Building and Environment 68 (2013) 215–224

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An investigation of coupling evaporative cooling and decentralized graywater treatment in the residential sector

Erica R. McKenzie [a,b,*], Theresa E. Pistochini [b], Frank J. Loge [a], Mark P. Modera [a,b]

[a] Civil and Environmental Engineering, University of California at Davis, Davis, CA, USA
[b] Western Cooling Efficiency Center, University of California at Davis, Davis, CA, USA

ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form
3 July 2013
Accepted 8 July 2013

Keywords:
Air conditioning
Evaporative cooling
Graywater
Peak power
Electricity
Water-energy nexus

ABSTRACT

Total electricity and water burdens, including both direct and indirect uses, were modeled for newly constructed and 15-year-old homes in six California climate zones for three air conditioning systems: standard air-cooled condensing unit, evaporatively pre-cooled condensing unit, and an evaporative condensing unit. Compared to the air-cooled condensing unit, average annual direct electricity savings were 17.7% and 11.3% for an evaporatively pre-cooled condensing unit and an evaporative condensing unit, respectively. The evaporative condensing unit provided greater savings at peak load than the evaporatively pre-cooled condensing units (peak power savings were 30.9% and 23.8%, respectively), which is promising for hot arid climates. Total water burden reflected direct (e.g., evaporation) and indirect (i.e., electricity generation) water use. The standard air-cooled condensing unit, which had only an indirect water burden, exhibited the lowest total water burden; the evaporatively pre-cooled condensing unit and evaporative condensing unit had similar total water burdens, which were approximately double the air-cooled condensing unit's total water burden. This is because the evaporatively pre-cooled condensing unit and evaporative condensing unit both required a substantial volume of water (average 30.8 and 28.1 L/h, respectively; up to 8.5% increased water consumption for a typical household) to achieve their electricity-saving and peak power reduction benefits. This additional water burden can be offset by implementing an in-home decentralized graywater treatment and reuse plan, where shower and clothes-wash water is treated and recycled in-home for evaporative cooling as well as irrigation and toilet flushing.

1. Introduction

Electricity and water are both limited resources and the demand for both is increasing, particularly in hot, arid, and populous locations such as the United States Southwest. Electricity and water are inextricably connected, as water is required to generate electricity, and electricity is necessary to treat and convey water. Nearly twenty percent of California's electricity uses are water-related, as electricity is required for water supply and conveyance, treatment, distribution, consumption, and wastewater treatment [1]. Drinking water and wastewater treatment are electricity-consuming elements of any developed country's water system, and the electricity required for water treatment will likely increase as water quality standards are made more restrictive and as developing areas implement water treatment strategies. Electricity required to supply and convey water reflects the electricity required move water from where it is abundant to the urban and agricultural areas where it is needed, and is therefore region-specific. For example, supply and conveyance of water to southern California requires 9.4 MJ/m^3, compared to 2.0 MJ/m^3 for water delivered to northern California consumers [1]. Similarly, water is required for electricity generation. In arid U.S. southwestern states, water is consumed due to evaporation associated with electricity generation, with source-weighted average estimates ranging from 1.4 to 4.4 L/MJ of electricity produced [2]. Understanding the complete water and electricity burdens, including both direct and indirect uses, are important components of holistically evaluating a technology. Technology evaluation should include both the total burden and its temporal distribution. Unevenly distributed burdens with large spikes (i.e., high peak demand) are challenging to meet and can significantly impact infrastructure cost (e.g. excessive investment in generation and distribution).

In the hot and arid Southwestern United States, air conditioning loads are the largest contributor to electricity demand. For example, on a peak hot summer day, cooling accounts for 44% of

* Corresponding author. Civil and Environmental Engineering, University of California at Davis, Davis, CA, USA. Tel.: +1 303 384 2218; fax: +1 303 273 3413.
E-mail address: ermckenzie@ucdavis.edu (E.R. McKenzie).

0360-1323/$ – see front matter
http://dx.doi.org/10.1016/j.buildenv.2013.07.007

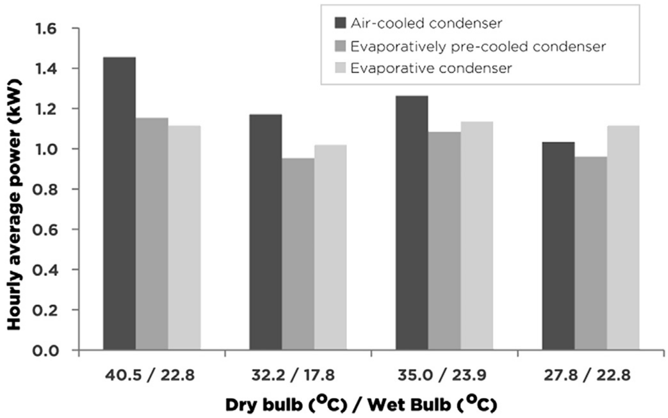

Fig. 1. Temperature-dependent nature of the hourly average power demand for a 15.8-MJ cooling load for three A/C systems in four climate conditions. The modeled air-cooled system has a coefficient of performance of 3.22 using R-22 refrigerant [8], the evaporative pre-cooled condensing unit has an evaporative effectiveness of 50% and the same air-cooled condensing unit [9], and the evaporative condensing unit has a coefficient of performance of 3.96 using R-410a refrigerant [10].

peak electricity demand in the residential sector in California [3]. Air-cooled air conditioning (A/C) systems reject heat from the condenser coil to the outdoor air via air forced over the condenser coil, and the capacity decreases and the power increases as the outdoor air dry bulb temperature increases (Fig. 1). In hot, dry climates, evaporatively-cooled technologies have been proposed as an electricity-saving alternative to standard air-cooled A/C units, however evaporating water also exerts a water burden. Evaporatively pre-cooled and evaporative condensing units are two evaporative cooling technologies that are being evaluated due to their improved efficiencies at elevated temperatures. The former is an after-market addition to a conventional air-cooled A/C, and the latter is a commercially available A/C system specifically designed to use water for cooling the refrigerant. Evaporative pre-cooled condensing units are air-cooled condensing units with an after-market addition of misting nozzles or a wetted pad to cool the outdoor air entering the condensing unit. The theoretical limit of cooling for evaporative pre-coolers is to the outdoor air wet-bulb temperature (T_{WB}), which on a peak summer day in dry climates may be 17–23 °C cooler than the T_{DB}. Evaporative condensing units have a combination of water and air flowing directly over the condenser coil and heat from the condenser is rejected into the water and air streams. In hot, arid locations, evaporative cooling technologies outperform conventional air-cooled A/C systems, and as shown in Fig. 1, the benefits of evaporative cooling over air-cooled systems increase at higher temperatures.

To protect human health and ensure long-term performance, the water used in evaporatively cooled technologies must be high quality, but does not need to be drinking water quality. For non-drinking water applications, the use of lower quality water from a variety of sources has been advocated [4]; these alternate sources include graywater. Graywater is water that has been used, but is only minimally contaminated. In the home environment, this typically includes shower water, clothes washing water, and non-kitchen sink water. For this reason, treated graywater is being proposed as a water source for evaporative cooling equipment to eliminate the additional water burden.

