Estimating Daily Domestic Hot Water Use in North American Homes

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Introduction

Water heating in the U.S. is a major component of total energy consumption used in buildings, accounting for approximately 18% of total consumption in the residential sector (EIA, 2010). While there are many factors influencing hot water energy use (location, fuel, combustion and heating efficiency and standby losses), the actual volume of water to be heated is a fundamental value for any reasonable estimate of hot water energy use.

Limitations of Previous Data

Measuring hot water volumetric consumption is more difficult than measurement of energy and thus, measurements are also more limited. Early studies on hot water use in single family residences included Weihl and Kempton (1985), Kempton (1986) and Perlman and Mills (1985).

Often cited, the Perlman data (1984) was taken on five residences in Toronto and another fifty homes in Ontario. Evaluation of the data showed that daily household hot water use for a typical household of four persons was 63.1 gallons—although with strong seasonal variation: 45.2 gallons per day in summer against 65.7 gallons in winter. Moreover, these data are potentially biased as the household size in the sample was 3.8 persons.

Further U.S. household size—which is a large factor in hot water demand-- has dropped over time. Figure 1 shows how household size has changed since 1940, dropping precipitously from 1970-1990. Also, machine-related hot water draws from both washing machines and dishwashers have become lower with newer, more efficient machines. In fact, it can be argued the four person household, chosen for the DOE test procedure was not typical even when the ASHRAE Project RP 430 was completed. Data from 1982-1983 were collected during which time data from the U.S. census showed that the typical occupancy of U.S. households was only about 2.8 persons.

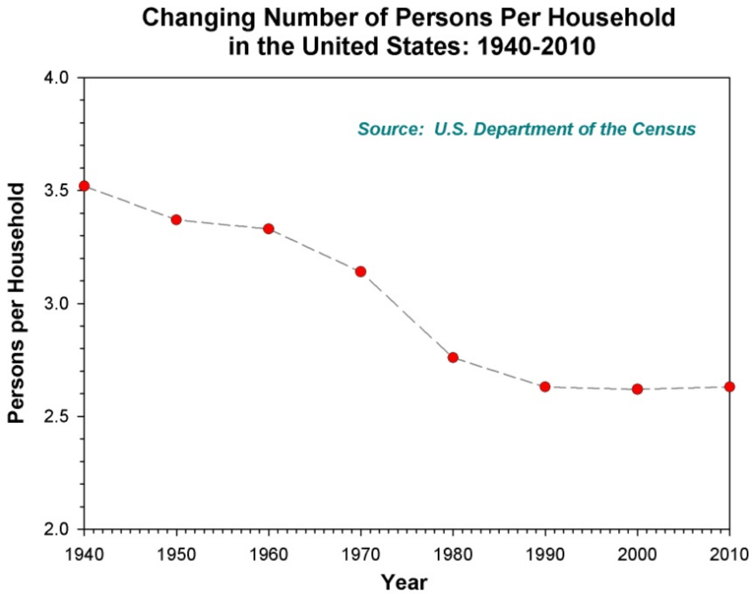

Figure 1: Changing occupancy in U.S. households, 1940-2010

Current occupancy is essentially unchanged since 1990. In single family homes, occupancy is slightly greater, but in the 2009 RECS data, the average number in the household was still only 2.8 persons. Thus, a “typical” household, as called out be Perlman et al., is much more a three person household than one with four persons. This presents a real bias in the original hot water flow volume adopted by DOE for its testing purposes.

In a follow-on research project designed to update the data on residential hot water use patterns, Becker and Stogsdill (1990) gathered, analyzed and reported on nine different data sets consisting of more than 3 million data points on hot water use in residences. This project included the data used by Perlman and Mills (1985) as well as a number of additional data sets that were gathered in both Canada and the continental U.S. This included measurements from 110 single-family residences from 11 utilities reported by Gilbert et al. (1985) which found average household hot water consumption to average 66.2 gallons. Included were, measurements from 142 homes in the Hood River Oregon area reported by Hirst, et al. (1987); and monitoring data from74 homes in Florida and 24 homes in North Carolina reported by Merrigan (1988). Each of these data sets contained measured hot water use data of one year or greater in duration, from which Becker reported the average hourly hot water use in gallons for the continental U.S.

