Supporting Information

for

Life Cycle Environmental Implications of Residential Swimming Pools.

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The Pool System

Figure 1 of the main text graphically summarizes the overall pool system. The system consists of the physical infrastructure, the processes that occur within the system, and the inputs and outputs. A brief description of the system, much of it taken from Wojtowicz *(1)* and O'Connell and Brayton *(2)*, follows. The primary components of the physical infrastructure are the pool basin, a pump, and a filter. The pump circulates the water through the filter to remove solids and to mix chemical additives. Pumps are electric. The filter removes solid particulate matter from the water. Sand, diatomaceous earth and cartridge are common types of filter.

System Inputs

Contaminants: These are unwanted substances that degrade the clarity and sanitary condition of the pool. Wind and rain borne dust, spores, and organic litter are constantly deposited and unfortunate insects and other animals meet their end in pools. Bathers introduce urine, sweat, and other wastes. Left untreated, algae and bacteria will flourish from these feed stocks.

Chemicals: Chlorine based sanitizers are the primary chemical additives. The most common ones in Arizona are trichloroisocyanuric acid (Cl3Cy where $Cy=(NCO)_3$) ('trichlor'), a solid tablet form, and calcium hypochlorite (CaOHCl), a solid granular form *(1)*. Others are sodium dichloroisocyanurate ($NaCl_2Cy$) ('dichlor') and sodium hypochlorite (NaOHCl). All forms of chlorination increase free available chlorine as hypochlorous acid (HOCl) and hypochlorite (OCl^-) in proportions relative to water pH. Hypochlorous acid is the much stronger biocide and maintaining pH at around 7.3, by adding hydrochloric acid (HCl) or soda ash ($NaCaO_3$) or alternative acids and alkalis, achieves optimal sanitation. Hypochlorite decomposes rapidly in sunlight (~90% in ~3 hours) to chloride (Cl) and atomic oxygen (O^-) unless protected by the addition of cyanuric acid. Algaecides (quaternary ammonium compounds, copper or silver based products), are used to combat algae that is too robust for chlorine. Flocculants, in the form of aluminum salts, are used as clarifiers.

Other forms of sanitation are salt water electrolysis to produce HOCl from H_2O and added NaCl, bromination, which is similar to chlorination and requires addition of brominated compounds, and ozonation to producing O_3 by corona discharge and UV radiation.

Water: Water is input from the municipal supply and from precipitation.

Electricity: to power the pump, and if using alternative sanitation methods electrolyzer and ozone generator.

System Outputs

Atmospheric Emissions: Water vapor is emitted through evaporation. Chloride (Cl), trichloromethanes ($CHCl_3$) , hypochlorous acid (HOCl) and hypochlorite (OCl^-) are vaporized.

Water Emissions: Water is lost from the pool as a result of backwashing, refill, overflow, leaks and usage, carrying with it some quantity of chemical inputs and products of chlorination reactions, including hypochlorous acid, hypochlorite, chloride, chloramines, trichloromethane, dissolved solids (calcium carbonate, sodium hydroxide, calcium hydroxide), hydrochloric acid, and filtrand.

System Processes

Evaporation: Evaporation rate increases with differential water vapor pressure between air and water surface, water temperature, wind speed and inversely with relative humidity of the air, as described by Penman. We use free water surface (FWS) evaporation as reported by the National Oceanic and Atmospheric Administration (NOAA) and is defined as "evaporation from a thin film of water having no appreciable heat storage" and closely represents reference evapotranspiration, ET_0 *(3).* FWS is calculated by NOAA from daily pan evaporation, ET_{pan}, mean air temperature, mean surface water temperature and wind speed measurements for specific locations. FWS evaporation is an approximation only for swimming pool evaporation for two main reasons. Firstly, over the course of complete year, FWS is equal to the evaporation from an open body of water, such as a swimming pool, but for any interim period, the two will differ due to the hysteresis effect of heat storage in the pool. Thus, evpoaration from the pool during spring is less than FWS evaporation as the pool water heats up, and greater in the fall as it loses heat. Secondly, micro climatic and other effects such as water circulation, heating or cooling from pool basin, surrounding walls and vegetation, may cause pool evaporation to differ from the local calculated FWS evaporation.

Circulation: Water is circulated by the pump to pass it through the filter and to mix chemicals. The generally accepted rule of thumb to achieve adequate mixing and cleaning is to circulate the entire pool volume at least once a day although the efficacy of this is questionable.

Filtration: Particulate matter and larger solids are caught by skimmer baskets or by the main filter.

Backflush: Periodically filters require cleaning. For sand filters this is achieved by pumping water in reverse through the filter to discharge the filtrand from the system, usually into the municipal sewer system.

Refill: After several years of operation, the accumulation of total dissolved solids (TDS - calcium and sodium hydroxides and carbonates) in the pool makes it increasingly difficult for chlorination and other chemical process to be effective. The only solution is to replace the water by discharging the old water and refilling from the water supply. The rate of accumulation of dissolved solids, and thus higher frequency of refresh, is faster in areas with higher evaporation and higher TDS. We also include water discharged when closing pools in winterizing regions (and subsequently added at the start of the open season) as refill.

Overflow: Water input from rain may increase the pool water level above the maximum operating level and require discharge to bring it back down or result in overflow if it rises to the top of the pool.

The Pool Model

General Model Description

We divided the pool year into an open (summer) and closed (winter) season and further distinguish closed season into winterizing regions where the pool is completely shutdown, and non winterizing regions where a low level of operation is maintained. Shutting the pool down is necessary in regions where there is a risk of damage to the pump or plumbing due to freezing and typically consists of draining the pool and all near surface pipes to below the water inlet level, usually 1 to 2 feet below operational level, and securely covering. During the winterized closed season no pumping or chemical treatment takes place. In warmer regions with no risk from freezing, in the closed season the pool is not being used and the water temperature is too cold and radiation level too low for vigorous algal growth but it is still necessary to run the pump for several hours per day and apply a reduced level of chlorination. At the start of the open season a double super-chlorination is applied and winterized pools need to be refilled back up to operational level. During the open season a daily chlorination doze is delivered by slowly dissolving trichlor supplemented by lower frequency super-chlorination. Pump running time is increased in open season relative to closed season to achieve an adequate concentration and sufficiently uniform distribution of chlorine throughout the pool when chlorine demand is greater due to higher temperature, greater UV radiation and pool use. All super-chlorination is by fast dissolving, calcium hypochlorite granules. The model is simplified in several respects. Some discussion of the main simplifications follows.

Water Balance

As noted above water enters the pool through precipitation and main water supply inlet, and exits the pool through evaporation, backwash, refill (discharge for TDS reduction or start of open season for winterized pools), splash (bather usage), leaks and overflow. To keep the water level within an operational range, usually dictated by the skimmer outlet, water must be added from the main supply when the level falls below the minimum, or discharged when it rises above the maximum. We model the water balance on a monthly aggregate water flux due to train, evaporation, backwash and refill, to arrive at a monthly adjustment, either a supply input or an overflow discharge, that is necessary to keep the water level within the operational range. Splash loss and leaks are ignored due to a lack of data. Some loss of accuracy is expected by balancing the water on a monthly basis as the inputs and outputs are not evenly distributed in time

Types of sanitization other than direct chlorination

It was assumed that all sanitization is by direct chlorination whereas bromination, ozonation, salt electrolysis and other methods are also common. The number of U.S. residential pools using one of these alternatives could exceed 40% *(6)* but our assumption may not be as invalid as it seems. Firstly, these alternative forms of sanitation reduce chlorination rather than eliminate it. If we make the broad assumption that on average, pools using alternative sanitation reduce chlorine consumption by 50%, then actual chlorine consumption is 80% (i.e. 100% - ((50%)(40%)) of consumption if all pools used only chlorination. Secondly, the alternatives also have an impact from chemicals used, and from electricity used in the case of ozonation and salt water chlorination. Lastly, bromination, the most common alternative, uses bromine compounds which are included in the same NAICS class (32518) as chlorinated sanitizers. Although bromine products are applied in lesser quantities, they are more expensive, thus the EIOLCA impact of bromination plus chlorination, is expected to be similar to that of chlorination only. Overall, without any detailed analysis of the alternative sanitation methods, we estimate actual impacts to be close to 90% or more of our calculated, chlorination only, impacts.

Chlorination limited to trichlor and calcium hypochlorite

The decision to use only trichlor and calcium hypochlorite for chlorination ignores the use of sodium hypochlorite, the other commonly used chlorinator, and to a lesser extent, dichlor. Prices for the products generally reflect the amount of chlorine they deliver, their convenience and utility. For example, sodium hypochlorite is the cheapest but it is has the lowest chlorine concentration, is bulky and rapidly loses its effectiveness. To achieve the same concentration of chlorine approximately 8 times as much sodium hypochlorite (<12% Free Available Chlorine (FAC)) by weight as trichlor (>90% FAC) must be added. Assuming a specific gravity of 1.2 g/cm^3 for NaOCl solution, 1 gallon is approximately equivalent to 1lb trichlor, so at prices of $0.50/gal *(7)(8)* and $1.05/lb *(9)* respectively, total cost for NaOCl is around 50% less than trichlor. However, FAC of NaOCl solutions is frequently less than 10% *(10)* and degrades further if not used immediately, thus the equivalent quantity is likely to be in the range 1.3 to 1.5 gallons, narrowing the cost difference to around 30%. Trichlor however, contains cyanuric acid for U.V. radiation protection. If we consider that use of sodium hypochlorite requires the addition of cyanuric acid separately then this could account for some of the remaining difference. Sodium hypochlorite greatly increases water pH and therefore also requires the addition of acidifiers such as muriatic acid, thus further reducing the difference. As all pool chemical products belong to NAICS 32518, total cost and hence EIOLCA results, will be comparable and so to a reasonable degree, the products are substitutable for our purpose.

Use of other chemicals

Secondary pool chemicals (acidifiers, algaecides, clarifiers, etc.) were omitted from the model because we could find no data on their usage. Unlike chlorination which is more routine in its application, these chemicals are applied if and when needed. Many of these are low volume - high value products and would therefore be expected to noticeably increase the annual cost of chemicals per pool and resultant EIOLCA impacts. From a macro economic analysis, total pool chemical market value is assumed to include most, if not all of these ancillary products. Cost of chemicals per pool determined by the top down, market value approach that we performed for comparison with the result of the bottom up, operational model approach, is therefore expected to be more accurate with respect to completeness.

Assume only sand filters

Not all filters are sand based. Diatomaceous earth (DE) are common but are essentially similar to sand in their backwashing requirements. Cartridge filters are less common and do not require backwashing. Thus in assuming all filters have the same backwashing requirements our model overestimates water loss from this procedure to some extent.

Ignoring use of pool covers

Pool covers can decrease evaporation greatly, prevent debris from entering the pool, and prevent UV radiation from destroying free, active chlorine, thus reducing water consumption, pumping time, and chemical use. One source reported 60% of Tucson area pools have covers but with less than 50% usage rates *(11)* but we were unable confirm this or find any other data supporting it. Direct observation using Google Earth did not support this finding either, with the incidence of covers in November 2005 appearing to be between 0 and 12 out of a total of 103 pools from 3 randomly selected Maricopa County neighborhoods *(12)*. The uncertainty in these observational results arises from being unable to positively identify 12 of the pools as being covered or uncovered. The overall reliability of this method has not been verified. Further indication of the low use of pool covers comes from a solar pool heating survey of pool owners in California, Arizona and Florida that found the incidence of cover use to be 13%, 0% and 1% respectively in these states (13).