In this study, three residential-scale A/C system types are modeled: air-cooled condensing units, evaporatively pre-cooled condensing units, and evaporative-cooled condensing units (Fig. 2). In the air-cooled condensing unit (Fig. 2, left) the outdoor air enters the condensing unit, removes heat from the condensing coil, and exits to the atmosphere. In the evaporatively pre-cooled condensing unit (Fig. 2, middle), water is evaporated into the outdoor air stream which decreases its dry bulb temperature. The pre-cooled air then enters a condensing unit identical to the air-cooled system. In the evaporative condensing unit (Fig. 2, right), the water evaporation process happens inside the unit. Re-circulated water is sprayed over a copper condensing coil while outside air enters the unit, absorbs both heat and moisture, and exits to the atmosphere.

For both types of evaporative cooling systems, drinking water and treated graywater are evaluated as water sources. The objectives of this study are to use modeling to: (1) evaluate direct and indirect electricity and water burdens associated with three residential-scale A/C systems, (2) evaluate the implications of the three A/C systems on peak electricity demand, (3) evaluate the implications of graywater reuse on total and peak water consumption, and (4) discuss the implications of coupling decentralized graywater treatment for reuse in and around the home, including with an evaporative condensing unit.

2. Materials, methods, and calculations

This study employs the results of previous experimental work on the effects of weather on air-cooled condensing units, evaporatively pre-cooled condensing units, and evaporative-cooled

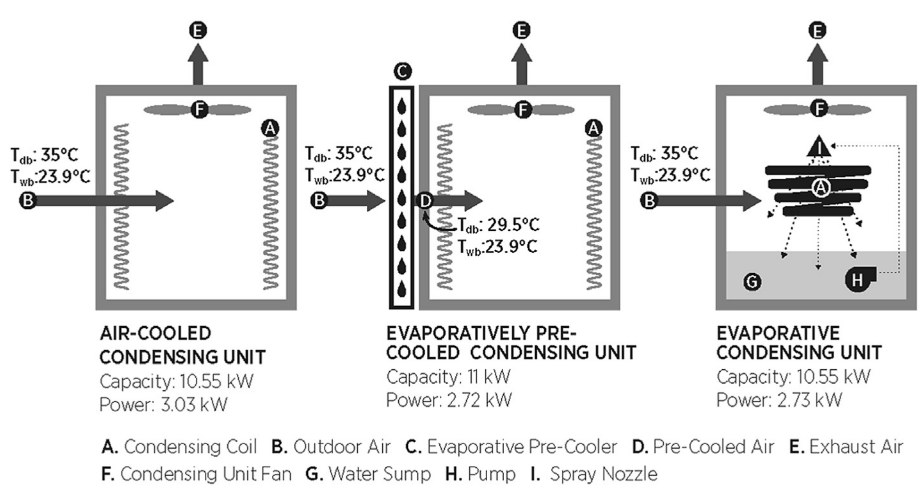

Fig. 2. Schematics showing air and water flows of an air cooled condensing unit, evaporatively pre-cooled condensing unit, and an evaporative condensing unit.

condensing units. In this study, the previous experimental results are applied to cover a full year's typical weather in six California climate zones. Using this approach, the empirical effects of weather can be more fully understood as they pertain to total electricity consumption, peak power demand, and water-energy interconnectedness. Via the model, confounding factors such as home construction and consumer behavior are avoided, and are not a component of this study.

2.1. Modeled home and cooling loads

A one-story, three-bedroom, four-occupant home was used as the stereotypical single-family residence. The home had a foot print of 164 m^2 with 450 m^3 conditioned volume which was treated as a single zone. Micropas v8.1, a California Energy Commission approved building modeling program, was used to estimate cooling loads for a new home and a 15-year-old home, where the new home had better insulation and windows. Micropas modeling, employed for six of sixteen California Energy Commission defined climate zones, covered a one-year timespan, with hourly resolution, employing typical meteorological year data. The simulated cooling loads are shown in Table 1. The baseline home air conditioning was achieved with an air-cooled condensing unit, and an evaporatively pre-cooled condensing unit or an evaporative condensing unit are examined as alternatives. The baseline home was also assumed to not reuse water (i.e., all consumed water is drinking water quality), but three graywater reuse scenarios are later examined. The household was assumed be a typical California household for electricity and water consumption, and total household annual consumption values were 23.8 GJ [3] and 659 m^3 [5] for electricity and water, respectively. For the purposes of economic analysis, the residential electricity rate was assumed to be $0.154/kWh (California 2011 residential average [6];), and the residential water rate was assumed to be $1.04/$m^3$ (average of Fresno, San, Diego, San Jose, and San Francisco [7]).

2.2. Cooling related electricity use in baseline and treatment homes

The power and cooling capacity of three cooling technologies physically tested in previous research, and their observed temperature-dependent trends, were scaled to reflect a 10.55 kW capacity unit at outdoor ambient conditions of 35 °C dry-bulb and 29.3 °C wet-bulb and used to inform the model in this study. The model was built using data from the three following laboratory experiments:

1. Air-cooled air conditioner: Faramarzi et al. [8] laboratory-tested a standard air-cooled condensing unit (17.58 kW at 35 °C dry-bulb with R-22 refrigerant) across six dry-bulb temperatures (T_{DB}) from 29 to 54 °C.
2. The same air-cooled air conditioner described in (1) retrofitted with an evaporative pre-cooler. The evaporative effectiveness of the pre-cooler (T_{DB} to T_{WB} conversion efficiency) was ~50% when averaged over all weather conditions that occurred during a field study in Davis, CA [9].
3. An evaporative condensing unit (10.17 kW at 35 °C dry-bulb and 23.9 °C wet bulb) with R-410a refrigerant was laboratory tested at ten ambient conditions representative of select California climate zones [10].

The appropriate temperature-dependent relationships are shown in Table 2 and the A/C system dependencies are as follows: air-cooled condensing unit performance depended on the dry bulb temperature (T_{DB}), the evaporative condensing unit performance depended on wet bulb temperature (T_{WB}), and the evaporatively pre-cooled condensing unit performance depended on both T_{DB} and T_{WB} (Table 2 equation (3)). For the evaporatively pre-cooled unit, the dry bulb temperature leaving the pre-cooler (T_{PC}) was calculated and applied as the entering air temperature for the air-cooled system. For the air-cooled, evaporatively pre-cooled, and evaporative condensing unit air conditioning systems, the temperature-dependent capacity (kW; Table 2 equations (1), (4) and (7)), the temperature-dependent power (kW; Table 2 equations (2), (5) and (8)), the fractional on-time to meet the simulated load (h; cooling load divided by capacity), and the electricity consumption (kWh; product of fractional on-time and power) were calculated for all three A/C systems for each hour of a modeled year. The average of the electricity consumption over the hour is also referred to as the hourly average power (kW). Peak demand was defined as the hour with the highest cooling demand.

Electricity required to supply, convey, treat, and distribute drinking water, and to treat wastewater were also included in a region-specific manner (northern California or southern California), where supply, conveyance, treatment, and distribution were applied to all drinking water, and electricity for wastewater was only applied as appropriate. The drinking water electricity total intensities were 0.9 kWh/m^3 in northern California and 2.9 kWh/m^3 in southern California, and 0.5 kWh/m^3 for wastewater treatment [1].