It is worthwhile examining a subset of these homes in some greater detail. Merrigan, in Florida from 1982-83, measured hot water use per household to average 60.0 gallons per day, in 74 homes with 3.53 average occupants. Consumption was found to roughly vary with occupancy: gallons per day averaged 44, 56, 68 and 72 gallons per day in homes with 2-5 occupants, respectively

Similarly, 24 homes monitored in North Carolina (Merrigan, 1985) showed average hot water consumption of 56.9 gallons per day, but with the average varying seasonally: 64 gallons in January down to only 48 gallons in July.

Measurement over a year long period by Abrams and Shedd on 13 single family homes in the Atlanta area with electric resistance water heaters showed 62.1 gallons per day of hot water consumption, but also with strong seasonal variation. However, these homes were intentionally chosen for high-occupancy (3.77 occupants per household)—considerably greater than typical occupancy single family now which is approximately 2.8 persons per household.

Also, with the advent of more efficient hot water fixtures and less hot water used for modern dishwashers and clothes washers, calls into question the validity of the older numbers. In particularly, the changing number of occupants per household is important as well as the more efficient appliances such that the 64.3 gallons per day used by DOE is almost certainly high as an average by about 15%. An EPRI evaluation of a compendium of studies in the late 1990s concluded that

"the figure of 64.3 gallons per day which was established in the 1960s and 1970s, and is currently used in U.S. Department of Energy testing and rating procedures—isn't representative of actual use…It would appear that there is general agreement among data sets collected since the 1980s that the average hot water consumption for single family residences is less than 50 gallons per day."[1]

Recent studies have included Lowenstein and Hiller (1996 and 1998), Mayer, 1999 and Henze et al., 2002). In 14 sites, Lowenstein and Hiller (1998) saw an average hot water consumption of 56.9 gallons per day with showers and baths accounting for 51% of consumption and dishwashing and clothes washing accounting for 11% and 13%, respectively. Henze et al. (2002) measured four Nebraska residences in significant detail using the flow-tracing methodology, but found only 35 gallons of hot water use per day with 59% of this coming from showers and baths, 17% from sinks and the 10% and 12% coming from dishwasher and clothes washer, respectively.

Another study, using the flow tracing methodology by U.S. EPA (Aquacraft, 2005) recorded hot water use in ten homes each in Seattle and the East Bay of California in 2003. Measured hot water use was 55.4 gallons in the Seattle Homes and 49.2 gallons per day in the East Bay homes. [2] Approximately 80% of hot water consumption was found to come from baths, showers and faucet use. These numbers were reduced by approximately 17-25% by installing more water conserving fixtures, although only half of these savings came from fixtures.[3]

Another assessment done by Lutz (2005) at LBNL examined fifty studies using a flow tracing methodology where it was concluded that average hot water use was approximately 52.6 gallons

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[1] Carl Hiller, "Electric Water Heating News," EPRI, Vol. 10, No. 2, Summer, 1997.

[2] One caution: these studies were only of two weeks duration. As will be shown, unlike overall water use, hot water varies significantly by season as the largest end-use, bath and hand washing are sensitive to temperature and thus to the mix of hot and cold to arrive at a favorable temperature—typically 105 F (see Abrams and Shed, 1996). At least six months of data spanning winter and summer are necessary to obtain representative data.

[3] Daily hot water use for clothes washing in the 20 monitored homes averaged 6.7 gpd, dropping to 3.0 gpd after more efficient horizontal-axis clothes washers were installed. Dishwasher hot water use averaged 2.2 gpd in the same sample. It is also interesting that the study showed that an average of 2.2 gpd of hot water use was due to fixture leakage.

per day of which approximately 20% (6.35 gallons) was waste due to draws waiting for hot water to reach household service points.

For the Building America Benchmark estimation, Hendron and Engebrecht (2009) came up with an estimation procedure based on the number of bedrooms. The estimates were based on using RECS data along with some empirical data sources. The study methodology does account for seasonal variation in inlet water temperatures using a sinusoidal estimate of annual inlet water temperature based on empirical data. For showers, baths, and sinks, the water usage is based on the average of three DHW studies (Burch and Salasovich 2002, Christensen et al. 2000, and CEC 2002).

Monitored Data

The authors compiled 92 sites worth of data where hot water draws were explicitly measured: a sample of ten homes in Homestead, Florida, 18 houses in California, 29 homes from Minnesota and 35 homes from Ottawa, Ontario. The homes had a variety of different water heating system types spanning from natural gas and electric resistance storage tanks as well as tankless gas and combi systems. Interestingly, we found no statistically systematic differenced associate with water heating system type.