Chlorine demand and climate

The maintenance schedule used in the model is mainly based on U.S. recommended practices plus one South African and one Australian reference, but it does not make any adjustment for local climate. Chlorine demand increases with temperature and UV radiation due to increased photolytic breakdown of HOCl / OCl^-, increased algal and bacterial growth, and increased volatilization of chlorine compounds. Thus, we expect chemical use in cities like Phoenix to be underestimated by the model and in Seattle to be overestimated.

Model Evaluation

Equations

First order water consumption W_1, is the annual water consumed directly from the main water supply by the pool, and is calculated by equation (1).

$$W_1 = \sum_{i=1}^{12} w_i \qquad (1)$$

Where
w_i = water use from supply in month i
and in the following water equations
F_i = water flux in month i
$P_{i,l}$ = precipitation in month i in location l.
$E_{i,l}$ = Evaporation in month i in location l.
B_i = Backwash in month i
R_i = Refill discharge in month i
L_{i-1} = Water level at the start of month i
L_i = Water level at the end of month i
L_{min} = Minimum water level
L_{max} = Minimum water level
s_i = Water surplus in month i

The water flux F_i in month i is the net change in water volume from precipitation, evaporation, backwash and refill processes and is calculated by equation (1.1).

$$F_i = P_{i,s} + E_{i,s} + B_i + R_i \qquad (1.1)$$

When $(L_{i-1} + F_i) < L_{min}$ there is a water deficit (w_i) in month i and the level must be adjusted upwards to the minimum.

$$w_i = L_{min} + (L_{i-1} + F_i) \qquad (1.2)$$

$$\text{and } L_i = L_{min} \qquad (1.3)$$

When $(L_{i-1} + F_i) > L_{max}$ there is water surplus (s_i) in month i and the level must be adjusted downward to the maximum.

$_{si} = L_{max} - (L_{i-1} + F_i)$ (1.4)

and $L_i = L_{max}$ (1.5)

When $L_{min} < (L_{i-1} + F_i) < L_{max}$ there is neither a surplus or a deficit and no adjustment is needed.

and $L_i = L_{i-1} + F_i$ (1.6)

And where

B_i = (Pump Flow Rate) (Duration) (Backwash Frequency) / 12 (1.1.1)

$R_i = 0$ (1.1.2a)
if not first month of open season
R_i = (Pool Volume) (Refill Frequency) (1.1.2b)
if it is the first month of the open season and pool is not winterized
R_i = Pool Volume – Winter Volume (1.1.2c)
if it is the first month of the open season and pool is winterized

First order electricity input (E_1) is defined as electricity consumed within the pool system and is calculated by equation (2).

$E_1 = P\ [\ H_oS + H_c(365\text{-}S)\ ]$ *(2)*

Where P is pump power (kW)
H_o is pumping hours per day in the open season
H_c is pumping hours per day in the closed season
S is the open season length in days

Chemical input quantity C_j for a chemical j is calculated by equation (3). No chemicals are applied in winterized pools during the closed season.

$C_j = D_i\ [\ F_{j,o}S + F_{j,c}(365\text{-}S)\ ]$ *(3)*

Where D_j is dose of chemical j per application (oz)
$F_{j,o}$ is application frequency of chemical j in the open season
$F_{j,o}$ is application frequency of chemical j in the closed season
S is the open season length in days

Second order water and electricity consumption of electricity and water supply systems are calculated using equations (4) and (5).

$W_2 = (E_1)\ (w_{e,l})$ *(4)*

$E_2 = (W_1)\ (e_{w.l})$ *(5)*

Where $w_{e,l}$ is the water consumption rate of the electricity supply to location l and e_w is the energy consumption rate of the water supply to location l. See below for more details on both of these supply consumptions. Total water and energy consumption is given by equations (6) and (7)

$$W = W_1 + W_2 \quad (6)$$

$$E = E_1 + E_2 + E_c \quad (7)$$

Where E_c is the energy consumed by pool chemical production (see below for more details on pool chemical calculations). Global warming potential G, is calculated using equation (8).

$$G = G_e + G_c \quad (8)$$

Where G_e and G_c are global warming potential of first (G_1) and second (G_2) order electricity consumption and of pool chemical manufacture respectively. G_e is calculated by equation *(8.1)* and more details for derivation of G_c are given later.

$$G_e = G1 + G2$$

$$= (g_{e,l})\,(E_1 + E_2) \quad (8.1)$$

Where $g_{e,l}$ is the global warming potential of consumed electricity in location l which is covered in more detail below.

Monte Carlo Simulation

A Monte Carlo simulation based on the above equations and the pool chemical impact equations was implemented in a Microsoft Excel spreadsheet. Each equation was evaluated 5,000 times for input parameters randomly drawn from a normal distribution, described by the input variable's mean and standard deviation, using Excel's NORMINV function. The mean and standard deviation were then computed for the set of 5000 evaluated results.

Monte Carlo simulation is a technique for representing parameter uncertainty and variability in model output. Parameter uncertainty arises from empirical inaccuracy, unrepresentivity or lack of data whereas variability is the result of inherent differences in sources and processes *(14)*. The data we use for many of the input parameters are impacted by one or both of these types of uncertainty. While Monte Carlo simulation will not reduce the uncertainty of inputs, it is a useful means of propagating the uncertainty through to the outputs.

Monte Carlo simulation requires input parameters to be characterized by a distribution function from which a value can be randomly drawn. For simplicity, we have assumed all input parameters to have a normal distribution, described by a mean value (m) and standard deviation (σ). A more sophisticated analysis would use several types of distribution in addition to normal, e,g. log normal, uniform or triangular, and apply the most appropriate one to each parameter *(15)*. Estimation of mean and standard deviation for each input parameter was arrived at on a case by case basis. Where several or more data points were available they were calculated. Where only 2 or 3 data points were available we calculated the mean but subjectively adjusted the standard deviation. Where only a single data point was available standard deviation was subjectively estimated, usually at 10% but less if the source was considered to be very good, or more (20%) if considered to be poor, for invariant data. Data points are often provided as a range in which case we would usually accept it as the mean ±1σ when it appeared to be representing the most common values, or in some cases as the mean ±6σ, when the range appeared to more closely represent lower and upper bounds.

Model Input Parameters for Standard Pool.

Chemical Application.

Model input parameters for chemical application are listed in Table 1. Chemical input data were collected from several pool maintenance guides and a mean and standard deviation calculated. Where sources report a range of values the midpoint was used.

Table 1: Chemical application parameters.

Item	Units	Value	SD	CV	Description	Sources
Trichlor Daily Dose	Oz per 10^3 gals	1.4	0.2	18%	The mass of trichlor applied per day as the base chlorination type during open season.	*(16)(17)(18)*
Cal-Hypo shock dose	Oz per 10^3 gals	14.6	3.2	22%	The mass of calcium hypochlorite applied as a super chlorination 'shock' treatment.	*(2)(16)(17)(18)(19)*
Open season shock period	Weeks	2.5	0.5	20%	The super chlorination period during open season.	*(2)(16)(17)(19)*
Closed season shock period	Weeks	4.0	0.4	10%	The super chlorination period during closed season.	*(17)(2)*

Chemical doses are per 10,000 Gallons.

Operational Parameters

Operational parameters are shown in Table 2. As with chemical application, mean values and standard deviations were derived from multiple sources. In the case of backwash period, the range of recommended values was large (1 to 4 weeks) and was judged to be more representative of the lower and upper bounds of this parameter. Standard deviation was then calculated as (upper – lower) / 6. Similarly for pool refill period, the large range of values (2 to 10 years) was taken as upper and lower bounds and standard deviation as (10 – 2) / 6.

Table 2: Pool operational parameters.

Item	Units	Value	SD	CV	Description	Sources
Open Season Pump Running Time	hours per day	9.2	1.8	19%	The number of hours per day that the pool pump is running during open season.	*(2)(16)(18)(19)(20)(21)(22)(23)(24)*
Closed Season Pump Running Time	hours per day	4.8	1.0	20%	The number of hours per day that the pool pump is running during closed season.	*(2)(16)(18)(19)(20)(21)(24)*

Backwash period	Weeks	2.5	0.5	20%	The number of times per year the pool filter is backwashed.	*(25)(26)(27)(28)*
Backwash Duration	minutes	3.5	0.9	25%	The duration of a single backflush.	*(25)(28)(29)*
Pool Refill Period	Years	6.0	1.3	22%	The number of times per year the pool water is replaced.	*(28),(29)(31)*

Pool Physical Characteristics

Model inputs for physical characteristics of the pool system are listed in Table 3. Little data were found on pump power and flow rate. Home Energy Magazine reports the range of pump power to be from 0.75 to 2.0 brake horsepower, consuming 0.9 to 2.0 kW (32), thus inferring an efficiency of 65 to 75%. A commercial market study by ADM Associates, cited in (20), determined the weighted average of pool pump power consumption to be 1.36 kW, broadly agreeable with the midpoint of the Home Energy Magazine range. Another source indicates that most pumps deliver around 0.75 HP *(33),* which draws 0.9 kW of power assuming the efficiency derived from the Home Energy Magazine power information. We calculated a mean and standard deviation from these data points. Pump flow rate, necessary to calculate backwash water discharge, was obtained from National Pool and Spa Institute data given in the Phoenix AMA Third Management Plan as a range of 50 to 75 gallons per minute (28). One other source compares well with this, putting the range at 55 to 70 *(29)*. Less definitive information can be found which suggest that these pump flow rate ranges are on the high side, but these were not concrete enough to use as a source. Based on performance data of currently available single speed pumps *(30)*, a flow rate range of 50 – 70 gpm would require a pump output of 0.75 to 1.5 HP assuming 30 feet of static head, consistent with the pump size determined above.

Data on pool surface area came from Maricopa County Assessor's Office for the year 2007 with a standard deviation computed from the full population *(34)*. The assessment data only includes inground pools, i.e. it does not include above ground pools. We assumed that the market for above ground pools in the Phoenix area is small, possibly less than the per capita above ground pool ownership rate of

0.0038 found in Utah, which is the lowest of any state *(35)*. We used this rate and a population of 3.9 million in 2007 *(36)* to arrive at an upper bound of 14,750 for the number of above ground pools in Maricopa. We arbitrarily assumed a lower bound of 1,000. Using the median of this range, we estimate the number of above ground pools to be 7,875, approximately 3% of the inground pool total. We estimated the surface are of above ground pools to be 2/3rd of inground pools and adjusted the average Phoenix pool surface area based on the mix of above and in ground surface areas.

Assessment data does not include pool depth. We subjectively estimated an average depth of 5 feet and a standard deviation of 0.5 feet, which results in an average volume of 16,494 gallons. Wojtowicz states average volumes of 29,000 and 15,000 gallons for inground and above ground residential pools respectively *(1)*. PK Data also suggest that our pool volume may be on the low side by stating that the average volume of new pools being built in 2008 was 21,000 gallons *(37)*.

The winter pool level is the level the pool surface is lowered to if it is shutdown for the closed season. We estimated this value and the range of levels that the pool can operate within. Taking the minimum operating level as the datum, the maximum pool level is a positive height above this, and the winter pool level is a negative height below.

Table 3: Pool system physical characteristics model inputs parameters.

Item	Units	Value	SD	CV	Description	Sources
Pump Power Consumption	kW	1.2	0.3	26%	The average power consumption of US residential pool pumps.	*(20)(32)(33)*
Pump flow rate	gallons per minute	63	10	16%	The average flow rate of pool pumps.	*(28)(29)*
Pool surface area, Maricopa	feet^2	442	113	25%	The average surface area of SFR swimming pools in Maricopa County including a small estimate for above ground pools.	*(34)(35)*
Pool depth, Maricopa	feet	5.0	0.5	10%	The estimated average pool depth of residential swimming pools in Maricopa County.	

Pool volume, Maricopa	gallons	16,494	4,512	27%	The calculated average volume of water contained in Maricopa County residential swimming pools.
Winter pool level	inches	18	6	33%	The height below the minimum operational level that the pool is lowered to in winter (if it is winterized).
Maximum pool level	inches	4	1	25%	The estimated range in pool level for proper operation.

SD = standard deviation; CV = coefficient of Variation

Climatic Parameters

In addition to operational parameters and physical characteristics of the pool system, the other group of model input parameters are local, climatic factors. Monthly FWS evaporation (Table 4) is derived from map 3 (Mean annual FWS evaporation map 1956 - 1970, calculated from measured E_{pan}, air temperature, surface water temperature and wind speed) and table 3 (monthly percentage of annual E_{pan} total) in NOAA's Evaporative Water Atlas for the U.S. *(3)*. Uncertainty arises in the evaporation data from several sources: original measurements, calculation of FWS, plotting of FWS, reading of FWS, variation of monthly percentage station from actual location. In addition, systematic error is introduced by ignoring heat storage hysteresis and possible temporal error if actual evaporation has significantly changed since the 1956 – 1970 period on which FWS data is based. One such source of possible change is urban heat island, noted in many cities, including Phoenix *(39)*. Overall, we assumed a coefficient of variation of 0.10 for monthly evaporation. Monthly precipitation (Table 5) is taken from observed weather report data sheets for each location with mean monthly averages for the period 1971 – 2000. We used a single station only for precipitation but there may be significant variation across the city area. We assume a coefficient of variation of 0.10 for monthly precipitation.

Table 4: Mean monthly free water surface evaporation (1956 – 1970) in inches for the nine sample cities. (source: from table 3 and map 3 in *(3)*)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Atlanta	0.9	1.4	2.6	4.0	4.6	5.2	5.3	4.8	3.5	2.7	1.6	1.3
Chicago	0.0	0.0	0.0	2.9	4.5	5.1	5.2	4.6	3.5	2.5	1.3	0.0
LA	1.5	1.8	3.3	4.4	5.8	7.0	7.3	7.4	5.0	3.6	1.8	1.4
New York	0.8	1.0	1.9	3.2	4.3	4.6	4.8	4.4	2.9	2.0	1.3	0.8
Phoenix	2.3	2.6	4.0	5.7	7.8	9.0	8.9	7.5	6.6	5.1	3.2	2.5
San Antonio	2.0	2.7	4.3	7.4	7.8	7.2	5.7	4.9	3.7	2.4	1.7	0.0
Seattle	0.1	0.6	1.1	1.6	3.0	3.9	5.5	4.5	2.8	1.3	0.6	0.3
St Louis	0.0	0.0	0.0	3.6	4.5	5.2	5.5	5.1	4.0	2.9	1.5	0.0
Tampa	2.3	2.6	3.7	4.6	4.8	4.5	4.7	4.4	3.9	3.6	2.6	2.3

Table 5: Mean monthly precipitation (1971 – 2000) in inches for the nine sample cities. (source: *(38)*)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Atlanta	5.03	4.68	5.38	3.62	3.95	3.63	5.12	3.67	4.09	3.11	4.1	3.82
Chicago	1.75	1.63	2.65	1.6	3.38	3.63	3.51	4.62	3.27	2.71	3.01	2.43
LA	3.33	3.68	3.14	0.83	0.31	0.06	0.01	0.13	0.32	0.37	1.05	1.91
New York	2.71	2.27	3.17	2.9	3.67	3.74	3.5	3.68	3.31	3.23	3.31	2.76
Phoenix	0.83	0.77	1.07	0.25	0.16	0.09	0.99	0.94	0.75	0.79	0.73	0.92
San Antonio	1.66	1.75	1.89	2.6	4.72	4.3	2.03	2.57	3	3.86	2.58	1.96
Seattle	5.13	4.18	3.75	2.59	1.78	1.49	0.79	1.02	1.63	3.19	5.9	5.62
St Louis	2.14	2.28	3.6	3.69	4.11	3.76	3.9	2.98	2.96	2.76	3.71	2.86
Tampa	2.27	2.67	2.84	1.8	2.85	5.5	6.49	7.6	6.54	2.29	1.62	2.3

Season length is important because it determines the duration that more intensive maintenance is necessary. Open season length is primarily related to water temperature and incident sunlight, and is demarcated by temperature and light levels sufficient to support algal growth and in some cases may be slightly longer than swimming season for unheated pools and less hardy swimmers. PK Data Inc. note that Florida has a 9 month swimming season and imply that several states including Arizona, Texas and Georgia have a season of 7 months or more *(40)*. However, there is no clear information on whether this includes heated pools, or whether it is a maximum, minimum or mean. Based on mean monthly temperatures, we estimated a threshold of 65°C as for open season (Table 6) which is close to PK Data's information for Arizona, Texas and Florida but reduced Georgia but 1 month. This is also similar to estimated season lengths in a National Resource Defense Council report *(41)* though our estimates tend to be a little (1 month) shorter, and in accordance with a National Renewable Energy Laboratory survey of pool owners in California, Arizona and Florida that found that usage rose from 20% to 38% between March and April and dropped from 40% to 17% from October to November *(13)*.

Table 6: Mean monthly temperature (1971 - 2000) for the nine sample cities and open season length (in months). Months with mean temperatures of 65°C are shaded, indicating the threshold for pool open season. (Source: *(38)*).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	***length***
Atlanta	42.7	46.7	54.3	61.6	69.8	76.8	80	78.9	73.3	62.8	53.4	45.4	***5***
Chicago	22		37.3	47.8	58.7	68.2	73.3	71.7	63.8	52.1		27.4	***3***
LA	58.3	60	60.7	63.8	66.2	70.5	74.2	75.2	74	69.5	62.9	58.5	***6***
New York	22.2		25	46.6	58.1	66.3	71.1	69	60.6	49.3		28	***3***
Phoenix	56.1	59.9	64.6	71.2	80.7	89.8	94.8	93.1	87.3	74.9	62.7		***7***
San Antonio	50.3	54.7	62.1	68.6	75.8	81.5	84.3	84.2	79.4	70.7	60	52.4	***7***
Seattle	40.9	43.3	46.2	50.2	55.8	60.7	65.3	65.6	61.1	52.7	45.2	40.7	***2***
St Louis	29.6	35.4	45.8	56.6	66.5	75.6	80.2	78.2	70.2	58.3	45.3	33.9	***5***
Tampa	61.3	62.7	67.4	71.5	77.6	81.5	82.5	82.7	81.6	75.8	69.3	63.3	***9***

Energy use to supply water

To calculate energy E_2 consumed to supply the first order water needs of the pool system we used a general U.S. energy intensity value for 7 of the 9 cities. For the other 2 cities, Phoenix and Los Angeles, we used more location specific values. For all energy intensity values we include only direct, operational energy consumption, ignoring the impact of construction, upstream supply chains (with the exception of treatment chemicals), and ancillary activities.

Arpke and Hutzler *(42)* found in the literature the range of values for water supply, which includes treatment and distribution and, though not clearly stated, we assume extraction, to be 0.4 to 2.5 kWh / 1000 gallons (deMonsabert and Liner in *(42)*; Dyballa & Connelly in *(42)*) and 0.8 to 2.9 kWh / 1000 gallons (Cantwell et al. in *(42)*) for wastewater treatment. Combining these gives a range of 1.2 to 5.4 kWh / 1000 gallons that we take as approximate lower and upper bounds to arrive at a mean value of 3.3 kWh / 1000 gallons with a standard deviation of 0.7.

Water supply in Southern California is known to be particularly energy intensive due to the reliance on two long distance transport systems *(43)*. We therefore sought more specific data to use for the Los Angeles water energy intensity. A California Energy Commission report *(44)* gave values of 9.7 kWh/1000 gallons for supply and conveyance, 0.1 for treatment, 1.3 for distribution, and 1.9 for wastewater treatment in Southern California. Combining these results in an overall value of 13 kWh / 1000 gallons for which we assume a coefficient of variation of 0.1.

Phoenix also relies on extensive water supply infrastructure. Municipal water supplied to the Phoenix Active Management Area comes from 4 sources: 1) groundwater, 2) surface water, primarily from the system of dams, reservoirs and canals of the Salt and Verde River basins to the north and east of Phoenix AMA, 3) the Colorado River, 300 km to the west, transported by the Central Arizona Project (CAP) canal, and 4) effluent. Processing stages can be reduced to a) Extraction and Transport, b) Treatment, c) Distribution, and d) Wastewaster Treatment. Using data from published literature a matrix of energy use by source and processing stage was constructed, and from the relative mix of sources, an overall energy intensity of 4.2 kWh / 1000 gallons (standard deviation 0.4) within the PAMA municipal sector was calculated (Table 7). Only one source of data was specific to Arizona, in particular the PAMA *(45)*. The others were U.S. wide.

Table 7: Energy consumption (kWh/1,000 gal) of municipal water supply in Phoenix AMA.

Processing Stage	Ground-water	Surface Water	CAP	Effluent

Extraction	0.61[a]	0.12[a]	4.70[d]	N/A
Treatment	0.01[a]	0.08[a]	0.08[a]	N/A
Distribution[b]	1.13	1.13	1.13	1.13
Wastewater Treatment	1.64[c]	1.64[c]	0.53[d]	3.56[d]
Total Energy Consumption (kWh/1000 gal) (Standard Deviation)	3.4 (0.4)	3.0 (0.4)	6.4 (1.0)	4.7 (0.8)
Total Municipal Water Consumption (acre-feet) [e]	304,100	393,000	302,000	21,600
Percent of municipal consumption	30%	39%	30%	2%
Normalized Energy Consumption (Standard Deviation)	1.0 (0.1)	1.1 (0.2)	1.9 (0.3)	0.1 (0.0)
Weighted Average Energy Consumption (standard deviation)	4.2	(0.4)		

Sources: [a]Burton in *(46)*; [b]deMonsabert and Liner in *(42)* and Burton in *(46)*; [c]Cantwell in *(42)* and Burton in *(43)*; [d]*(45)*; [e]*(4)*.

Water use to supply electricity

A National Renewable Energy Laboratory (NREL) report provides state by state water consumption estimates for both thermal and hydro electric generation and, using the generation total for each class, an overall water intensity *(47)*. The total generation data is from 1995 (Energy Information Agency Electric Power Annual 1995). The reported results include U.S. average generation losses (0% for hydro, 6% for others), and transmission and distribution losses (9% combined), and are therefore per consumed unit of energy, and are for water withdrawals only, i.e. they do not include 'pass through' cooling water that is returned to the water system. Water losses from hydro reservoir evaporation are calculated using locale specific evaporation rates. Hydro reservoirs have numerous other uses besides electricity generation but while these were acknowledged in the NREL report, no adjustment is made to the hydro water intensity. We make two adjustments to the NREL results. First, we adjust the hydro water intensity using an economic allocation. Pasqualetti and Kelley *(48)* considered this issue in an Arizona based study. Electric power was estimated to account for 55% of the value of the water, with recreation, agriculture and domestic water supply accounting for 24%, 19% and 2% respectively. This allocation was noted as being a "starting point for further discussion rather than a definite finding". Despite its geographical specificity, we use this value to adjust the water intensity of hydro generation for each state. The second adjustment we make is to recalculate the overall water intensity for each state from the original NREL thermal water intensity, the economically allocated hydro water intensity, and 2006 generation totals obtained from EGRID 2007 *(49)*. Results and data for each of the cities are presented in Table 8.

Table 8: Water consumption of state electricity generation for the nine sample cities. Sources: thermo and hydro water consumption rates *(47)*, Hydro generation percent *(49)*, economic allocation of hydro *(48)*.

City	State	Hydro generation percent	Thermo Water Gals / KWh	Hydro Water Gals / KWh	Allocated Hydro Water Gals / KWh (55%)	Weighted Total Water Use Gals / KWh
Atlanta	GA	0.027963	0.6	47.42	26.08	1.31
Chicago	IL	0.000665	1.05	0	0	1.05
Los Angeles	CA	0.198833	0.05	20.87	11.48	2.32
New York	NY	0.168852	0.85	5.57	3.06	1.22
Phoenix	AZ	0.064107	0.32	64.85	35.67	2.59
San Antonio	TX	0.003355	0.44	0	0	0.44
Seattle	WA	0.706843	0.29	3.19	1.76	1.33
St Louis	MO	0.013706	0.31	0	0	0.31
Tampa	FL	0.001211	0.14	0	0	0.14

Greenhouse Gas Emissions from state electricity consumption.

We state electricity emissions data from eGRID *(49)* converted to CO_2 equivalents using 100 year global warming potentials *(50)* and adjusted for U.S. average GTD losses of 11% *(51)*.

Macro U.S. Pool Chemical Market

Although not used in the model, we also calculate the value of pool chemicals used per pool (as needed to determine impacts using the EIOLCA model) using a top down macro market approach in contrast to our bottom up pool maintenance model approach.

Pool and Pool Chemical Market Growth

For top down pool chemical assessment it was necessary to have the number of pools in the U.S. and the size of the pool chemical market in 2002. Although we did have several data points for these parameters, they were not for 2002, and so we needed to be able to time adjust our data. We used information on growth from several sources covering different ranges over the period 1997 to 2007 to construct a single set of annual growth factors. We assumed interchangeability of pool growth and pool chemical market growth. Wojtowicz states pool growth at approximately 2.2% per annum between 1992 and 2002 *(1)*. SRI Consulting, as quoted in *(52),* estimate pool chemical market growth at between 3% and 4% from 1999 to 2004 and data from PK Data Inc. (53) infers pool growth of 4.0% and 3.7% in 2005 and 2006. Figure 1charts the resultant set of growth factors.

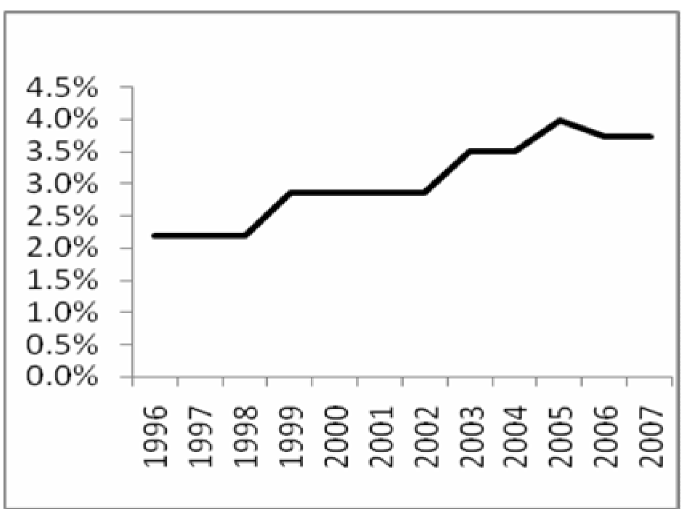

Figure 1: Estimated residential pool and pool chemical market growth, 1996 to 2007.

Number of Swimming Pools in the U.S.

We used 3 data points for the total number of residential swimming pools in the U.S., each from a different year (Table 9). To get the number of pools in any given year, each original number was adjusted using the annual pool and chemical market growth factors (see above). The number of pools for that year was then taken as the mean of the 3 adjusted numbers. We assumed a coefficient of variation for each data source of 5%. The primary need for the number of pools in the U.S. was to calculate the cost of pool chemicals per pool in 2002 for EIOLCA assessment of pool chemicals impact.

Table 9: Data for total number of residential pools in the U.S.

Year	Number of U.S. residential pools	Notes	Source
2006	8,572,330	Inground + above ground	*(53)* from market research.
2002	6,840,000	90% of 7,600,000 pools are residential	The National Spa and Pool Institute cited in *(1)*
2001	6,500,000	Inferred from the total number of residential pool pumps	*(54)* of unknown derivation.

From the above, we calculate the total number of pools in the U.S. in 2002 to be 6,981,550 with a standard deviation of 361,769 and 8,367,580 (standard deviation 460,043) in 2007.

Pool Chemicals Market Value

The value of the pool chemicals market was derived in similar fashion to the number of pools in the U.S. Three values for total market size obtained from trade article sources, each for a different year (Table 10), were adjusted to the desired year using the annual pool and chemical market growth factors and the mean of the adjusted values calculated. A coefficient of variation of 10% for each of the original values was assumed.

Table 10: Data for Pool Chemical Market Value

Year	Pool Chemical Market Value	Notes	Source
1998	$850,000	“recreational” water treatment market value	*(55)*
1999	$850,000	Swimming pool chemicals market	*(56)*
2008	$1,200,000	U.S. *residential* pool chemical market. We assume this is the total swimming pool market and not just residential.	*(57)*

We are interested in the residential pool share only of the total market value. We estimated this share to be between 45-55% based on commercial pools representing “about one half of the treated water” *(1)* and the commercial market being “about the same size as the residential market” *(56)*. In using the first source an equivalency between volume of water treated and value of chemicals used is assumed. The same assumption was used again to remove the value of chemicals used for spa treatment from the total residential market value. According to Wojtiwicz *(1)*, the average spa volume is 550 gallons which is 3% of the average pool size of approximately 16,000 gallons of our model. Thus the total residential pool only, chemical market value is calculated as 97% of 50% of the total pool chemical market.

From the above, the total 2002 pool chemical market values is $938 million (standard deviation $94 million) and the residential pools only market value is $455 million (standard deviation $46 million).

Annual Cost of Chemicals per Pool

For comparison with cost of chemicals per pool estimated from the operational schedule, we also calculate the cost per pool from the total 2002 residential pool chemicals market value of $455 million and the 6,981,550 estimated number of residential pools in the U.S. in 2002 to be $65 ±10 per pool. The model estimated cost ranges from $12 ±4 (Seattle) to $59 ±21 (Tampa). While the results overlap in their upper and lower ranges they are substantially different. There are numerous possibilities for this difference, not least uncertainty of data. The model estimated result ignores some chemicals, for example acidifiers and algaecides, and is thus artificially low. Also, the model does not take into account climatic conditions (other than season length) which would be expected to increase chemical use in warmer, sunnier locations like Arizona. By the same token, chemical use in colder areas is expected to be below average but this is unlikely to balance out as there are likely more pools in the south that consume more than the recommended amount than northern, colder pools that consume less.

Results

Model results for the nine cities are listed in the tables below chemical consumption, water consumption, energy consumption and CO_2 equivalent emissions.

Chemical consumption

Table 11: Model results for chemical use of standard pool in nine sample cities.

City	Trichlor (lb)		Calcium hypochlorite (lb)		Total Chem Qty (lb)		Chem Cost $	
Seattle	8	(3)	5	(2)	13	(4)	12	(4)
Chicago	12	(4)	7	(3)	19	(7)	18	(7)
St Louis	20	(7)	12	(6)	32	(11)	30	(11)
San Antonio	28	(9)	27	(10)	54	(17)	49	(17)
New York	12	(4)	7	(3)	19	(7)	18	(7)
Atlanta	20	(7)	12	(6)	32	(11)	30	(11)
Tampa	36	(12)	29	(13)	65	(22)	59	(21)
Phoenix	28	(9)	27	(9)	54	(17)	49	(16)
LA	24	(8)	26	(9)	50	(16)	45	(15)

Notes. All quantities are in lbs. Standard deviation in parenthesis. Cost is in 2002 producer price.

Water Consumption

Table 12: Model results for water consumption (gallons) of standard pool in nine sample cities.

Cities	Backwash		Refill		Net Evaporation		Direct, by pool		electricity supply		Total	
Seattle	544	(140)	5118	(2092)	2233	(610)	7895	(2512)	819	(295)	8715	(2524)
Chicago	808	(208)	5081	(2076)	863	(382)	6752	(2256)	963	(352)	7715	(2276)
St Louis	1371	(354)	5047	(2059)	1820	(604)	8238	(2446)	468	(167)	8706	(2454)
San Antonio	3258	(840)	2906	(1122)	5206	(1457)	11370	(2456)	1388	(434)	12758	(2491)
New York	816	(208)	5143	(2052)	796	(359)	6754	(2215)	1121	(392)	7875	(2250)
Atlanta	1343	(338)	5102	(2030)	816	(454)	7261	(2238)	2026	(745)	9287	(2376)
Tampa	3247	(823)	2933	(1177)	-215	(571)	5965	(1522)	481	(156)	6446	(1532)
Phoenix	3243	(820)	2885	(1100)	15640	(3983)	21768	(4835)	8219	(2603)	29987	(5457)
LA	3205	(810)	2890	(1113)	9604	(2480)	15700	(3409)	6986	(2203)	22686	(4057)

Notes. Standard deviation in parenthesis.

Energy Consumption

Table 13: Model results for energy consumption (kWh) of standard pool in nine sample cities.

Cities	pool pump		water supply		pool chemicals		Total	
Seattle	617	(213)	26	(10)	107	(41)	750	(216)
Chicago	918	(320)	22	(9)	158	(62)	1098	(326)
St Louis	1533	(528)	27	(10)	265	(104)	1825	(539)
San Antonio	3166	(934)	38	(12)	440	(155)	3644	(945)
New York	916	(309)	22	(9)	163	(62)	1102	(317)
Atlanta	1544	(544)	24	(9)	270	(102)	1838	(555)
Tampa	3440	(1056)	20	(7)	532	(200)	3992	(1077)
Phoenix	3179	(955)	90	(22)	437	(154)	3706	(968)
LA	3004	(892)	204	(49)	398	(145)	3606	(907)

Notes. Standard deviation in parenthesis.

CO2 Equivalents Emissions

Table 14: Model results for CO_2 equivalent emissions (kg) of standard pool in nine sample cities.

Cities	pool pump		water supply		pool chemicals		Total	
Seattle	105	(38)	4	(2)	24	(9)	134	(39)
Chicago	531	(194)	13	(5)	36	(14)	579	(195)
St Louis	1451	(522)	26	(10)	60	(24)	1537	(523)
San Antonio	2196	(689)	26	(8)	100	(35)	2322	(690)
New York	388	(138)	9	(4)	37	(14)	434	(139)
Atlanta	1109	(406)	17	(7)	61	(23)	1187	(407)
Tampa	2358	(766)	14	(5)	121	(46)	2492	(768)
Phoenix	1888	(601)	54	(14)	99	(35)	2041	(604)
LA	831	(263)	57	(15)	90	(33)	978	(267)

Notes. Standard deviation in parenthesis.

Water and energy use per pool open day

Another perspective of the results takes into account the varying utility of pools in different cities. Figure 2 shows water and energy use per pool open season day to be more evenly distributed than annual totals. The high water use in Seattle reflects the brevity of the season and the high relative overhead of the winterizing refill. Phoenix and Los Angeles, despite their long seasons, are still the highest users of energy and water.