2.3. Cooling related water use in the baseline and treatment homes

Total water use includes both onsite use as well as indirect water consumption for electricity generation. Cooling related water consumption reflects both of these components. Water was directly

Table 1
Characterization of six California climate zones and modeled cumulative annual cooling load.

California climate zone	California reference city	CDD at refrence city (°C)[a]	Annual cooling load (GJ)	
			15-year-old home	New home
CZ02	Napa	556	11.4	6.9
CZ09	Los Angeles civic center	813	21.5	15.1
CZ10	Riverside	1015	26.1	21.1
CZ12	Stockton	739	23.2	13.3
CZ13	Fresno	1249	42.9	28.6
CZ15	El Centro	2449	72.9	57.1

[a] CDD is cooling degree day; using hourly data, applicable for hours where T(dry bulb) > T(reference), CDD = [T(reference)−T(dry bulb)]/24, where T(reference) = 18.3 °C.

Table 2
Air-conditioner modeling calculations. T_{DB} is the dry-bulb temperature, $T_{DB,ref}$ = 35 °C, T_{WB} is the wet-bulb temperature, $T_{WB,ref}$ = 23.9 °C and T_{PC} is the post-evaporative pre-cooler dry-bulb temperature.

Equation	System component	Calculation	Source
Air-cooled condensing unit			
1	Capacity (kW)	$-0.081 \times (T_{DB}-T_{DB,ref}) + 10.55$	[8]
2	Power (kW)	$0.056 \times (T_{DB}-T_{DB,ref}) + 3.03$	[8]
Evaporatively pre-cooled condensing unit			
3	Pre-cooled T (°C; T_{PC})	$T_{DB}-0.5 \times (T_{DB}-T_{WB})$	[9]
4	Capacity (kW)	$-0.081 \times (T_{PC}-T_{DB,ref}) + 10.55$	[8]
5	Power (kW)	$0.056 \times (T_{PC}-T_{DB,ref}) + 3.03$	[8]
6	Water (L/hr)	30.82	[8]
Evaporative condensing unit			
7	Capacity (kW)	$-0.087 \times (T_{WB}-T_{WB,ref}) + 10.55$	[10]
8	Power (kW)	$0.026 \times (T_{WB}-T_{WB,ref}) + 2.73$	[10]
9	Water − evaporation (L/hr)	$0.403 \times (T_{DB}-T_{WB}) + 15.8$	[10]
10	Water − bleed (L/hr)	6.85	[10]

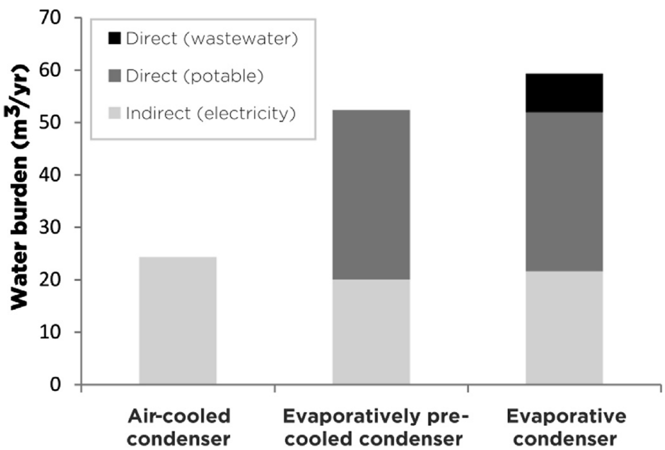

Fig. 3. Total annual water burden associated with cooling a 15-year-old home in climate zone 13 (e.g., Fresno).

consumed in the evaporative-cooled technologies (i.e., the evaporative pre-cooled condensing unit and the evaporative condensing unit). The evaporatively pre-cooled condensing unit consumed 30.82 L/full load hour ([9]; Table 2 equation (6)). The evaporatively pre-cooled condensing unit supplied water via misting nozzles at a constant flow rate independent of temperature. This pre-cooler configuration is currently purchasable, through other evaporative pre-coolers configurations (e.g., a temperature-dependent water-use rate unit) are also available.

In evaporative condensing units, water is consumed via evaporation and also for a bleed to remove dissolved solids that would otherwise accumulate in the system. The evaporation rate was dependent on the wet bulb depression (T_{DB}–T_{WB}; Table 2 equations (7)–(9)). The system bleed rate was assumed to be 6.85 L/h (Table 2 equation (10)), which was the average bleed rate among the laboratory test conditions [10]. Bleed water is assumed to be sent to the wastewater treatment plant (this assumption is discussed later).

Indirect water use for electricity generation was assumed to be 2.15 L water/MJ electricity [2] and was added to the total direct water burden of each cooling system based upon its electricity consumption.

2.4. Graywater production and treatment

Graywater sources considered in this study included clothes-washing effluent and shower water. It was assumed that each occupant took a daily shower lasting 8 min with 9.5 L/min water consumed. The household was assumed to wash seven loads of laundry each week, and each laundry load required 68 L. Many graywater treatment trains have been proposed, tested, and put into practice. Their mechanisms, capital cost, operation and maintenance, energy intensity, and effectiveness vary [11]. The energy intensity of residential graywater treatment is currently unknown and likely varies with the treatment system and source water, but for this analysis it is assumed to require negligible electricity; this assumption is evaluated later. The graywater treatment train capacity is assumed to be 2000 L, and graywater that cannot be stored is assumed to be processed as wastewater. Beneficial reuse of treated graywater reduced the household's wastewater volume and in some reuse scenarios displaced baseline drinking water use. The embedded electricity implications of avoided wastewater and displaced drinking water were included at their appropriate values.

2.5. Demonstration home

Electricity and drinking water-use records were obtained for a one-story, three-bedroom, four-occupant home located in Davis, California. The electricity record had hourly resolution. Time-of-day-dependent baseline electricity was averaged for one month in which no heating or cooling was employed. Baseline water use was based on one year's worth of water use with bimonthly resolution (~60 day cycles). Monthly baseline water use was approximated via interpolation. The produced data (Figs. 4B and 6) are intended for demonstration purposes.