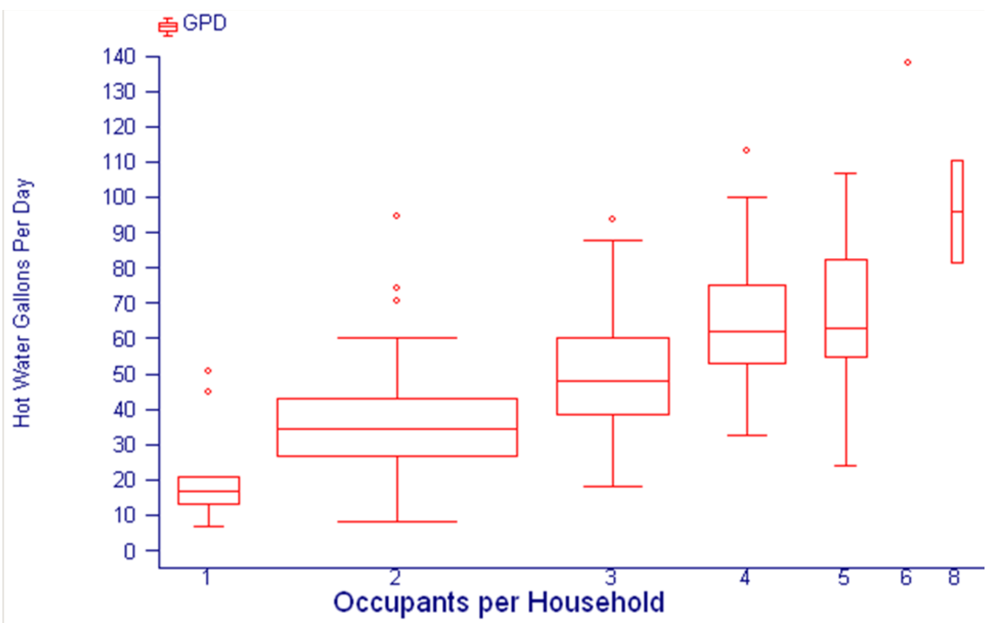

Figure 2: Variable width box plot of gallons of hot water use per day vs. occupants. Box width is proportional to the number of homes in the sample with that number of occupants.

The overall sample had characteristics as shown above in Figure 2. There were 2.8 occupants per household with 47.3 gallons per day of use. However, the Ottawa sample did not have important age-distribution and inlet hot water temperature data and had fairly low occupancy in many of the homes. Thus, we reduce the sample down to 56 homes from Minnesota, California and South

Florida. This sample, which was used for our analysis, had about three occupants per household and 50.7 gallons per day of hot water use. Table 1 summarizes the sample:

Table 1
Characteristics of Sample Used for Analysis

Characteristic	Value
Hot Water Gallons per Day	50.7
Occupants per household	3.16
Adults per household	1.59
Young adults per household	0.14
Teenagers per household	0.52
Children per household	0.64
Seniors per household	0.20

Estimating Hot Water Demand

Unfortunately, past models of household hot water use have been limited based on bias in the household size such that many older studies had households with greater than 3 occupants which is not typical of recent housing trends. Also, it is important to obtain information on modern fixtures and appliances. This comes largely because hot water consumption is not only an issue related to fixtures, tank and plumbing, but also on hot water consumption habits, household member behavior and associated use.

Machine Related Hot Water Consumption

Estimates on clothes washer and dishwasher hot water use are taken from FSEC-CR-1837-10, where the actual hot water use is derived from algebraic derivation from the DOE energy guide label.[4] However, we do update here for the RECS 2009 data based on occupancy to determine cycles per year for clothes washers and dishwashers

Clothes Washers

Washer cycles per year (CWcpy) = 123 + 61 * (Occupants)

Given the water factor and estimated hot water use in that work, one can show that about 38% of the estimated water use (the Water Factor), is hot. However, the Cadmus report[5], showed about 13% of washing machine water was hot in actual metering of 115 laundry systems. Other studies (detailed in the Cadmus report) showed about 18%, but nothing close to 38%. Given that, we

[4] Parker, D, P. Fairey and R. Hendron, June 2011. "Updated Miscellaneous Electricity Loads and Appliance Energy Usage Profiles for Use in Home Energy Ratings, the Building America Benchmark and Related Calculations." FSEC Report No. FSEC-CR-1837-10, Florida Solar Energy Center, Cocoa, FL (http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1837-10-R01.pdf)

[5] Korn, D, and S. Dimetrosky, 2010. "Do the Savings Come Out in the Wash? A large Scale Study of In-Situ Residential Laundry Systems." Proceeding of 2010 ACEEE Summer Study on Energy Efficiency in Buildings, ACEEE, Washington, DC.

make a simple adjustment that the estimated hot water use from the DOE procedure is reduced by 50% (0.5) to match what is seen in the field.