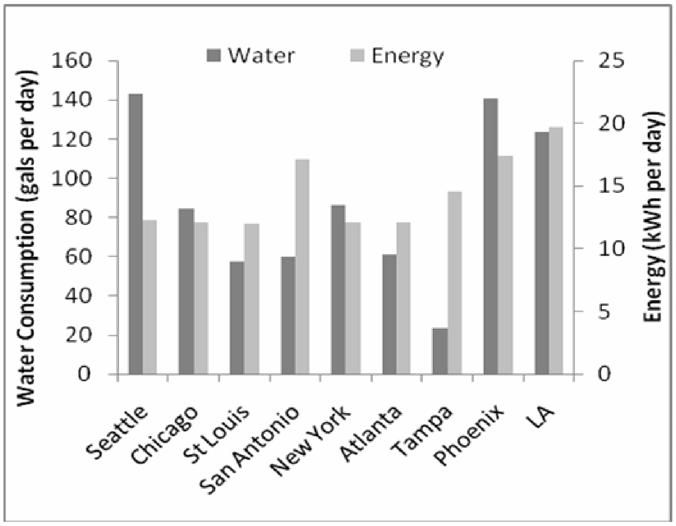

Figure 2: water and energy consumption per open season day in 9 U.S. cities.

Monte Carlo simulation results for Phoenix

Results are evaluated using Monte Carlo simulation containing 5,000 individual results. Figure 3 shows frequency distributions of the individual results for one run of the Monte Carlo simulation for total water consumption, total energy use and total greenhouse gas emissions in Phoenix.

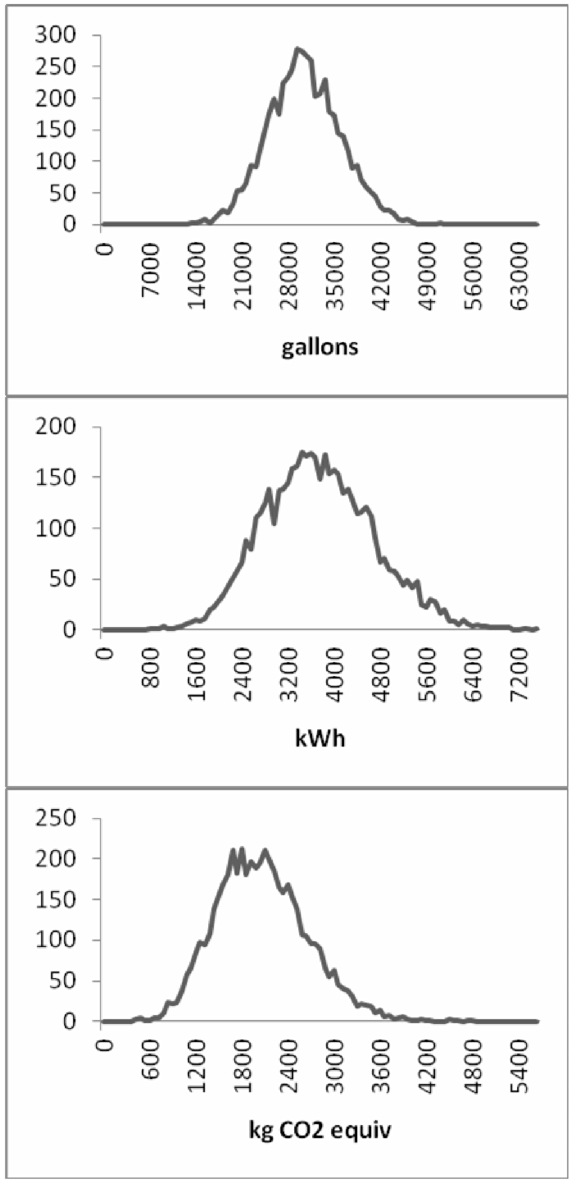

Figure 3: Frequency distribution of Monte Carlo simulation results for standard pool in Phoenix. a) water , b) energy, c) GHG

Normalization at Household and County Level

To put the Phoenix results in context we normalize direct, first order single pool results against the average Phoenix household. Pool water consumption is estimated at 13% an average Phoenix SFR household *(58)*. Normalized electricity use and GHG emissions are estimated at 22% and 20% respectively using statewide per capita averages adjusted by 2.82 persons per household in Maricopa *(59)(60)(61)*. Normalized household electricity use and GHG emissions are expected to be overestimated as they include multifamily housing types, which tend to be less resource intensive than

SFR, and more use of natural gas than is common in Maricopa County. Note that residential GHG emissions do not include transport.

Table 15 shows the derivation of the normalization reference values used to evaluate pool impacts per Maricopa County household. A specific single family residential consumption value was only used for water consumption, coming (indirectly) from the City of Phoenix water utility (58). Values for electricity and GHG emissions were more generally estimated from state level household or residential impacts and demographic data. This introduces some geographical error from variation in energy use across the state, and aggregation error from variation by different types of household, into the results. We speculate that average per capita electricity consumption for Arizona is less than the average for Maricopa County due to the more common use of natural gas for space heating in many of the other counties, and that greenhouse gas emissions follow a similar pattern for the same reason. Thus our reference values for electricity and greenhouse gas emissions are likely to be an underestimate. Also, using general non specific household and general residential sector totals is likely to reduce the reference values below the average SFR due to the typically lower energy consumption of multi-family dwelling types. The normalized impacts for electricity use and GHG emissions, as a percentage of the reference value, is therefore expected to be overestimated.

Table 15: Normalization reference values for Maricopa County households

Impact	Annual Household Impact	Notes	Sources
Water Consumption	165,575 gals	Average per SFR, City of Phoenix, 2000 (626,702 litres).	*(58)*
Electricity Consumption	14,472 kWh	Average per capita consumption of electricity in Arizona homes, 2005 (5132 kWh) multiplied by the average number of persons per household in Maricopa County in 2006 (2.82).	*(59)(60)*
Global Warming Potential	9.3 MT CO_2 equivalent.	Total Arizona residential emissions in 2007 (21 MMT CO_2 equivalent) divided by Arizona population (6,353,421) in	*(60)(61)*

	2007, multiplied by the average number of persons per household in Maricopa County in 2006 (2.82). Note that residential emissions do not include transport.

Comparison of Phoenix subdivisions with and without community pools

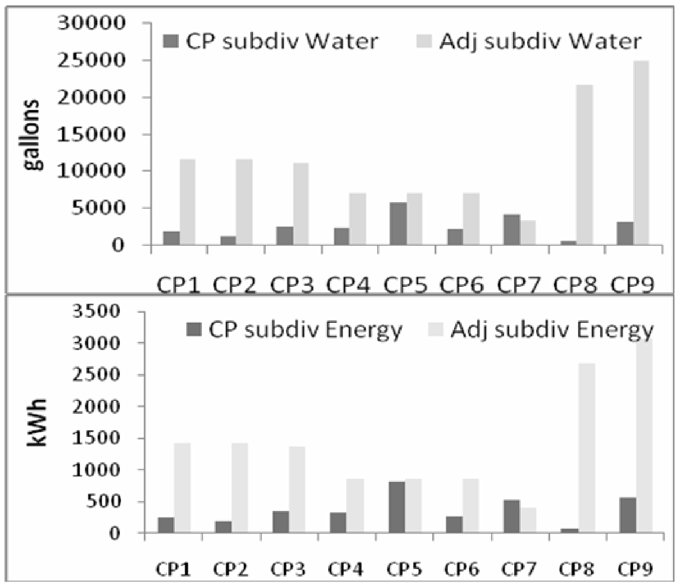

Figure 4: Comparison of per household (a) water and (b) energy consumption in 9 Phoenix area subdivisions (CP1 to CP9) with community pools and adjacent subdivisions without.

From a sample of nine subdivisions the impacts per household are usually much less in subdivisions with a community pool than in neighboring subdivisions without a community pool (Figure 4, Table 16). The mean number of houses in community pool subdivisions is 124 (standard deviation 68) and the mean community pool volume is approximately 43,000 gallons and mean private pools per household 0.05. Neighboring subdivisions have a mean private pool per household of 0.44. Community pools are assumed to operate all year round, to run the pump 16 hours per day on average, and we estimated pump power from pool volume. In seven cases the ratio of water use per household in community pool subdivisions to no community pool subdivisions ranges from 0.03 to 0.34 and 0.03 to 0.37 for energy use. However, two cases illustrate that this is not a general rule with ratios of 0.82 and 1.21 for water and 0.95 and 1.26 for energy. The first of these subdivisions (CP5) is very small (24 houses) and although the community pool is small, the year round operation plus 3 private pools, result in the highest per household water and energy use of any of the community pool subdivisions. For the other subdivision (CP7), exceptionally high consumption of the community pool subdivision is not the cause of the high ratios but rather, it is the exceptionally low pools per household (0.11) of the neighboring subdivision.

Table 16: Data and results for comparison of subdivisions with/without community pools.

ID	CP Volume (gals)	CP subdiv Houses	CP subdiv Private Pools	CP subdiv PPPHH	Adj subdiv Houses	Adj subdiv PPPHH	CP subdiv Energy per HH	CP subdiv Water per HH	Adj subdiv Energy per HH	Adj subdiv Water per HH	CP / Adj Energy per HH	CP / Adj Water per HH
CP1	50266	200	9	0.05	401	0.39	263	1875	1432	11591	0.18	0.16
CP2	26704	46	0	0.00	401	0.39	193	1137	1432	11591	0.13	0.10
CP3	51332	129	7	0.05	186	0.37	352	2454	1375	11124	0.26	0.22
CP4	46675	163	10	0.06	188	0.23	324	2404	867	7018	0.37	0.34
CP5	23936	24	3	0.13	188	0.23	827	5781	867	7018	0.95	0.82
CP6	39307	191	11	0.06	188	0.23	277	2117	867	7018	0.32	0.30
CP7	39607	121	14	0.12	115	0.11	530	4090	419	3390	1.26	1.21
CP8	22739	186	2	0.01	69	0.72	87	577	2685	21730	0.03	0.03
CP9	84150	55	0	0.00	95	0.83	567	3145	3082	24937	0.18	0.13
Avg	42746	124	6	0.05	203	0.44	380	2620	1643	13298	0.41	0.37
SD	19017	68	5	0.05	121	0.28	225	1568	1037	8388	0.42	0.39

Notes: CP: community pool; Adj: adjacent; HH: household; PPPHH: private pools per household; Water in gallons; Energy in kWh.

Mass balance analysis of pool chemical consumption

For verification we compared the mass of pool chemicals consumed as calculated by the model against the actual U.S. consumption quantities. Using the number of pools in the U.S. in 2007 as 8.4 million, the model predicts total U.S. consumption of 108,779 short tons for trichlor. We estimate actual consumption at approximately 166,000 short tons, calculated from 2004 consumption of 148,251 *(9)* and average annual growth of 3.8% from 2005 to 2007 (see pool and pool chemical market growth). According to SRI International as cited in *(62)*, pool and spa treatment make up 83% of the U.S. chlorinated isocyanurate ('chloriso') market, thus reducing the total consumption to 137,671 short tons, almost 29,000 short tons greater than our model result. Several reasons can plausibly explain the difference. Actual consumption data does not differentiate between trichlor and dichlor whereas the model only includes trichlor. Dichlor is commonly used for shock treatment but we ignored it and assumed all shock is performed with calcium hypochlorite. The model is limited to single family residential pools but community, hotel and apartment pools are expected to consume some chlorisos as well. Similarly, the model does not include spas but the actual consumption data does although from our previous estimates, spa share of the residential pool market is small (less than 3%). There are also factors that would increase the difference between model and actual. As discussed previously, a significant number of pools use alternatives to direct chlorination or use chlorine forms other than trichlor whereas we simply assumed all pools use trichlor for background chlorination. Some of this will be made up for by use of dichlor instead of trichlor, thus staying within the overall chlorisos market. Also mentioned previously, we used a season length appropriate for Arizona which, assuming it to be longer than average, will cause the total U.S. consumption to be overestimated.

Performing a similar analysis for calcium hypochlorite, the model predicts a total consumption of 108,779 short tons whereas market data indicates an actual consumption of 104,316 short tons in 2007 based on 1999 consumption of 80,0000 *(7)*, and annual growth of 3.4% between 2000 and 2007. After removing other uses of calcium hypochlorite of 17% *(63)* the total consumption for pool sanitization is 86,193. We speculate that the model result is greater than actual primarily due to the assumption that all shock treatment of all pools is done by calcium hypochlorite. We know that sodium hypochlorite and dichlor are also commonly used as shock treatments. SRI Consulting in *(63)* put the calcium hypochlorite share of the market at between 20% and 60%, with strong geographical variation, although it is not clear exactly what is meant by the “market”. However, if we assume 50% of pools are shocked with calcium hypochlorite then the model total comes down to 54,389 short tons. Considering also that some pools, particularly in the mid west and east *(1)*, use calcium hypochlorite for their background chlorination, will account for at least some of the 32,000 short ton shortfall. As with trichlor, the longer Arizona season will also tend to overestimate the model result, even more so as the model continues shock treatment throughout the closed season whereas a large proportion of U.S. pool population do not.

Use of calcium hypochlorite by community, apartment and hotel pools is excluded from the model and will thus reduce the model result.

There are too many uncertainties and unknowns to conclude that the results of the model can or cannot be verified by a mass balance analysis. However, the mass balancing exercise is in rough agreement with model results and does not indicate the existence of any gross error.

Cost Balance of Pool Chemicals

We also compare the cost of pool chemicals from the model to the cost per pool estimated using a top down, macro market approach. The estimated value of the residential pool chemicals market (excluding spas) is \$454 ±46 million in 2002 and the estimated number of residential pools in 2002 is 6.98 ±0.36 million giving a total cost per pool of \$65 ±10. This is substantially higher than the model results of \$12 ±4 (Seattle) to \$59 ±21 (Tampa). As with the mass balance, there are too many uncertainties to explain this difference but we mention some of the more notable possibilities below.

The top down cost includes all chemicals whereas the bottom up model costs is for chlorination only. Other chemicals used include acidifiers and alkalizers which are relatively bulky but inexpensive, and flocculants and algaecides which are low volume but high value. Including these in the model result would reduce the difference. The application rates used in the model are non specific U.S. rates. The model does account for locale specific season length, which directly relates to chemical use, but it does not make any adjustment based on climatic conditions. Higher temperatures and direct radiation increase hypochlorite breakdown into chloride and oxygen and thus increase chlorination need. Thus model results for locations such as Phoenix, San Antonio and Tampa are expected to be underestimated. By the same token, cooler, less sunny locations are expected to be overestimated. However, the greater number of pools in the higher consumption, southern locations could mean that their aggregate weight far exceeds that of the low consumption locations and this may further account for the difference between model and macro results.

Pool Pump Energy Consumption

The results indicate that pool pumps are large consumers of household electricity, ranging from 600 kWh (Seattle) to 3440 kWh (Tampa) annually. This is no surprise, but just how large our result is may be surprising to some. Lawrence Berkeley National Laboratory estimated average U.S. consumption per pool pump at 1,500 kWh annually in a 1997 residential study *(64)*. The data from which they arrived at this result is not given. We assume it is based on the power rating of shipped equipment and estimated usage. This is approximately half of our result for warmer, year round locations, and is broadly comparable to our results for winterizing locations and we therefore surmise the LBNL result assumes winterization. NRDC *(48)* also questioned the applicability of the LBNL result to the overall U.S.

There is some empirical evidence in support of our pump energy consumption result. A project in central Florida collected detailed end-use load data from 204 houses and found that pool pumps used an average of 4200 kWh per year in the 24% of houses that had pools *(65)*. This is 24% of the total average household consumption of 17130 kWh within the study. In another study, looking at standby power consumption in 10 California homes, it was noted that the average power consumption was 6,769 kWh but the consumption of the only house with a pool was 20,060 kWh, almost twice the 2nd highest consuming house's consumption *(66)*. This is far from conclusive proof, and there were certainly other contributory factors, but it is consistent with high consumption of pools.

Mitigation Measures

There are numerous opportunities to reduce the impact of individual pools and across the area. We present some possibilities below and suggest some policies and incentives that could be used to encourage them.

Technical and operational measures

The following measures are readily available and their uptake is affected by cost, required effort and will of pool owners.

Pool Covers. Reductions of 30-50% in water consumption and 35-65% in chemical consumption are possible *(67)*. But, even though a pool has a cover this does not mean it will be used. The inconvenience of uncovering and covering before and after use is believed to be the primary reason for their scarcity. If this is so, then covering the pool during winter when the pool is not used in those warmer areas that do not normally do so should not be an inconvenience. Using the model, it was found that water consumption is reduced by 31% and 27% and energy consumption by 40% and 45% in Phoenix and Los Angeles respectively when the pool is covered and shut down for the winter and the open season is reduced by 1 month.

Pump Rating and efficiency. Newer pumps can be more efficient and appropriate sizing of pumps can optimize the amount of energy used. Downsizing of pumps can often reduce energy consumption by 40% *(67)(68)* but care must be taken that functional performance still provides adequate turnover of water and is capable of driving the vacuum cleaner. Introducing a variable frequency drive to the system can meet the performance requirements and achieve energy savings of 40% or more *(69)*.

Solar Powered Pool Pump. Solar photovoltaic powered pumps are well suited to pool use as the power source availability coincides with ideal circulation periods. The potential to reduce non renewable electricity consumption by close to 100% exists *(70)*.

The above solutions incur some lifecycle impact of their own, for example, replacing or converting pumps to solar PV. Upgrading existing systems may therefore not be a net benefit. Implementing in new pools is a much safer decision. There are other technical solutions that are potentially beneficial but their effectiveness and environmental impacts are uncertain.

Monolayer evaporation retardants are cetyl alcohol or silicon thin film barriers, formed on the water surface, that have been used to reduce evaporation from reservoirs. The main obstacle to their wider use is cost *(71)*. Monolayer products are available for use on pools.

Truck mounted filtering to remove dissolved solids from pool water and return the conditioned water to the pool can eliminate annualized water loss of approximately 2,900 gallons per year (for the standard pool) from the standard practice of discharge and refill *(72)* in non winterized locations. It also reduces the need for wastewater treatment plants to remove chlorine and prevents the accumulation of dissolved solids in the local hydrological system. The eventual fate of the removed solids is unknown.

Maintenance practices. Fine tuning pump running time to the actual needs of the individual pool as opposed to generally recommended guidelines can reduce can reduce energy and chemical consumption. A Florida Atlantic University study of 120 Florida pools reported in *(67)* found daily circulation time could be reduced to less than 3 hours saving on average 60% on electricity cost. Careful and knowledgeable chemical application can minimize chemical consumption. For example, pH above 7.3 decreases the bactericidal effectiveness and increases photolytic decomposition of chlorine due to the predominance of hypochlorite over hypochlorous acid and thus leads to higher chlorination rates than are necessary at pH 7.3.

Policy: incentives and regulation

The above measures can be effective at reducing water and/or energy use of pools but at this stage their adoption is entirely up to the homeowner. Public measures can be used to encourage or enforce change. Homeowners spend a considerable sum for pool ownership, estimated at about $100 per year for water, $300 - $400 per year for electricity and between $200 - 360 per year for chemicals in Phoenix. There is thus a financial incentive for homeowners to practice better pool management. Conservation measures often suffer market failures however due to incomplete information and other factors *(73)*. Policy has a role in educating and providing incentives. Regulation of residential pool use is also a possibility, though clearly more politically challenging. We list some possible incentives and regulations below

Subsidies to purchase efficient pool technology. Governments from federal to the local level subsidize the purchase of energy efficient technologies by homeowners. While these policies mainly target technologies "in the home" such as photovoltaics, the same strategy could also be applied to encourage adoption of pool technologies.

Smart metering of energy and water use. Homeowners generally have incomplete information on the structure of their energy and water use. By and large the only data is monthly aggregated consumption listed on bills. Smart metering technologies both allow more timely information and also can disaggregate energy and water use by application. With this additional information homeowners can more clearly recognize the resource cost of pool use and presumably become more apt to take action to reduce *(74)*.

Educational measures. Smart metering motivates homeowners to mitigate pool and other major sources of energy and water use, but in many cases residents may not know what measures to take. Educational campaigns can play a role in informing residents of their options.

Incentives to Fill-In Existing Pools. Not all residents who own pools want them: in addition to the aforementioned financial cost, pools require time to maintain and occupy space in yards. Utilities could offer rebates to fill-in pools in much the same way they have done to replace high consumption residential irrigation systems with xeric landscaping.

Building codes can be used to enforce minimum standards. Title 24 of the California building codes becomes effective January 1st 2010 and includes minimum efficiency standards for pool pumps *(75)* for new construction and replacement.

Planning Permission for New Pools. Avoiding construction of new pools will begin to reduce ownership rates and cumulative impacts. Limiting pool surface area reduces consumption. Development of new neighborhoods could be encouraged to include community pools and discouraged from building private, SFR pools that would, as our results show, reduce per household impact.

Pricing of Water. Using progressive rates, pricing can be targeted at excessive consumption and avoid penalizing basic needs water use. However, the pricing magnitude to achieve the desired result would have to be large due to the current small proportion of water costs in the average household budget *(77)*.

Enforced use of Pool Covers. Cities have it within their authority to impose regulations requiring the use of pool covers but are generally unwilling to use it unless in a situation of sever water shortage *(76)*. Note however, from a water conservation perspective, pool covers appear only to be useful in arid climates, particular in summer.

Residential pools in Phoenix, Arizona

Maricopa County, population 3.7 million in 2006 *(78)*, is dominated by Phoenix and surrounding cities, and has one of the highest concentrations of pools nationwide at 0.074 pools per capita *(34)*. In 2007, 28%, or 278,302 of the 1.08 million single family residential (SFR) properties in the county had an inground pool *(34)*. We conservatively estimate an additional 7875 above ground pools using the rate of 0.0038 per capita in Utah, the lowest of any state *(35)*, as an upper bound and a nominal 1000 as lower bound. This brings the total number of SFR pools to 286,177 with an estimated combined surface area almost 12 km2. This does not include communal, municipal, and hotel pools.

The population of Maricopa County is projected to grow to 5.8 million by 2025 creating a need for more than 500,000 new SFR homes, assuming 0.27 SFRs per capita *(78)(34)*. Whereas the ratio of SFRs to population was fairly constant at 0.27 between 2003 and 2007, the ratio of inground pools to SFRs increased from 0.24 to 0.26 in the same period. 37% of new homes built in this time had a pool *(34)*. There is a clear trend that pools are increasing at a faster rate than housing and population (Figure 5).

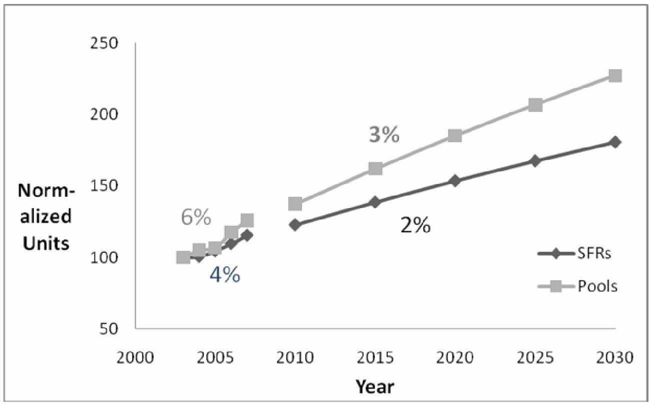

Figure 5: Growth in SFR homes and SFRs with pools in Maricopa County, Arizona, from 2002 to 2007, and forecast to 2030. (2002=100). Sources: *(34)(78).*

Comparative Household Efficiency Savings

Water appliance and fixture efficiency savings daily per capita water use and potential savings date are taken from the Handbook of Water Use and Conservation listed in *(79)* and adjusted by 2.59 persons per average U.S. household in 2000 *(80).*

For central air conditioning, refrigerators and lighting we estimate energy savings as follows. Relative savings are arrived at by taking the 2007 stock appliance rating or in the case of lighting an assumed base rating, and replacing it with commonly available efficient appliances in 2009. Efficiencies and ratings of available efficient models are obtained from EPA Energy Star data *(81)* for refrigerators and lighting and from a commercial supplier for central air conditioners *(82)*. For refrigerators and air conditioning units we went back to the source to get the 2007 stock rating *(83)*. For lighting, we assume energy savings of 67% based on replacement of all remaining incandescent bulbs with compact fluorescent lamps (CFL) where 89% of sockets are incandescent to begin with *(84)* and a CFL bulb uses 75% less electricity than an incandescent. (We acknowledge this is an upper bound as for various reasons CFLs are unlikely to achieve a full 75% reduction in energy use compared to an incandescent bulb and it is also unlikely that CFL can be used in every light socket in a house). Using the percentage reduction in energy use we calculated the annual energy saving per household from the average energy consumed per household for that appliance in 2007 as reported by the Energy Information Agency in the 2009 Annual Energy Outlook (AEO, updated for the American Recovery and Reinvestment Act) *(85).*

We also estimate energy savings for clothes washer and dishwasher using general Energy Star statements that Energy Star rated models of these products use 30% and 10% less energy respectively than regular non Energy Star models *(81)* and household energy consumption in 2007 for these products is 90 kWh and 245 kWh per year as reported in AEO 2009 *(85)*. This yields annual energy savings of 27 kWh and 25 kWh for clothes washers and dishwashers respectively.

Table 17: Estimated energy savings from selected U.S. household appliance upgrades

Electricity	Total Site Energy Consumed (quads)[a]	Energy Consumed per Household (kWh)	Percent of Household total	Standard / Stock Rating 2007	Readily Available Technology Rating 2009	Reduction in consumption	Saving per Household (kWh)
Space Heating	0.28	727	6%				
Space Cooling	0.88	2272	19%	11.56 SEER[b]	18 SEER[d]	36%	813
Water Heating	0.42	1085	9%				
Refrigeration	0.39	995	8%	642 kWh[b]	450 kWh[e]	30%	298
Cooking	0.11	271	2%				
Clothes Dryers	0.27	689	6%				
Freezers	0.08	210	2%				
Lighting [c]	0.73	1889	15%	100	25	67%	1266
Clothes Washers	0.03	90	1%			30%[e]	27
Dishwashers	0.10	245	2%			10%[f]	25
Color Televisions and Set-Top Boxes	0.36	929	8%				
Personal Computers and Related Equipment	0.15	395	3%				
Furnace Fans and Boiler Circulation Pumps	0.13	332	3%				
Other Uses 2/	0.82	2108	17%				
Delivered Energy	4.75	12239					

Notes

[a]US residential consumption (114 million homes), from *(83)*.

[b]2007 stock appliance ratings from *(83)*.

[c]Assumes replacement of all incandescent lighting by CFL where 89% of light sockets are incandescent *(84)* to startand CFLs use 75% less energy than incandescent *(81)*.

[d]Available models range from 16 to 21 SEER and are all EnergyStar *(82)*.

[d]EnergyStar rated refrigerators available in 2009 range from 381-533 kWh annual energy consumption *(81).*
[e]EnergyStar qualified clothes washers use about 30% less energy than regular washers *(81).*
[f]EnergyStar qualified models are, on average, 10% more energy efficient than non-qualified models *(81).*

For central air conditioning we adjusted the saving from an average U.S. household to a Phoenix household by using the relative consumption values reported for this appliance in the U.S. and in warm climate zones by the 2005 Residential Energy Consumption Survey Housing Characteristic tables (86). These tables report that 2001 consumption in warm climates was 6,096 kWh which is 175% of the U.S. average of 3,488 kWh. Adjusting the savings of 813 kWh in Table 17 by this amount results in an estimated saving of 1,421 kWh for Phoenix. The other appliances do not vary significantly from the U.S. average.

Household savings from refrigerators exceeds savings from a single appliance. One reason for this is that there are more refrigerators than there are households. Another possible reason is that the annual consumption rating of refrigerators is systematically understated.

Literature Cited

(1) Wojtowicz, J. A. Water Treatment of Swimming Pools, Spas, and Hot Tubs. In *Kirk-Othmer Encyclopedia of Chemical Technology;* John Wiley & Sons: New York; [online] 2004; http://mrw.interscience.wiley.com/emrw/9780471238966/home/.

(2) O'Connel, G., Brayton, P. W. *Swimming Pool Operator's Handbook,* 3rd ed.,; Maricopa County Department of Health Services: Phoenix, AZ, 1980.

(3) National Oceanic and Atmospheric Administration. *Evaporation atlas for the contiguous 48 states*. NOAA Technical Report NWS 33. U.S. Department of Commerce: Washington, DC, 1982.

(4) Arizona Department of Water Resources. *Arizona Water Atlas.* Volume 1 (Introduction), 2008. http://www.azwater.gov/dwr/Content/Find_by_Program/Rural_Programs/content/water_atlas/default.htm (accessed Jan 2009).

(5) Arizona Meteorological Network, University of Arizona. Evapotranspiration: Relationship to Pan Evap. and Lakes & Ponds. http://ag.arizona.edu/azmet/etpan.htm (accessed June 5 2009).

(6) Kennedy, W. PK Data Inc. Personal Communication, Apr 2009.

(7) *Chemical Market Reporter*: 49, November 06, 2000.

(8) *Chemical Market Reporter*, 259 (3), 25, January 15, 2001.

(9) U.S. International Trade Commission. *Chlorinated Isocyanurates from China and Spain*. Publication 3782, 2005. http://www.usitc.gov (accessed Nov 2008).

(10) Arizona Department of Agriculture. *We put chlorine manufacturers and retailers to the test: here's who passed and failed.* Press Release, May 24, 2006. http://www.azda.gov/main/PressReleaseChlorine-Results2006.pdf (accessed Feb 2009).

(11) Woodard, G. Shifting Patterns of Water Demand: Socio-Demographic Challenges for Water Managers. Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA), College of Engineering & Mines, University of Arizona, 2003. http://www.sahra.arizona.edu/kt/media/files/Phoenix_03-20-2003/Gary_Woodard.pdf (accessed 22 Mar 2008).

(12) *Google Earth*, 2009, http://earth.google.com/.

(13) National Renewable Energy Laboratory. *Report on Solar Pool Heating Quantitative Survey.* NREL/SR-550-26485, 1999. http://www.nrel.gov/docs/fy99osti/26485.pdf.

(14) Huijbregts, M.A.J. Application of uncertainty and variability in LCA. Part I: A general framework for the analysis of uncertainty and variability in life cycle assessment. *Int. J. LCA*, **1998**, 3(5), 273 - 280.

(15) Heijungs, R.; Huijbregts, M. A. J. *A review of approaches to treat uncertainty in LCA*. In Complexity and integrated resources management. Proceedings of the 2nd biennial meeting of the International Environmental Modelling and Software Society (iEMSs), edited by C. Pahl-Wostl et al. Manno, Switzerland: International Environmental Modelling and Software Society.

(16) Par Pool and Spa. Pool Care Tips and FAQs. Compare Types of Chlorine. http://www.parpool-spa.com/Page/Help/Pool/Pool_Care_Comparisons.html (accessed Mar 2008).

(17) Australian Pesticide & Vetinary Medicines Association. Pool and Spa Products – Label Change. http://www.apvma.gov.au/registration/labelchg.shtml (accessed Mar 2008).

(18) Arch Chemicals Inc. HTH Pool Care Guide, 2007. http:// www.archchemicals.com/Fed/HTH/Docs/HTH_Pool_Care_Guide.pdf (accessed Sep 2008).

(19) Pool Support, Inc. Online pool manual. http://www.poolmanual.com/poolmanual.aspx (accessed Sep 2008).

(20) Allen, S.D. *Energy savings through automatic seasonal run time adjustment of pool filter pumps*. Allen Concepts Inc. 2005. http://www.tightwatt.com/white-paper/index.html (accessed Apr 2008)

(21) Inyo Pool Products Inc. Frequently Asked Questions - Pool Pump Questions. 2008. http://www.inyopools.com/poolanswers_pumps.aspx#pumps5 (accessed Mar 2009).

(22) U.S. Department of Energy. Installing and Operating a Swimming Pool Pump for Energy Efficiency. Energy Efficiency and Renewable Energy, 2005. http://www.eere.energy.gov/consumer/your_home/water_heating/index.cfm/mytopic=13290 (accessed April 2008).

(23) Arizona Pool Pros. Frequently Asked Questions. http://www.arizonapoolpros.com/faqs.htm (accessed Sep 2008).

(24) National Spa and Pool Institute (South Africa). Energy Saving Tips for Swimming Pools. http://www.nspi.co.za/articles-2006/nspi-energy-saving-tips-for-swimming-pools.html (accessed Sep 2008).

(25) Pool & Spa Warehouse. How to Backwash your Filter. http://www.poolandspawarehouse.com/tip14.asp (accessed May 2009).

(26) Laguna Pools. Pool Owners Frequently Asked Questions. http:// www.lagunapools.com/ownerfaq.htm#HowOftenShouldIBackwashDiatomaceousEarthFilter (accessed May 2009).

(27) PoolCenter.Com. Pool Info: Filter. http://www.poolcenter.com/filter.htm (Accessed May 2009).

(28) Arizona Department of Water Resources. *Third Management Plan for Phoenix Active Management Area 2000 - 2010.* 1999. http://www.azwater.gov/dwr/Content/Publications/files/ThirdMgmtPlan/tmp_final/default.htm#Phoenix.

(29) Couture, B.; Grotte, J.; Deware, M. *The Comprehensive Guide to Swimming Pool Ownership*, [Online], http://www.ecosmarte.com/Ebook/SwimmingPoolGuide.pdf (accessed Jan 12 2009).

(30) Hayward Industries Inc. Inground pools: pumps. http://www.haywardnet.com/inground/products/pumps (accessed November 3, 2009).

(31) Gelt, J. Water recreation makes big splash in Arizona. Water Resources Research Center, College of Agricultural and Life Sciences, University of Arizona, http://ag.arizona.edu/AZWATER/arroyo/083recr.html (accessed Apr 2008).

(32) Sanchez, M. Miscellaneous water under the energy bridge. *Home Energy Magazine* [Online], March/April 1999, http://www.homeenergy.org/archive/hem.dis.anl.gov/eehem/99/990304.html (accessed May 2 2008).

(33) Pump and Filter Resource Warehouse. Swimming Pool Pumps - An overview. http://www.pump-and-filter.com/swimming-pool/swimming-pool.html (accessed April 2008).

(34) Maricopa County Assessor's Office. Property assessment records 2002 – 2007. Available by request. Accessed 2008.

(35) P.K. Data, Inc. *Waveline* **2008**, 15. http://www.pkdata.net/PKData/Waveline/15/Waveline%2015.htm (accessed Dec. 26, 2008).

(36) U.S. Census Bureau. Fact Sheet for Maricopa County, Arizona, 2005 – 2007. http://www.factfinder.census.gov (accessed Sep 2008).

(37) PK Data Inc. *Waveline* **2008**, 16. http://www.pkdata.net/PKData/waveline/16/waveline16.htm (accessed Dec 2008).

(38) National Oceanic and Atmospheric Administration. *Observed weather reports*. U.S. Department of Commerce, National Weather Service. http://www.weather.gov/climate/index.php?wfo=ffc (accessed November 2009).

(39) Guhathakurta, S., Gober, P. The impact of the Phoenix urban heat island on residential water use. *Journal of the American Planning Association*, 2007, 73(3), 317-329.

(40) PK Data Inc. *Waveline* **2008**, 17. http://www.pkdata.net/PKData/Waveline/17/Waveline%2017.htm (accessed Dec 2008).

(41) Rivera, J.; Calwell, C.; Moorefield, L. *Synergies in Swimming Pool Efficiency: How Much Can Be Saved*. Natural Resources Defense Council, 2008.

(42) Arpke, A.; Hutzler, N. Domestic water use in the united states: a life-cycle approach, *J Ind. Ecol.* **2006**, 10(1), 169-84.

(43) Cohen, R.; Barry, B.; Wolff, G. *Energy Down the Drain: The Hidden Costs of California's Water Supply*. Natural Resources Defense Council: New York, 2004. Available at http://www.nrdc.org/water/conservation/edrain/contents.asp (accessed Apr 2008).

(44) *Refining Estimates of Water Related Energy Use in California*. CEC-500-2006-118. California Energy Commission: Sacramento, CA, 2006. Available at http://www.energy.ca.gov/2006publications/CEC-500-2006-118/CEC-500-2006-118.PDF (accessed November 11, 2009).

(45) Crittenden, J.; Lyons, E.; Zhang, P.; Benn, T.; Costanza, M.; Li, K. Life cycle assessment of three water scenarios: importation, reclamation, and desalination. Presented at First Western Forum on Energy & Water Sustainability, 22 March 2007. http://www2.bren.ucsb.edu/~keller/energy-water/3-3%20John%20Crittenden.pdf (accessed March 2009).

(46) Elliot, T,; Zeier, B.; Xagoraraki, I.; Harrington, G.W. *Energy use at Wisconsin's drinking water facilities*, Report 222-1. Energy Center of Wisconsin: Madison, WI, 2003. http://www.ecw.org/prod/222-1.pdf (accessed Dec 2008).

(47) Torcellini, P.; Long, N.; Judkoff, R. *Consumptive Water Use for U.S. Power Production*. NREL/TP-550-33905. National renewable Energy Laboratory: Golden, CO, 2003.

(48) Pasqualetti, M.; Kelley, S.M. The water costs of electricity in Arizona. Executive Summary. Arizona Water Institute, http://www.azwaterinstitute.org/media/Cost%20of%20water%20and%20energy%20in%20a.z, 2009

(49) U.S. Environmental Protection Agency. *Emissions & Generation Resource Integrated Database, eGRID2006;* Version 2.1., 2007. http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2006V2_1_Summary_Tables.pdf (accessed April 2008).

(50) US Environmental Protection Agency. *Greenhouse Gases and Global Warming Potentials*, Table 2., 2002. http://www.epa.gov/climatechange/emissions/downloads/ghg_gwp.pdf.

(51) Energy Information Agency. *Annual Energy Review 2007*. Diag 5, Electricity Flow. U.S. Department of Energy: Washington, DC, 2007. http://www.eia.doe.gov/aer/pdf/pages/sec8_3.pdf (accessed Sep 2008).

(52) Rin-rin, Y. Bubbling Back Up, *Pool and Spa News* [Online], 4 June 2004. http://www.poolspanews.com/2004/061/061qmr_market.html.

(53) P.K. Data, Inc. US Pool & Spa Market, Media Fact Sheet, 2006. http://www.apsp.org/clientresources/documents/PK%20Data%20Free%20Info%20-%202006.pdf (accessed Mar. 22, 2008).

(54) Energy Information Agency. *End-use Consumption of Electricity 2001*. U.S. Department of Energy: Washington, DC, 2001, http://www.eia.doe.gov/emeu/recs/recs2001/enduse2001/enduse2001.html (accessed Apr 2009).

(55) *Chemical Market Reporter*, 254 (8): 28, August 24, 1998.

(56) Making a splash in pool chemicals, *Chemical Week*, 161 (18): 30, May 12, 1999.

(57) Compass Forms Salt Water Pool Unit, *Chemical Week*, **2008**, 31.

(58) Wentz, E. A.; Gober. P. Determinants of small-area water consumption for the City of Phoenix, Arizona. *Water Resour. Manag*. **2007**, 21(11), 1849-63.

(59) U.S. Department of Energy. Electric Power and Renewable Energy in Arizona. Energy Efficiency and Renewable Energy. http://apps1.eere.energy.gov/states/electricity.cfm/state=AZ.

(60) U.S. Census Bureau. T1 Population Estimates, Arizona, Detailed Tables. http://www.factfinder.census.gov (accessed Apr 2009).

(61) Arizona Climate Action Initiative. *GHG Emissions Inventories (Final Arizona GHG Inventory and Reference Case Projection, CCS, June 2005).* Arizona Department of Environmental Quality: Phoenix, AZ, 2006. http://www.azclimatechange.gov/download/O40F9347.pdf (accessed June 2009).

(62) Wojtowicz, J. A. Water Cyanuric and isocyanuric acids. In *Kirk-Othmer Encyclopedia of Chemical Technology;* John Wiley & Sons: New York; [online] 2004; http://mrw.interscience.wiley.com/emrw/9780471238966/home/.

(63) Jarvis, L. Pool Chemicals Enjoy Strong Demand As Prices and Margins Gain Momentum. ICIS, http://www.icis.com/Articles/2000/07/17/117563/pool-chemicals-enjoy-strong-demand-as-prices-and-margins-gain.html (accessed Mar 2008).

(64) Wenzel, T. P.; Koomey, J.G.; Rosenquist, G. J.; Sanchez, M. C.; Hanford, J.W. *Energy Data Sourcebook for the U.S. Residential Sector LBNL-40297*. Lawrence Berkeley National Laboratory: Berkeley, CA, 1997. http://enduse.lbl.gov/info/Pubs95_99.html (accessed May 2009).

(65) Parker, D.S. Research highlights from a large scale residential monitoring study in a hot climate. *Energ. Buildings*, **2003**, 35(9), 863-876.

(66) Ross, J. P.; Meier, A. Whole-House Measurements of Standby Power Consumption. In Proceedings of the Second International Conference on Energy Efficiency in Household Appliances. Naples (Italy): 2000. Association of Italian Energy Economics (Rome). Also published as Lawrence

Berkeley National Laboratory Report LBNL-45967. http://www.osti.gov/bridge/servlets/purl/793739-FoRVRe/native/793739.pdf (accessed May 2009).

(67) U.S. Department of Energy. Swimming Pool Heating. Energy Efficiency and Renewable Energy. http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=13290 (accessed Jan 3 2010).

(68) Parker, D.; Sherwin, J.; Sonne, J.; Barkaszi, S.; Floyd, D.; Withers, C. Measured Energy Savings of a Comprehensive Retrofit in an Existing Florida Residence. For the Florida Energy Office, 1997. http://www.fsec.ucf.edu/en/publications/html/FSEC-CR-978-97/ (accessed June 2009).

(69) Hameiri, Z.; Spooner, T.; Sproul, A.B. High efficiency pool filtering systems utilising variable frequency drives. *Renew. Energ.* **2009**, 34(2), 450-455..

(70) Kehret, R. DIY Solar Pool Pump Project. Northern California Solar Energy Association, http://www.norcalsolar.org (accessed June 2009).

(71) Basso, E. Alteration of the water balance of lakes. *Lake. Reserv. Manage.* **2000**, 5(1): 5-9.

(72) Bloom, A. No drain on environment, *The Arizona Republic*, 28 Aug 2008.

(73) Levine, M.D.; Koomey, J.G.; McMahon, J.E.; Sanstad, A.H.; Hirst, E. Energy Efficiency Policy and market Failures, *Annu. Rev. Energy. Environ.* **1995,** 20, 535-555.

(74) Parker, D.; Hoak, D.; Meier, A.; Brown, R. How Much Energy Are We Using? Potential of Residential Energy Demand Feedback Devices. Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: American Council for an Energy Efficient Economy (also LBNL-63383). August 2006. pp 1-211: 1-222.

(75) California Code of Regulations, Title 24 § 150(p).

(76) City of Phoenix, Water Services Department. Water Supply Questions and Answers. 2007. http://phoenix.gov/WATER/drtfaq.html (accessed April 2008).

(77) Balling, R.; Gober, P. Climate variability and residential water use in the City of Phoenix, Arizona. *J. Appl. Meteorol. Clim.*, **2007**, 46.

(78) U.S. Census Bureau. 2006 population estimates, Maricopa County, Arizona. General Demographic Statistics. http://factfinder.census.gov (accessed Sep 2008).

(79) American Water Works Association. Water Use Statistics, 2009. http://www.drinktap.org/consumerdnn/Home/WaterInformation/Conservation/WaterUseStatistics/tabid/85/Default.aspx .

(80) U.S. Census Bureau. Occupied Housing Characteristics 2000, Table GCT-H6, http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=01000US&-_box_head_nbr=GCT-H6&-ds_name=DEC_2000_SF1_U&-redoLog=false&-mt_name=DEC_2000_SF1_U_GCTH5_US9&-format=US-9.

(81) Energy Star. U.S. Environmental Protection Agency, 2009. http://www.energystar.gov/index.cfm?fuseaction=find_a_product.

(82) Carrier Corporation. Central Air Conditioners. http://www.residential.carrier.com/products/acheatpumps/ac/index.shtml (accessed Jan 2009).

(83) Energy Information Administration. *Annual Energy Outlook, 2008*. Report No. DOE/EIA-0383, Supplemental Table 21. U.S. Department of Energy: Washington DC, 2008. http://www.eia.doe.gov/oiaf/archive/aeo08/supplement/supref.html.

(84) Energy Star. *CFL Market Profile*. U.S. Department of Energy: Washington, DC, 2009. http://www.energystar.gov/ia/products/downloads/CFL_Market_Profile.pdf (accessed May 2010).

(85) Energy Information Administration. *Annual Energy Outlook*, *2009 with Projections to 2030, Updated Annual Energy Outlook 2009 Reference Case with ARRA*. Report #: SR-OIAF/2009-03, Table 4. U.S. Department of Energy: Washington, DC, 2009. http://www.eia.doe.gov/oiaf/servicerpt/stimulus/aeostim.html.

(86) Energy Information Administration. Residential Energy Consumption Survey (RECS), 2005, http://www.eia.doe.gov/emeu/recs/contents.html.