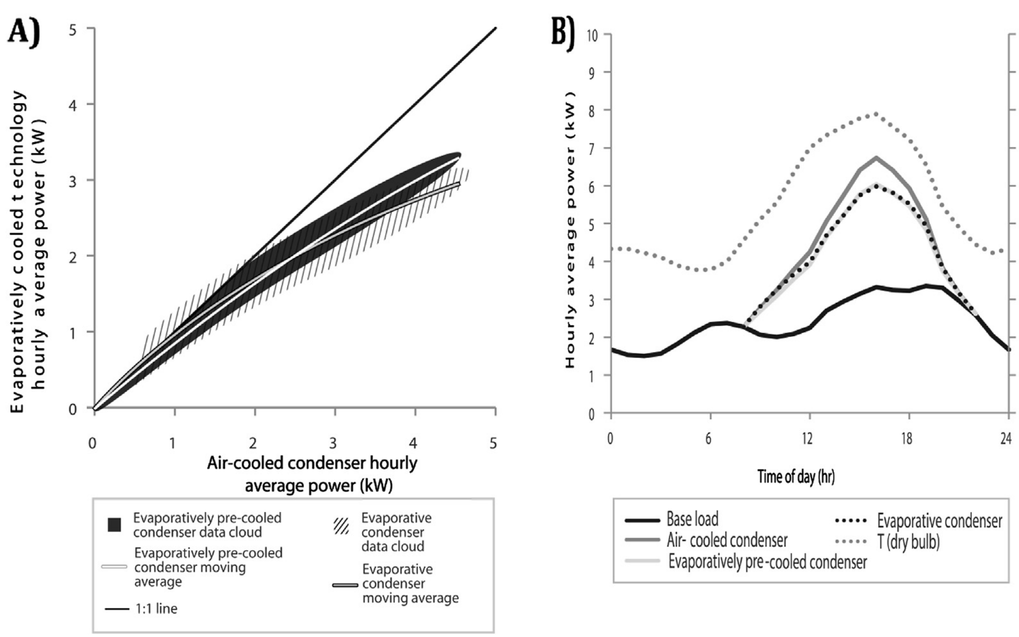

Fig. 4. Contrasting system power demands for evaporative cooling technologies and air-cooled A/C units based on modeled load and system performance. A) Modeling data points for new and old houses in six California climate zones (2, 9, 10, 12, 13 and 15) with a 1:1 line included as a reference. The data cloud represents the distribution of points for a given evaporatively-cooled technology; due to the number and overlap of points, individual points are not shown. B) The demonstration 3-bedroom, 4-occupant home in climate zone 12 and the effect of the three cooling technologies on peak electricity demand.

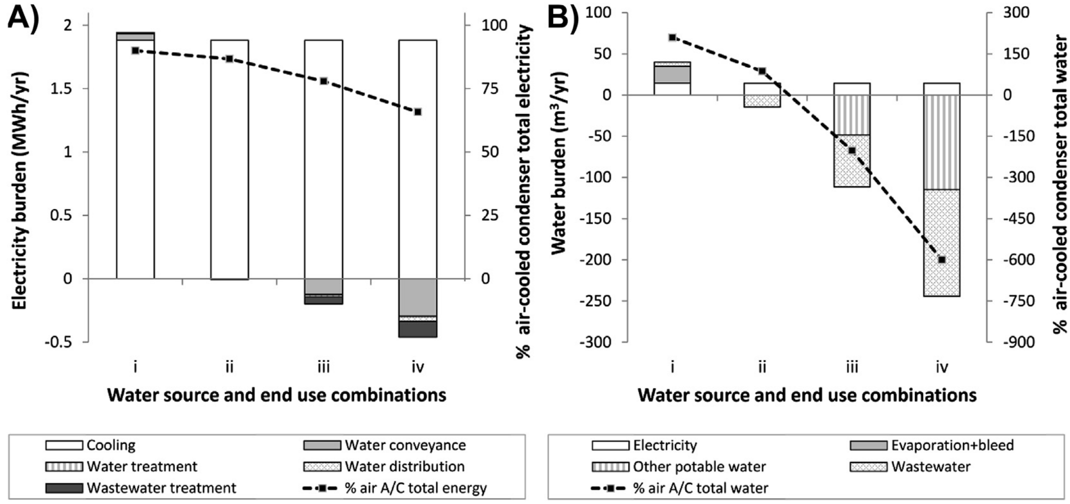

Fig. 5. Comparison of total annual A) electricity and B) water burdens for various evaporative condensing unit-graywater coupling schemes for a new home in climate zone 13 (e.g., Fresno). The line represents the evaporative condensing unit A/C and graywater systems' combined performance compared to an air-cooled A/C system with no graywater reuse. The four displayed scenarios are evaporative condensing units with: i) no graywater (i.e., all drinking water); ii) graywater used only with an evaporative condensing unit; iii) graywater used with an evaporative condensing unit and for irrigation (May–Oct); and iv) all graywater assumed to be beneficially reused. Note that 100% of air-cooled A/C indicates that the systems exert an equivalent burden.

3. Results

Previously recorded empirical temperature-dependent effects on three residential-scale condensing units were used to inform models that encompassed six California climate zones across one full year of typical weather. The following sub-sections discuss this study's results on electricity consumption, peak power demand, and water consumption (total and temporal distribution). Additionally, the potential costs and benefits of a decentralized greywater treatment and reuse opportunity are evaluated.

3.1. Water and electricity burdens for three residential A/C systems

Cooling loads and associated electricity consumption varied widely among the six analyzed California climate zones (Table 1). The direct electricity and water burdens associated with cooling 15 year-old homes with each of the three cooling systems are shown in Table 3; results for a new home's electricity and water burden are shown in the appendix (Table S1). A climate zone 12 study of field-placed residential units found that, on average, 462 kWh/yr electricity were saved through the use of an evaporative condenser compared with an air-cooled condenser [12]. The modeled electricity savings found in this study for climate zone 12 (102 and 134 kWh/yr for a new and 15-year old home, respectively) were less than observed, which may be due to differences in weather patterns, home size, home construction, or consumer behavior, however it indicates that the electricity savings may be more than this study predicts. Total electricity use was dominated by the cooling unit (direct electricity use; Table 3), which accounted for > 96% of cooling-related electricity for all modeled homes and A/C units (demonstrated in Fig. 5A, column i; i.e., <4% of electricity was devoted to water-related electricity expenditures). Total and direct electricity burdens were greatest for the standard air-cooled condensing unit, and annual total electricity savings were 15.3 and 9.0%, respectively, for evaporatively pre-cooled air and evaporative condensing unit units. Older homes have larger cooling loads due to simulation assumptions that older homes have less insulation and higher infiltration rates. The increased cooling loads result in increased electricity consumption to cool the older home, which lead to increased nominal direct electricity savings (MWh/yr) but decreased percentage electricity savings when evaporatively pre-cooled condensing units or evaporative condensing units were employed. For example, a new home in Fresno, CA could realize electricity savings of 0.39 MWh/yr (18.0%) or 0.28 MWh/yr (12.9%) for an evaporatively pre-cooled and evaporative condenser units, respectively, compared to the baseline home with an air-cooled condensing unit. For a 15-year old home in Fresno, the electricity savings would be 0.56 MWh/yr (17.6%) and 0.36 MWh/yr (11.3%) for an evaporatively pre-cooled and evaporative condenser units, respectively. Electricity savings for all climate zones for new and 15-year old homes are included in the appendix (Tables S1 and S2).

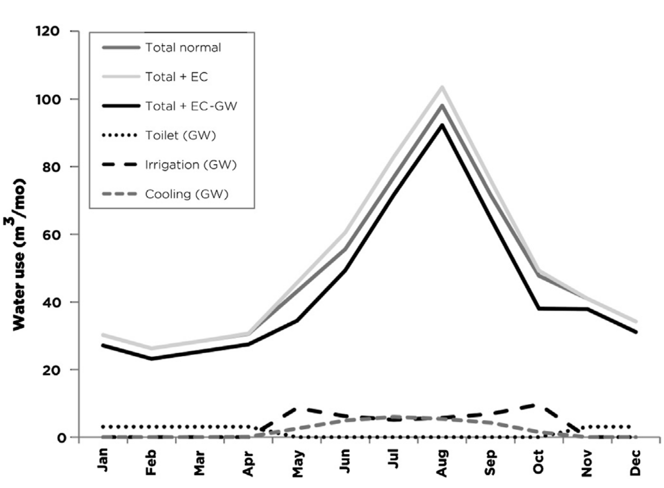

Fig. 6. Effect of graywater reuse on a home's drinking water consumption, where graywater (GW) is reused for evaporative condensing unit (EC) cooling, landscape irrigation, and toilet flushing. Solid lines represent drinking water use. Dotted and dashed lines represent graywater applied to the particular end uses.

Evaporatively cooled technologies result in electricity savings, but require direct water consumption. Considering only annual cumulative direct electricity and water use, the evaporatively pre-cooled condensing unit used 59 L water/kWh electricity saved, while the evaporative condensing unit used 101 L water/kWh

Table 3
Annual direct electricity and water burdens to cool a 15-year-old house.

California climate zone	Air-cooled condenser		Evaporatively pre-cooled condenser			Evaporative condenser		
	Full load (h)	Electricity (MWh)	Full load (h)	Electricity (MWh)	Water (m^3)	Full load (h)	Electricity (MWh)	Water (m^3)
CZ02	290	0.8	276	0.7	8.5	284	0.7	7.9
CZ09	545	1.5	524	1.3	16.2	546	1.4	14.7
CZ10	670	1.9	638	1.6	19.6	656	1.7	18.4
CZ12	591	1.6	565	1.4	17.4	585	1.5	16.1
CZ13	1102	3.1	1049	2.6	32.3	1080	2.8	30.3
CZ15	1916	5.8	1798	4.6	55.4	1828	4.7	53.8

electricity saved. The evaporatively pre-cooled condensing unit and evaporative condensing unit A/C systems used similar amount of water on site (direct use; demonstrated in Table 3), but the evaporatively pre-cooled condensing unit produced greater electricity savings.

A 15-year-old home in climate zone 13 (e.g., Fresno) would directly consume 30.3 m^3 of drinking water for cooling with an evaporative condensing unit, which is a 5% increase in the home's total annual water consumption. The apportioned total water consumption for all three cooling technologies is shown in Fig. 3. Total electricity and water burdens vary dependent on the cooling load and thus climate zone (as well as inhabitant choices), but exhibit similar trends. Water burden in the conventional system was entirely associated with electricity generation, while in evaporatively pre-cooled air or evaporative condensing unit A/C systems there was an additional water burden due to water evaporation and bleed. Note that the bleed is counted as both a drinking water burden and as a wastewater burden, on the assumption that it is disposed of as wastewater. Bleed water has been used for landscape irrigation, which would nullify the wastewater burden, however the bleed water's elevated salinity may be detrimental to the landscape, soil, and nearby ecosystem. The total water burden of the evaporatively-cooled systems was approximately double that of the air-cooled A/C system, depending on climate zone (evaporatively pre-cooled condensing unit: 201–226%; evaporative condensing unit with bleed disposed of as wastewater: 227–255%).

3.2. Evaporative condensing unit effects on peak electricity demand

Electricity and water demands have seasonal and diurnal variability [3,13,14]; increased demand requires either storage capacity within the system (e.g., batteries, water towers), or that additional infrastructure/capacity can be brought online quickly to meet demand (e.g., backup plants). Both options are costly and typically result in decreased system-wide efficiency. Therefore, both for electricity and water, reducing peak demand can be as important as reducing total quantity consumed.

In arid regions like California, the economic impact of peak electricity demand can be as large as the economic implications of total consumption. Residential A/C accounts for 2% of California's total annual electricity consumption, but accounts for 15% of peak electricity system-wide demand and 44% of the demand from the residential sector, giving it the highest peak-load to electricity consumption ratio of any California end use sector [3]. Therefore, the value proposition for electricity savings from evaporatively-cooled technologies is associated with peak load reduction. Fig. 4A contrasts modeled air-cooled and evaporatively-cooled technologies power demand based on hourly data with a cooling burden (21,133 points across all modeled climate zones). The data show that the evaporative condensing unit savings increase as demand increases. Based on these modeling results, evaporative condensing units reduced peak hourly average power demand by up to 1.40 kW (30.9% reduction) compared to the baseline residential A/C system, while evaporatively pre-cooled condensing units reduced hourly average peak demand by up to 1.08 kW (23.8% reduction). Fig. 4B shows the hourly demand for the demonstration home in climate zone 12 on a hot day; the figure includes the demonstration home's observed base load (no heating or cooling) with the modeled cooling loads for the three technologies superimposed. Fig. 4B further demonstrates the contribution of cooling to peak load and the potential for evaporatively-cooled technologies to reduce this peak load. Based on results from an evaluation of field tested units in climate zone 12, an evaporative condensing unit would reduce average peak demand by 0.23 kW per ton of nominal capacity and maximum peak demand by 0.27 kW per ton of nominal capacity on a peak day [12]. This is similar to the modeled climate zone 12 new home and 15-year old home peak power reduction values of 0.24 and 0.25 kW per nominal ton, respectively, calculated in this analysis. Owing to this potential, several utility companies (e.g, Sacramento Municipal Utility District (California), Southern California Edison (California), and Xcel Energy (Colorado)) offer or have offered rebates for the purchase of evaporatively-cooled technologies. Xcel Energy's review of its electric program components determined that residential evaporative cooler rebates achieved the highest cost effectiveness score of all assessed residential and business sector approaches [15].

Based on these analyses, it can be seen that evaporative condensing units produce a slightly greater total electricity and water use than evaporatively pre-cooled condensing units, however in hot, dry climates, they can also produce larger peak power demand savings. The marginal costs associated with peak power demand are greater than base load, and therefore the associated positive impacts with peak power demand reduction are also greater. An evaporatively pre-cooled air A/C should be considered as a retrofit option for an existing air-cooled A/C system that will result in total electricity and peak demand reductions, at a modest increase in direct water burden. By contrast, the evaporative condensing unit provides slightly lower cumulative electricity savings with comparable water burdens, but yields greater peak power demand savings. Evaporative condensing units should therefore be considered the better choice for new construction in hot dry climates where peak power demand reduction is an important consideration.

3.3. Impact of using graywater for evaporative cooling

Evaporatively-cooled technologies directly and indirectly consume water, and the timing corresponds with typical annual peak water consumption (summer, largely for irrigation needs), but graywater reuse offers the potential to offset that burden. Graywater is produced onsite at the residence and is conventionally thought of as a waste stream, though in this scenario, graywater is considered an asset to be used in place of drinking water. In a four-person household, where each person showers daily and there are seven loads of laundry per week, the annual total graywater volume is 134 m^3/yr, which considerably exceeds the water demand for the evaporatively pre-cooled condensing unit or evaporative condensing unit technologies (modeled evaporative technology direct water use range for a new home was 8–55 m^3/yr). Because installing the components necessary for a graywater treatment system (i.e., dual plumbing and treatment train) is most easily accomplished during construction, the following contrasts are based on a newly constructed home with graywater treatment and an evaporative condensing unit, though the implications on water burden would be similar for an evaporatively pre-cooled condensing unit. Four graywater reuse scenarios are evaluated: (i) no graywater; (ii) graywater is reused for the evaporative condensing unit only; (iii) graywater is reused for the evaporative condensing unit and for landscape irrigation, where irrigation is assumed to occur only during the six-month period between May and October, and (iv) beneficial reuse is found for all of the household's graywater.

As shown in Fig. 5, both electricity and water savings can be achieved by coupling graywater and evaporative condensing unit systems, where the magnitude of savings depends on the reuse scenario. Reasonable electricity savings (215 kWh or 10% of total annual cooling-related electricity consumption for a new home in climate zone 13) can be gained by using an evaporative condensing unit with drinking water (column i) rather than an air-cooled condensing unit; however, this option has approximately double the total water burden as compared to an air-cooled condensing unit. The use of treated graywater with an evaporative condensing unit (no other beneficial reuses; column ii) further reduced total electricity use minimally (70 kWh annually) compared to column i, and results in a decreased water burden compared with that of an air-cooled condensing unit (i.e., the total water burden of an evaporative condensing unit with graywater is 86% of an air-cooled condensing unit). Total water and electricity savings increase when graywater reuse options are expanded to include landscape irrigation (column iii) or if all graywater is beneficially reused (column iv), where "beneficial use" could include winter landscape irrigation and toilet flushing. In columns iii and iv, graywater reuse obviates a drinking water burden, thus the total water burden and the comparison to air-cooled A/C become negative, indicating that the unit is a resource rather than a burden. For a new home in climate zone 13 (e.g., Fresno) that had an evaporative condensing unit and beneficially reused all graywater, direct and total annual electricity consumption were reduce by 278 kWh and 738 kWh, respectively. The same home reduced direct drinking water consumption by 115 m^3, reduced wastewater production by 129 m^3, and reduced electricity generation-associated indirect water burden by 2 m^3.

California water utilities are required by the state constitution to reduce total and peak water demand, and often use water price structures to help satisfy this mandate. Various water pricing schemes have been employed in an effort to curb drinking water consumption, but water demand, particularly for indoor water use, has been demonstrated to be fairly inelastic [16]. For a water pricing structure to influence residential water consumption, households must be informed about the pricing structure and be willing to make behavioral adjustments [14]. Graywater reuse is an alternative approach to total and peak water demand reduction and has been demonstrated to reduce total and peak drinking water consumption [13], however traditional graywater treatment and reuse is also infrastructure intensive (i.e. dual piping). Using graywater to irrigate landscapes can help alleviate some peak demand. Decentralized graywater treatment and reuse offers total and peak drinking water demand reduction benefits, but decreases the amount of dual piping required. The potential drinking water reduction for a CZ 12 home is shown in Fig. 6, where water is reused for the evaporative condensing unit, for summer landscape irrigation, and for toilet flushing. Given the conservative graywater production estimates used in this study, it is expected that graywater reuse for irrigation could replace approximately 12% of a household's summer landscape irrigation (about 50 m^3).

4. Discussion

4.1. Benefits of coupling evaporative condensing A/C with treated graywater

Coupling graywater reuse and evaporative condensing units would reduce total and peak electricity and water burdens. There are, however, other potential benefits of the coupled system: 1) appropriate pairing of the water source quality and use optimizes water treatment burdens, and 2) graywater reuse could potentially enable evaporative condensing unit water management strategies that minimize mineral scale formation (e.g. increased purge frequency or bleed rates). Both ancillary benefits should result in reduced total electricity consumption.

Efficiencies in the water system can be realized by appropriately pairing source water quality with the intended use, where embedded electricity is reduced by decreased treatment rigor. Decentralized water treatment also essentially eliminates conveyance burdens, though limited on-site pumping may be required. The importance of these efficiencies is likely to be amplified as drinking water demand increases (e.g, population growth [4]) and as drinking water and wastewater regulations become more restrictive resulting in required additional treatment with the associated additional costs [1]. For example, in 2001 the U.S. standard for arsenic in drinking water was reduced (from 50 μg/L to 10 μg/L) at an estimated annualized national cost of $181 million [17]. Evaporative condensing units do not require drinking water, which is required to be very high quality so that human health is not endangered [18], while reuse of non-drinking water for appropriate purposes would avoid the additional associated cost. The use of alternative water sources and water reuse for designated-appropriate purposes has been encouraged, and water reuse is increasing 15% each year [4]. In California, graywater for evaporative condensing units must be disinfected tertiary water, meaning it has been coagulated, filtered, oxidized, disinfected and meets turbidity, coliform, and coliphage standards; this is the highest-quality recycled water and can therefore be used for any purpose where recycled water is acceptable, including landscape irrigation, toilet flushing, and decorative fountains [19].

Scale formation on an evaporative condenser coil can reduce heat transfer and impede airflow, resulting in decreased evaporative condensing unit efficiency. The modest direct water burdens calculated in this study would increase if higher bleed rates were employed; evaporative condensing unit water management research is on-going to determine the optimal bleed rates for long-term evaporative condensing unit performance. For some water chemistries, high bleed rates may reduce mineral scale formation and therefore improve long-term evaporative condensing unit performance. In locations where a large direct water burden exists (due to either high use and/or elevated bleed rate), an alternative water source is particularly important due to the volume of water. If a higher bleed rate were found to be beneficial, the bleed water would be of a lower salinity and therefore better suited for landscape irrigation, thus again turning a waste-product (the bleed water) into a valuable resource (water for landscape irrigation). Finally, preliminary data suggests that calcium and magnesium (common contributors to mineral scale) may be bound by laundry constituents (e.g., particles or surfactants such as soaps or detergents). Physical treatment processes that remove particles and surfactants may also remove some of the scale-forming constituents, thereby improving the evaporative condensing unit's long-term performance.

4.2. Economic considerations of coupled evaporative condensing A/C and graywater treatment

Economic considerations are an important factor in evaluating a technology's viability. Ghisi and de Oliveira [20] considered three scenarios for reducing drinking water consumption and found graywater treatment and reuse to be the most cost-effective system (based on Brazilian pricing), compared to rainwater or combined rainwater-graywater, despite ample rainfall in the region. A graywater-evaporative condensing unit-coupled system will save electricity and water, yielding annual savings to the owner, but a more in-depth economic evaluation is required, to better understand the importance of the following: climate, home status (e.g., building envelope, here represented by age), A/C and graywater treatment system capital cost, and utilities rates (water, wastewater, and electricity). The previous discussion illustrated the intersection and importance of climate and home status; hotter climate require greater cooling, as do homes with lesser building envelopes (i.e., older homes, as represented in this study). Consumer decisions (e.g., thermostat settings) will also influence cooling burden, as will the use of an economizer (or open windows at night) to promote ambient nighttime cooling.

A simple payback period (P = capital cost ($)/annual savings ($/yr)) is a simple way to understand the relative economic considerations. To calculate a simple payback period, the following assumptions were employed: an air-cooled system and air handler were assumed to cost $6820; an evaporative condensing unit and air hander were assumed to cost $8770, less a $1000 utility rebate[1] ($7770 cost to consumer); the graywater treatment system was assumed to cost $1,000.[2] The A/C unit costs are well understood, though the evaporative condensing unit pricing is based on a low-volume manufacturer and the price may be reduced in the future as the production volume increases. Graywater treatment train cost is not well defined; however the treatment train cost will substantially influence the calculated simple payback. Under these assumptions, a consumer with a new home in climate zone 13 with an evaporative condensing unit would save $43/yr on electricity compared to an air-cooled A/C system ($0.154/kWh; California 2011 residential average), but would pay $21/year for the necessary water ($1.04/m^3; typical of 2010 CA cities). The simple payback period for the evaporative condensing unit supplied with drinking water varied by climate zone with a range of 10 years to greater than the expected life of the product; in the case of climate zone 9, the electricity savings were less than the cost of the water, given the assumed electricity and water rates. When a graywater treatment system is included and used extensively (evaporative cooling, landscape irrigation, and toilet flushing), the simple payback period ranges from 11 to 24 years, depending on the climate zone. In climate zone 13, new home savings would be $43/year saved on electricity and $62/year on water. In climate zones that require less cooling, the savings associated with the A/C system are less, but water-related savings are increased.

[1] The peak electricity demand savings associated with a 10.55 kW evaporative condensing unit was calculated to be 1.2 KW with our Micropas simulations, which at a cost of $1000/KW for peak power, translates to a utility value of $1200; $1000 has been offered by some California utilities, so this number is employed.

[2] This assumed cost for a graywater treatment system is much more uncertain than the A/C equipment costs, as there is not currently a mainstream market for these systems. Moreover, this cost assumes that current regulations that treat residential graywater treatment systems like industrial facilities will be overturned or unenforced.

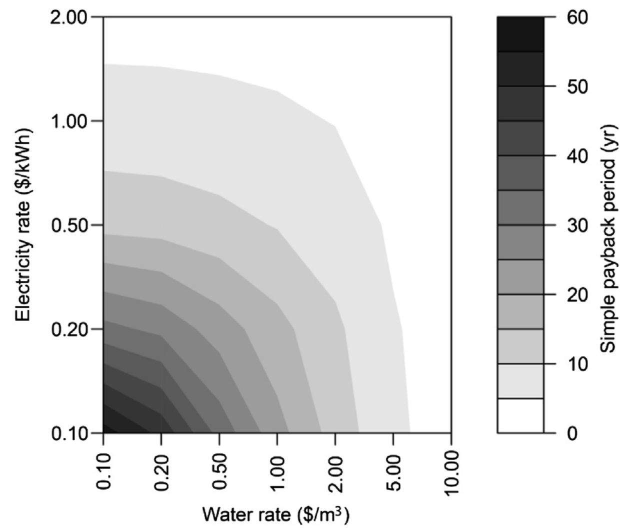

Fig. 7. Rate dependence of the simple payback period for a Fresno house with combined graywater-evaporative condensing unit, where graywater is used for the evaporative condensing unit, irrigation, and toilet flushing.

Electricity and water rates, which vary temporally and geographically, substantially affect the simple payback period. Among major US cities, water rates vary from $0.20 to $2.14/m^3 [7] and are over $9/m^3 elsewhere [4], while electricity in the U.S. costs $0.08–0.37/kWh [6]. The importance of the electricity and drinking water rates is demonstrated in Fig. 7, which shows the simple payback period for a coupled graywater-evaporative condensing unit system for a new home in Fresno. When rates are low, the simple payback period is over 50 years, which exceeds the unit's life expectancy. When rates are high, the payback period is reduced to fewer than 5 years and is 1.7 years for the highest evaluated rates scenario. An acceptable payback period would be achieved any time that electricity costs are over $0.50/kWh or water rate costs over $2.00/m^3. Tier pricing for electricity and water (currently employed in many locations), electricity time-of-use pricing, and direct metering for wastewater (not currently commonly employed) would all make the proposition more attractive by increasing annual savings. In California, if the peak day pricing rate structures currently planned for light commercial customers were to be applied to residential customers, the payback periods would be reduced significantly, due to the large peak demand reduction associated with evaporative condensing units.

4.3. Necessary considerations and future work on evaporative condensing A/C and graywater treatment

For the savings associated with coupled graywater-evaporative cooling systems to be realized, such systems must be widely adopted; however, regulatory, attitudinal, cost, and technical barriers to widespread adoption remain. These barriers include the cost of and exposure to evaporative cooling systems and residential graywater treatment systems, as well as the development and certification of a commercially viable residential graywater system. A commercially viable graywater treatment system must be low-cost, low-maintenance, aesthetically acceptable, and have a small footprint. The graywater system must comply with regulations, and permitting and monitoring must be streamlined (e.g., a certified system). The potential repercussions of diverting wastewater also must be considered. While reducing the volume of wastewater is likely a positive impact for treatment plants, particularly those that are currently overburdened, decreased flows can increase solids concentration in the sewerage, possibly resulting in blockages.

Beyond graywater treatment train development and certification, there are human and environmental health concerns that must be considered (these are discussed in depth elsewhere [21]). Human and ecological risks can be minimized by including limitations on graywater's potential sources and reuses, and placing requirements on treatment level. Exposure risk can be limited via a single-family system (rather than larger-scale systems), and disinfection can be employed to further reduce risk associated with pathogens [21]. There are potential pathogenic risks with both evaporative cooling (e.g., legionella which is an acknowledged risk with cooling towers) and graywater systems (e.g., fecal coliforms, rotovirus) and disinfection with a residual concentration should be employed so as to minimize these risks. Graywater reuse for irrigation allows for the potential release into the environment of a myriad of harmful constituents, including chlorine, salts, surfactants, pharmaceuticals, and personal care products that are not completely removed by most graywater treatment processes [21]. Disinfection, often accomplished via chlorination, is a required component of the California graywater treatment train [19]; however, chlorine released into the environment can be toxic to organisms and can react with organic matter to form disinfection byproducts, which are carcinogenic and harmful to human and environmental health [22].

Mineral scale formation within an evaporatively cooled A/C system impedes the flow of air, reduces heat transfer, and negatively impacts the performance of mechanical systems (e.g., pumps). Research into water management and treatment approaches for evaporative coolers will improve their long-term performance and increase the electricity savings realized by these systems. While graywater may alleviate some mineral scale formation, coupling graywater with evaporative condensing units may result in a different type of fouling based on the organic matter contained within the treated graywater. Further research is required to understand this potential impact. Furthermore, disinfectants must be selected carefully, as some disinfectants include calcium (i.e., $Ca(ClO)_2$) that may promote scale formation within an evaporative condensing unit. Depending upon the results of this research, and the particular application, it may make sense to use graywater to offset irrigation and toilet flushing rather than evaporative cooling.

4.4. Assumption validation and sensitivity analysis

Sensitivity analyses were applied to the assumptions regarding the cooling systems temperature dependence, the graywater production volume, and graywater treatment electricity burden. The air-cooled condensing unit's power and capacity T_{DB}-dependence was highly linear with $R^2 > 0.99$. The evaporative condensing unit T_{WB}-dependence was less clearly defined and the $R^2_{capacity} = 0.39$ and $R^2_{power} = 0.94$, with p-values of 0.5 and <0.01, respectively. The evaporative condensing unit capacity is clearly less T_{WB}-dependent than the unit's power.

Graywater production estimates and treatment requirements are two central components to the total electricity and water burden reductions observed in analyzing a coupled evaporative condensing unit-graywater system. Graywater production estimates in this study were conservative, such as may be found in the home of an electricity- and water-conscientious family. Both shower water and clothes washer volume estimates were conservative, in accordance with the California Green Building Code and new California standards. This results assume 364 loads/yr, which is within the California family typical range of 300–400 loads/yr, but the laundry capacity (68 L/load; based on the 2011 California water efficiency standard) is only 40% of a typical top-loading washing machine [5]. Similarly, shower estimates are based on low-flow shower heads (9.5 L/min), which consume half the water volume of high-flow shower heads [5]. Graywater production estimates are likely low, and total annual volume is potentially more than double for a household that has not implemented higher water efficiency appliances, many of which are required in new California home constructions. Water use for irrigation (landscaping and overwatering; 435 m^3) constitutes 66% of a typical California household's annual water use, and far exceeds annual graywater production volume, even if that value were doubled. In many areas, landscape irrigation is not necessary in the winter season, yet beneficial reuse is needed if the total electricity and water burdens are to be claimed (case iv in Fig. 5). Selection of the appropriate reuse scenario (iii or iv, Fig. 5) should be made with care, based on the irrigation season, so that electricity and water savings are accurately reflected. Treated graywater can also be used for toilet flushing, which accounts for four percent of a typical California household's annual water use. If graywater were used for toilet flushing in the winter, this would consume 13.1 m^3 of treated graywater; however, this would leave 54 m^3 of water that was not reused each winter. Some climates may require landscape irrigation over a greater portion of the year, which would provide further opportunities for graywater reuse.

Finally, the electricity burden of treating the graywater varies based on the treatment system [11]. One estimate put the electricity intensity of water reuse on par with the least electricity intensive approaches to producing drinking water (high-quality groundwater; ~0.4 kWh/m^3), which is much lower than typical surface water sources (~2.5 kWh m^3) or ocean desalination (4.4 kWh/m^3) options [23]. Though electricity is needed for graywater treatment, savings can be realized due to avoided supply, conveyance, and wastewater treatment. Assuming graywater requires 0.4 kWh/m^3 to treat, it would require 54 kWh to treat the annual total produced graywater, which is ~10% of the average annual electricity savings for the combined evaporative condensing unit-graywater system.

5. Conclusions

Evaporatively-cooled A/C technologies offer an attractive approach to meeting cooling loads in hot, arid climates while saving electricity and noticeably reducing the peak residential demand associated with residential cooling, where evaporatively pre-cooled condensing units save more electricity annually (e.g., 6–19% for new homes) while evaporative condensing units provide greater peak power savings (i.e., 1.2 kW (31%) for a new home in climate zone 15). Similarly, graywater treatment and appropriate reuse reduces drinking water demand, drinking water peak demand, and wastewater volume. Treated graywater can be used with an evaporative condensing unit, for toilet flushing, or for landscape irrigation. Treated graywater may provide more favorable water quality, enable better evaporative condensing unit water management strategies, or simply provide an alternative water source to eliminate the additional water burden. The economic feasibility of a coupled system will be highly dependent on the environment, unit costs, and utility rates. Using typical U.S. utility rates, the simple payback period for the combined system is ~15 years, though this number will potentially drop as evaporative condensing units and graywater treatment systems become cheaper and as utility rates increase.

Acknowledgments

This report was prepared as a result of work sponsored by the California Energy Commission (Energy Commission) grant number 500-08-042 and the University of California (UC). It does not necessarily represent the views of the Energy Commission, UC, their employees, or the State of California. The Energy Commission, the State of California, its employees, and UC make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission or UC, nor has the Energy Commission or UC, nor has the Energy Commission or UC passed upon the accuracy or adequacy of the information in this report.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2013.07.007.

References

[1] Navigant. Refining estimates of water-related energy use in California. Sacramento, CA: California Energy Commission; 2006.
[2] Pistochini T, Modera M. Water-use efficiency for alternative cooling technologies in arid climates. Energy and Buildings 2011;43:631–8.
[3] Brown RE, Kooney JG. Electricity use in California: past trends and present usage patterns. Energy Policy 2003;31:849–64.
[4] Hightower M, Pierce SA. The energy challenge. Nature 2008;452:285–6.
[5] ConSol. Water use in the California residential home. California Homebuilding Foundation; 2010.
[6] EIA US. Electric power monthly. U.S.E.I.A.; 2012.
[7] Walton B. The price of water: a comparison of water rates, usage in 30 U.S. Cities. Circle of Blue; 2010.
[8] Faramarzi R, Coburn B, Sarhadian R, Mitchell S, Pierce RA. Performance evaluation of rooftop air conditioning units at high ambient temperatures. ACEEE Energy Efficiency in Buildings 2004.
[9] Modera M, Pistochini T, Brown K. Evaporative condenser pre-cooling. Western Cooling Efficiency Center; 2011.
[10] Faramarzi R, Lutton J, Gouw S. Performance comparison of evaporatively-cooled condenser versus air-cooled condenser air conditioners. ACEEE Energy Efficiency in Buildings 2010.
[11] Abu Ghunmi L, Zeeman G, Fayyad M, van Lier JB. Grey water treatment systems: a review. Critical Reviews in Environmental Science and Technology 2011;41:657–98.
[12] Keesee M, Bisbee D. The aquachill. Sacramento Municipal Utilities District; 2010.
[13] Willis RM, Stewart RA, Williams PR, Hacker CH, Emmonds SC, Capati G. Residential potable and recycled water end uses in a dual reticulated supply system. Desalination 2011;272:201–11.
[14] Lyman RA. Peak and off-peak residential water demand. Water Resources Research 1992;28:2159–67.
[15] Energy X. Demand-side management annual status report 2011. Exel Energy; 2012.
[16] Arbués F, Garcia-Valinas MA, Martínez-Espiñeira R. Estimation of residential water demand: a state-of-the-art review. Journal of Socio-Economics 2003;32:81–102.
[17] Tiemann M. Arsenic in drinking water: regulatory developments and issues. DTIC Document 2007.
[18] E.P.A. US. Safe drinking water act. Washington D.C.; 1976
[19] Regulations CCo. Title 22: regulations related to recycled water. California Department of Public Health. California Department of Public Health; 2009.
[20] Ghisi E, de Oliveira SM. Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. Building and Environment 2007;42:1731–42.
[21] Maimon A, Tal A, Friedler E, Gross A. Safe on-site reuse of greywater for irrigation – a critical review of current guidelines. Environmental Science & Technology 2010;44:3213–20.
[22] E.P.A. US. Wastewater technology fact sheet dechlorination. Washington DC; 2000.
[23] Kenney DS, Wilkinson R. The water-energy nexus in the American West. Edward Elgar Pub; 2012.