Again, from FSEC-CR-1837-10 hot water gallons per cycle:

Clothes washer hot water use per cycle:

Standard vintage clothes washer: 9.62 gallons per cycle * 0.5 =4.8 gallons per cycle
Standard clothes washer 2008 or later: 4.62 gallons per cycle * 0.5 = 2.3 gallons per cycle
Energy star clothes washer: 3.0 gallons per cycle * 0.5 = 1.5 gallons per cycle

As a reality check, the Cadmus study metered an average hot water use of 3.8 gallons for standard clothes washers and 2.9 gallons for Energy Star washers. As another reasonability check, the Aquacraft study estimated 6.7 gpd in Seattle and East Bay, California in their baseline data and 3.0 gpd for more efficient horizontal-axis type clothes washers.

Impact on daily hot water gallons per day: = above gallons per cycle * (CWcpy/365)

Dishwashers:

Dishwasher cycles per year (DWcpy) = 91 + 30 (Occupants)
DW gallons per cycle (DWgpc) = 4.64 * (1/EF) - 1.9295

Where:

EF = Dishwasher energy factor (EF)

A standard base unit has an EF of 0.46
A minimum energy star unit has an EF of 0.65, which results in:

Base unit: 8.0 gallons per cycle
Energy Star unit: 5.3 gallons per cycle

Note that we assume that hand washing and a base unit dishwasher have the same impact on hot water use (8.0 gallons per washing cycle) in that studies show no advantage to hand washing and regression analysis in a large utility sample of 171 homes found no significant change (reduction or increase to monitored hot water energy use) from having a dishwasher in the 81% of household in the sample with a dishwasher (Parker, 2002).

The impact on daily hot water gallons per day of a dishwasher is then:

DWgpd = DWgpc * (DWcpy/365)

Thus, a 3 occupant home with a base unit would use 4.0 gpd and an EnergyStar unit would use 2.8 gpd. This compares to the Aquacraft (2005) data which showed an average 2.2 gpd in twenty measured households. Interestingly, three households (15% of the sample) had cold water plumbed to the dishwasher which then did not serve to increase water heating loads.

Total daily hot water use:

The Building America Benchmark (Hendron and Engebrecht, 2010) provides a useful framework for a hot water estimation procedure. It estimates total daily hot water use as a function of fixture use where skin sensitivity makes the consumption temperature delivery dependent versus that for machines that are not:

Total Hot Water Use = Fixture Gallons per Day + CWgpd + DWgpd

For a 3 bedroom home, and a basic clothes washer and dishwasher, the values just described are:

CWgpd = 4.8 * 306/365 = 4.0 gpd
DWgpd = 8.0 * 181/365 = 4.0 gpd

Fixture hot water use:

In the Building America procedure, the fixture gallons per day is obtained versus household bedrooms.

Fixture Gallons per day = F_{mix} * (30 + 10.0* Nbr) [6]

Where:
F_{mix} = the fraction of fixture water consumption that is hot
Nbr = Bedrooms (or occupants)

F_{mix} is determined by the target temperature, generally assumed to be 105 F at point of end-use (T_{use}), the hot water supply temperature (T_{set}) and the inlet mains water temperature (T_{mains}). The DOE Building America Benchmark procedure includes a detailed estimation procedure to show how mains water temperature varies by month:

$$T_{mains} = (T_{amb,avg} + offset) + ratio * (\Delta T_{amb,max}/ 2) \cdot \sin (0.986 \cdot (day\# - 15 - lag) - 90)$$

Where:

T_{mains}	=	mains (supply) temperature to domestic hot-water tank (°F)
$T_{amb,avg}$	=	annual average ambient air temperature (°F)
$\Delta T_{amb,max}$	=	maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,avg,january}$) (°F)
0.986	=	degrees/day (360/365)
day#	=	Julian day of the year (1-365)
offset	=	6°F
ratio	=	0.4 + 0.01 ($T_{amb,avg}$ – 44)
lag	=	35 – 1.0 ($T_{amb,avg}$ – 44)

[6] The specific values for various end uses can be seen in the original reference in Table 10. Showers: 14.0 +4.67(bedrooms); Baths: 3.5 + 1.17(bedrooms); