temperature and is close to 100% relative humidity, direct ECs are most effective in dry climates (Saman, Bruno & Liu 2009). In an indirect EC, cool air produced by direct evaporative cooling transfers conductive cooling across a heat exchanger to the supply air stream. Because the evaporatively-cooled (working) air stream never mixes with the supply air, the supply air becomes cooler without an increase in its humidity. An Indirect/direct EC contains an additional stage of direct cooling after the supply air has been cooled indirectly (Saman, Bruno & Liu 2009). These technologies significantly extend the climatic extent beyond that of direct evaporative cooling.

The most recent design in evaporative cooling is the development of the Maisotsenko Cycle (M-cycle). The M-cycle works by cooling both the working air and the supply air in a number of stages. Each stage contributes to cooling by lowering the wet-bulb temperature. The cumulative result is a lower supply air temperature (close to dew-point) than is possible with conventional evaporative cooling technologies. The key difference between this and other indirect processes is that the working air that is accumulating moisture is exhausted at each stage, enabling more cooling to take place and no increase in humidity to the final supply air stream (Bisbee 2010).

Direct ECs and M-Cycle ECs represent the lower and upper bounds of the cooling spectrum, respectively. Direct ECs have the simplest design, and, therefore, are the least expensive, but are limited to very specific climatic conditions. M-Cycle ECs, on the other hand, are the most expensive due to their complex design, but are effective in the widest range of climatic conditions. This study will focus on direct ECs and M-Cycle ECs as these represent the two ends of the entire spectrum of evaporative cooling technologies in applicability, complexity, and cost.

Empirical studies show that evaporative cooling can contribute to over 10% of a household's annual water use (Bisbee 2010). Moreover, this water is consumed during the summer months, which is often associated with the dry season in the climatic regions where evaporative cooling is applicable. Although vapor-compression ACs may consume as much water as ECs when water consumed in generating electricity at the power plant is accounted for (Pistochini & Modera 2011), the water used at the power plant is not necessarily associated with areas of water scarcity. As water scarcity is often a real and significant problem in many of the areas where ECs have the potential to be deployed, the onsite water consumption of ECs must be taken into consideration and mitigated if possible.

One potential method of mitigating the amount of potable water consumed by ECs is to use greywater (GW) in these systems. GW is wastewater collected separately from sewage flow that originates from a clothes washer, bathtub, shower, and sink. It does not include wastewater from a kitchen sink, dishwasher, or toilet. In developed countries, household GW is a reliable daily source of water. On average, bath and shower water contributes 50 L per person on a daily basis and a clothes washer contributes 30 L per person per day (Willis et al. 2011).

Currently most indoor household GW systems are limited to toilet flushing. In addition to the components to store and transfer the water, a GW system used for toilet flushing needs a filtration and disinfection stage. Filtration technologies range from metal or nylon filters to depth filtration using sand or activated carbon. Disinfection is most commonly achieved through chemicals, such as chlorine and bromine, or UV radiation. As all these systems do not directly decrease biological oxygen demand (BOD) concentrations, water quality will quickly deteriorate with residence time, and if not closely monitored, fall below acceptable standards. As a result, the literature also recommends an additional biological treatment stage to reduce monitoring and maintenance and ensure acceptable BOD concentrations (Nolde 2005).

Motivation

If the deployment of ECs is to be encouraged on a large scale, the on-site water consumption of these technologies needs to be accounted for and reduced in areas of water scarcity. Several studies have addressed water consumption of ECs on a regional scale (Heidarinejad et al. 2009; Saman, Bruno & Liu 2009; Zhou et al. 2009), however, to our knowledge, no global studies have been undertaken to address this issue. This study seeks to determine where in the world residential EC cooling is appropriate and how much water is consumed by an EC in these locations on a daily basis. As utilizing GW for evaporative cooling is a novel concept, it will also discuss the feasibility of doing so, taking cost into consideration.

Methods

Global Deployment of ECs

We obtained temperature and humidity data for 1400 cities from American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. (ASHRAE 2009). We used ASHRAE guidelines to determine the most appropriate cooling technology for each city. We set a heat index of 26 °C., the upper bound of the ASHRAE summer comfort zone, as the minimum temperature for where RACs would be desired. We chose a maximum dew-point temperature of 20 °C, a suggested upper boundary for humidity (Coolerado, 2012). As direct ECs increase the humidity of the air, we chose a wet-bulb temperature of 20 °C for their upper humidity limit. In locations where ECs were applicable, we assumed that cooling was not needed during summer storms or monsoons.

We entered our results into ArcGIS, a geographic information systems software, for analysis. Because the original dataset did not contain geographic coordinates, we joined it to an existing point shapefile[1] that contained the city name, which matched 1050 cities successfully.

[1] A shapefile is a geospatial vector data format for geographic information systems software.

Water Consumption of ECs

We focused our study on the water consumption of ECs in single-family residential homes because they provide a consistent source of GW on a daily basis. The results will need to be appropriately scaled for other kinds of residential housing. The water consumed by ECs is utilized for two purposes: water evaporated to provide the cooling effect, which is directly related to cooling load, and bleed water to clean the system's components and prevent mineral build-up, scaling and fouling.

Water Consumption Due to Cooling. The daily cooling load was calculated to determine the water consumption required to cool the space. Cooling load is driven by conduction of outdoor heat into the home, solar radiation, infiltration of outside air, and generation of heat by internal sources. We based our cooling load calculations on standardized methods provided by ASHRAE (1979), which are listed in Table 1. This paper will not provide a detailed explanation of these methods, but instead will outline our assumptions. Because most design variables vary from one home to the next, we used a standard set of assumptions to provide a common comparison. We based our assumptions on regional averages where possible. Unless stated otherwise, we used the assumption that would yield the highest cooling load in order to provide the most conservative results.

Although house sizes vary across the globe, they can be categorized into two broad categories: average house size in the United States, Canada, and Australia (200 m^2); and average house size of the rest of the world (100 m^2) (BBC 2009). We used these categories to determine the dimensions of the cooled space in our model. For simplicity, we assumed a single story, a square floor plan, a flat roof, 2.5 m walls, and fenestration area of one fourth of the wall's surface area.

Coefficients of transmission (U-values), which represents the amount of heat that can be conducted through a given material, and rate of infiltration can vary significantly from one home to the next. However, we chose to use the U-values that reflected minimal insulation and maximum heat transfer into the cooled space: 0.76 W/m^2K for the roof, 0.51 W/m^2K for the walls, and 5.68 W/m^2K for windows. We used a standard infiltration rate for residential homes of 0.033 L/s (ASHRAE 1979).

For sources of internal heat generation, we assumed that lighting and load due to appliances would be negligible in residential homes compared to the overall heat gain over the course of a summer day. We assumed four occupants who are seated and/or doing light work.

The amount of water consumed by an EC for a given cooling load varies widely from one model to the next, based on the components used. Water efficiency varies from 0.45 mega joules cooling delivered per liter of water consumed (MJ/L) to 2 MJ/L. Older and cheaper models tend to use more water than newer more expensive ones. In addition, an EC's water efficiency will decrease if the actual cooling demand strays too far from the EC's rated capacity. The M-cycle EC reports an average rate of 1.44 MJ/L, but at peak temperatures it produces 1.33 MJ/L

(Kozubal and Slayzak 2010). In this study we used 1.33 MJ/L, dividing the daily cooling load by this value, to determine water consumption due to cooling.

Many of the factors that make up our water consumption calculation can be highly variable and change the final outcome significantly. To address this issue, we conducted a sensitivity analysis on a number of variables that compares the location-based water consumption range established by the model, to the amount that each variable can increase that range. The variable and their ranges are listed in Table 2.

Table 1. Equations Used to Calculate Cooling Load[2]

Load from Sunlit Roofs and Walls

q_1 = U-value × A × $\sum_{i=7}^{21}$ $CLTDcorr._i$

$CLTDcorr._i$ = $CLTD_i$ + LM + (2% design DBT - 95 deg. F)

Conductive Load through Windows[3]

q_2 = U-value × A × $\int_7^{21} t_{max}(1 - (h-h_{max}) / w)^2)\, dh$

Radiative Load through Windows

q_3 = A × $\sum_{i=7}^{21}$ $CLF_i \times SHGF_{max}$

Load due to Infiltration

q_4 = 1.1 × IR × A × $\int_7^{21} t_{max} \times (1 - (h-h_{max}) / w)^2)\, dh$

Load due to Internal Heat Gain[3]

q_5 = heat gain from occupants × # of occupants

Total Cooling Load = $q_1 + q_2 + q_3 + q_4 + q_5$

Nomenclature:

U-value = coefficient of transmission *A* = area of surface
CLTD = Coaling Load Temperature Difference
LM = Latitude Month Correction
DBT = Dry-Bulb Temperature
t_{max} = difference between 2% design DBT and indoor temp.
h = hour of the day
h_{max} = hour of day when t_{max} occurs
w = distance between h_{max} and h at the x-intercept
CLF = Cooling Load Factor for glass
$SHGF_{max}$ = Maximum Solar Heat Gain Factor
IR = Infiltration Rate

Water Consumption Due to Bleeding. The amount of water that is required for bleeding the system is dependent on the amount of dissolved minerals in the water and the technique used to wash the system. In general, more sophisticated techniques yield less water consumption (Saman, Bruno & Liu 2009). There is a general consensus that when the dissolved mineral content is higher more water is required to bleed the system. However, the relationship between water hardness and bleed rates is very complex and has not yet been established. For example, Heinemeier and Pistochini (2009) found that despite large amounts of mineral build-up in an EC system, the performance of the EC did not deteriorate significantly, and the bleed rate

[2] ASHRAE (1979) uses imperial units in all its equations and calculations. Therefore, in our methods we used imperial units in our calculations, but report all my values with metric units.
[3] The indoor temperature for all locations was set at a constant 26 deg C. We modeled the daily temperature profile of each location as a parabolic curve and integrated over this curve to calculate the daily cooling load due to infiltration and conduction through fenestration surfaces.

recommended by the manufacturer was excessive. Therefore, we did not quantify the exact amount of water due to bleeding. Instead we classified each location by the likelihood that dissolved mineral content (measured as alkalinity in mg $CaCO_3$ eq. /L) would contribute significantly to water consumption. A concentration from 0 to 60 was classified as low, 60 to 120 mg/L as medium, 120 to 180 mg/L as high, and above 180 mg/L as very high. Alkalinity data for 857 water stations was provided by the United Nations Environment Programme's Global Environment Monitoring System (Hodgson 2012).

Table 2. Variable Ranges for Sensitivity Analysis

Factor	Range		Units
	Lower Bound	Upper Bound	
Home Size (Floor Area)	75 (average home size of the UK, European country with the smallest homes)	215 (average home size of the USA, country with the largest homes)	m^2
U-Values	Roof: 0.033; Wall: 0.077; Window: 0.57 (New building code requirements in California, a state leading in building energy efficiency)	Roof: 0.76; Wall: 0.51; Window: 5.7 (minimal insulation)	W/m^2K
Shade	Full shade on East or West side of house	No Shade	N/A
Water Efficiency	0.37 (EDR 2010)	1.49 (Cooperman, Diekmann & Brodrick 2011)	L/MJ

Results and Discussion

Figure 1. Geographic Suitability of Evaporative Cooling Technologies

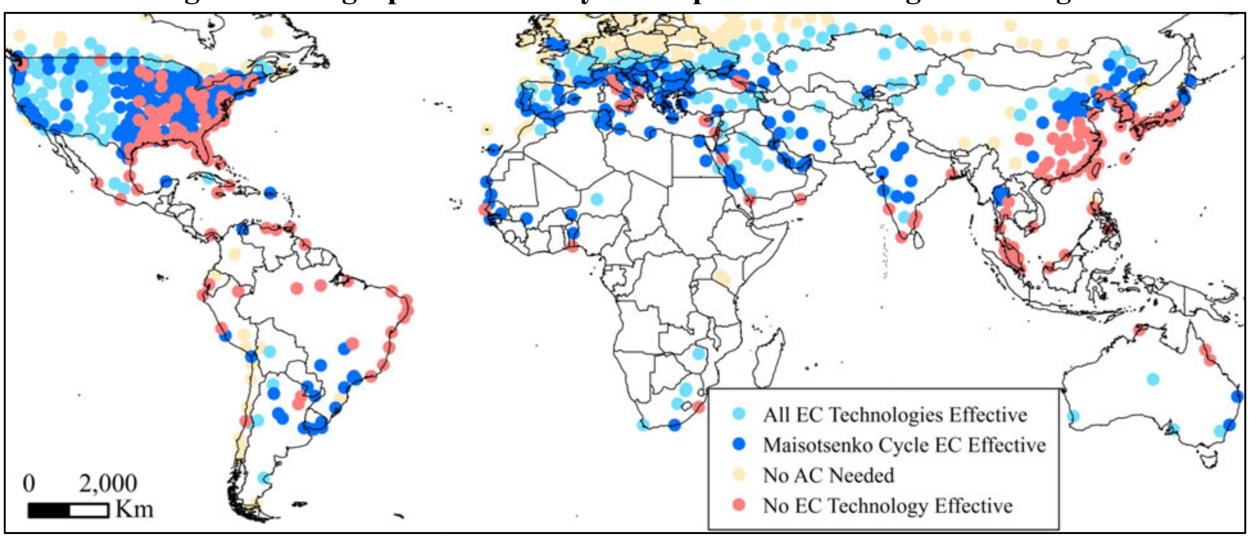


Figure 1 illustrates the areas where evaporative cooling is effective. Direct ECs and all other evaporative cooling technologies are effective for 40% of the cities where RACs are likely to be deployed, based on comfort conditions alone. The M-Cycle EC adds 200 cities to this count, increasing total EC coverage to 69% of cities. Seventeen of the 50 most populated metropolitan areas of the world (Sivak 2009) are included in this count (labeled in blue in Figure 3). Replacing vapor compression RACs with ECs in these cities would have the largest impact on reducing global greenhouse gas emissions. In addition, in many of these cities, RACs contribute significantly to the total electricity load, leading to supply shortages during peak demand times (Lin & Rosenquist 2008; Sathaye & Gupta 2010). ECs, as the most energy efficient AC, can help reduce these shortages.

Figure 2 illustrates the daily, per household water consumption of ECs. This is the amount of water that is required if the EC is running all day long. Hence, it is an overestimate of water consumption during weekdays, when much of the day is spent at work, or for low-income populations, where the amount of cooling that the EC provides is limited for financial reasons. In most cities of Europe, East Asia, and South America water consumption due to cooling is less than 300 liters/household/day (L/h/d). At this rate, GW produced by a four-person household can supply most of the water demanded by an EC. In most cities in the Middle East, South Asia, Australia and the United States, ECs consume between 300 and 500 L/h/d. GW can supply 40 to 67% of this demand, however, this percentage will increase with more people per household. Since water scarcity is a problem in these regions of the world (Smakhtin et al., 2004), utilizing GW in evaporative cooling can remove a significant barrier to the deployment of ECs and should be seriously considered.

Figure 2 also illustrates the impact that alkalinity is likely to have on EC water consumption. The Mediterranean, the Middle East, Northern India, and the Midwestern and Southwestern United States are regions with high alkalinity levels. There is a high likelihood that bleeding of ECs in these regions will contribute significantly to its water consumption. Further research is needed to be able to quantify this contribution. In these regions especially, care should be taken to encourage the use of ECs with sophisticated bleeding techniques, such as timed drain-off or salinity-level monitoring systems.

Figure 3 illustrates the results of the sensitivity analysis. The model establishes a location-based water consumption range of 450 L/h/d. Home size can increase this range by almost 300 L/h/d or 67%. Although some of this range was already captured in the model, by distinguishing homes in the United States, Canada, and Australia from the rest of the world, the sensitivity analysis emphasizes the importance of home size in cooling load and resulting water consumption due to cooling. Reducing the space to be cooled will greatly decrease energy and water consumption in these countries.

U-values can increase the range by 170 L/h/d, or 38%. The geographic range of U-values was not captured in the model. Therefore, for certain areas of world where building practices lead to decreased conduction through the building envelope, such as California and Europe, this model has over-estimated the cooling load and resulting water consumption of ECs. Including partial shading of the house in the model increased the range by 70 L/h/d or 15%. This variable had the least effect on the overall model range, although shading the roof and other parts of the house would no doubt increase the range.

Figure 2. Geographic Distribution of EC Water Consumption and Alkalinity Levels

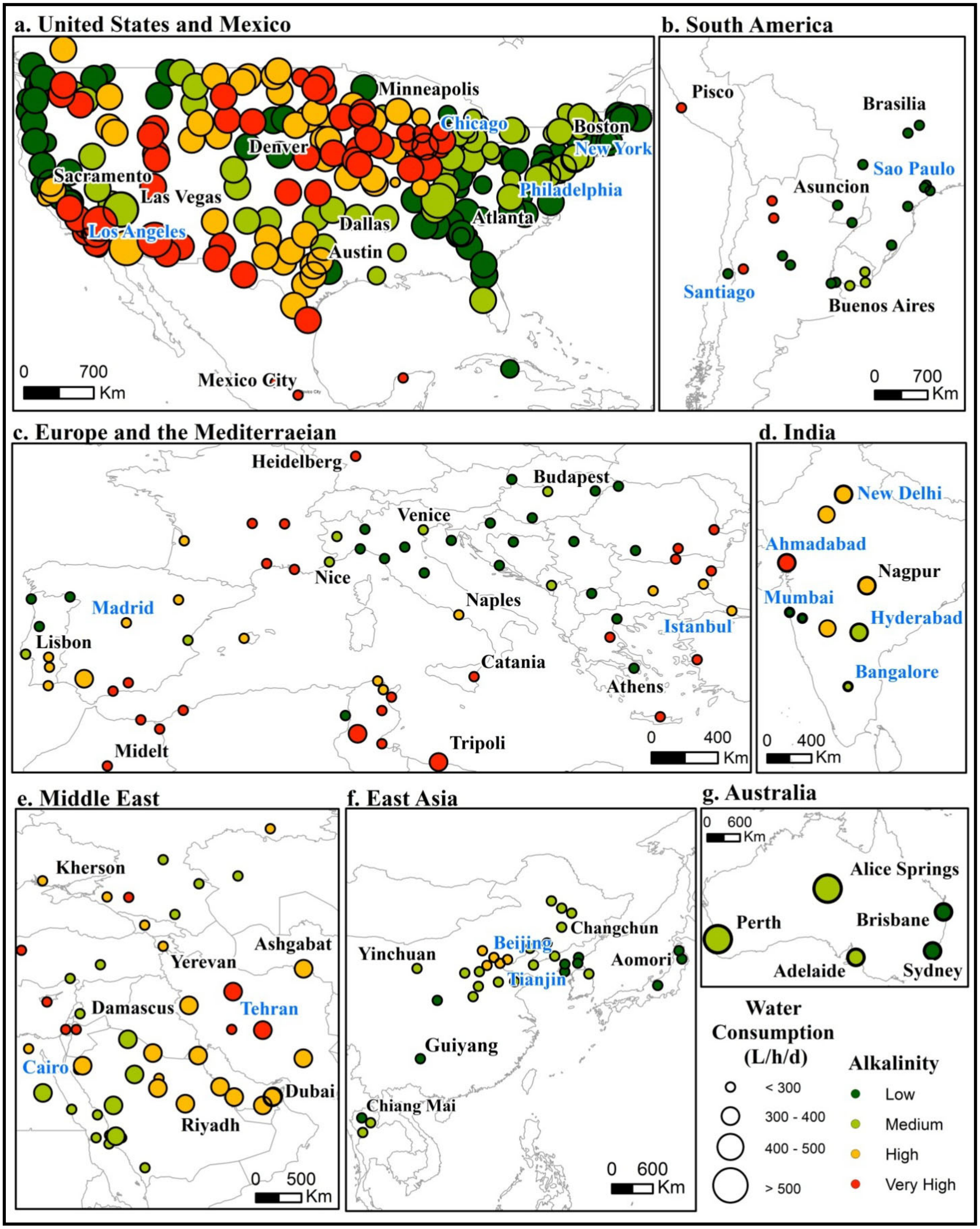
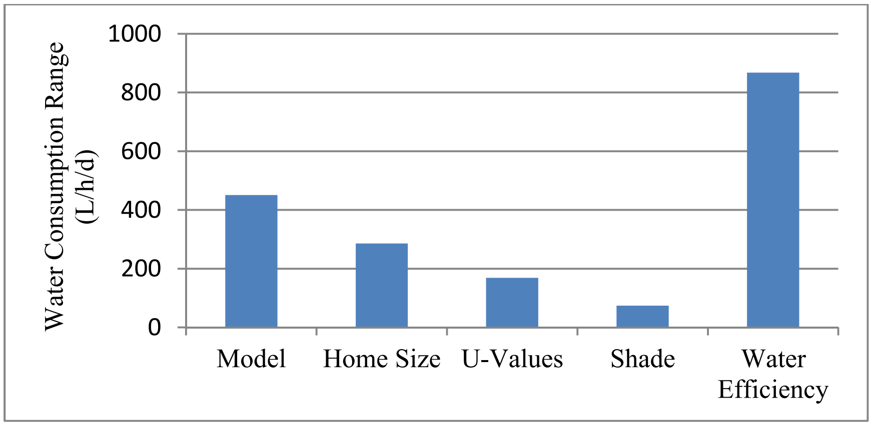


Figure 3. Results of Sensitivity Analysis: Variation in Water Consumption Range



Taking the water efficiency of the EC into account has the largest effect on water consumption, almost doubling the range of the original model. EC water consumption is highly sensitive to the technology and ECs with more sophisticated engineering (and most likely higher upfront costs) can greatly reduce water consumption. In our model we used the water efficiency of the M-cycle EC, which is relatively high, to represent the water efficiency of all ECs. Hence, the model may significantly underestimate water consumption of evaporative cooling if cheaper, less water-efficient technologies are deployed.

Comparing the results of our model to other studies can validate its accuracy. The water consumption rates predicted for China are similar to rates estimated by a regional study of evaporative cooling in China by Zhao et al. (2009). A tested M-cycle EC in Sacramento, California and a modeled direct EC in Adelaide, Australia consumed double the amount of water predicted by our model. This is most likely due to an inclusion of bleed water and a lower water efficiency ratio, respectively.

Our model demonstrates that under conservative cooling load assumptions, GW can supply 40 to 100% of the water consumed by ECs. To capture these water savings, a GW system should be modeled after systems used for toilet flushing because similar levels of human exposure are expected for direct and indirect/direct ECs. This includes a filtration, disinfection and biological control unit. The cost of a comprehensive GW system is rather variable. In Germany, the total upfront costs for the system and installation as a retrofit were 6000 USD for a single-family home (Nolde 2005). A regression analysis based on the daily treatment capacity of GW systems in Britain estimated a capital and installation cost of 3000 USD for a 200 L/day system. The cost decreased for apartment buildings, dropping below 1000 USD per home in a new building with more than ten units (Friedler and Hadari 2006). Inexpensive disinfection technologies, such as UV Waterworks^{TM}, can decrease the cost even more, bringing a single-family system down to less than 1700 USD (Gadgol 1996). In this price range, the combined cost of a direct EC and GW system is actually less than the average cost of a comparable vapor compression AC.

Several considerations should be taken into account when evaluating the cost of a GW system. First of all, in a new home the piping costs are minimal compared to the costs of the treatment equipment (Friedler and Hadari 2006). Therefore the GW system used for evaporative cooling should also be used for year-round toilet flushing – a water demand of 20 L/person/day (Willis et al. 2011) – decreasing the payback period significantly. Moreover, indirect and M-cycle ECs may not require as stringent treatment mechanisms as other ECs because the water that is evaporated never actually comes into contact with the indoor environment. Hence, the cost of the EC and the cost of the GW system should be evaluated together when deciding on which method of cooling to use.

In areas of water scarcity the benefits of a GW system are substantially higher than the costs. A benefit-cost analysis conducted on a GW system used for toilet flushing in schools in Madhya Pradesh, India demonstrated that the annualized benefits of avoiding building new infrastructure and increasing water availability amounted to 1800 USD. The annualized system costs only added up to 260 USD – a cost benefit ratio of 7 (Godfrey, Labhasetwarb & Wate 2009). This case study demonstrates that cost should not be a barrier to the deployment of GW systems in areas of water scarcity.

Conclusion

ECs provide significant gains in energy efficiency compared to vapor compression ACs, but simultaneously greatly increase the AC's onsite water demand. This can be a major deployment barrier in areas of the world that suffer from water scarcity. To address this concern, this study determined where in the world evaporative cooling is suitable. We conservatively estimated the water consumption of ECs in these cities, and the potential that greywater can be used to reduce the potable water demand of ECs.

ECs covered 69% of the cities where RACs are likely to be deployed, including 17 of the world's 50 most populous cities. Water consumption due to ECs ranged from 200 to 650 L/h/d, with the potential for greywater to provide 100% to 40% of this amount, respectively. In the Mediterranean, the Middle East, Northern India, and the Midwestern and Southwestern United States alkalinity levels are high and water used for bleeding will likely contribute significantly to EC water consumption.

Upfront costs for household GW systems are variable. They depend on the country in which they are marketed, the specific technologies used, and how many households and the type of EC that the GW system serves. In many cases the combined cost of a direct EC and GW system can be lower than a comparable vapor compression AC. Moreover, regions of the world that face problems of water scarcity find that the benefits substantially outweigh the costs.

This study demonstrates that GW systems have the potential to considerably reduce the potable water demand of evaporative coolers. Currently, it is only an introduction of concept, however, and future research is needed to test its applicability and practicality.

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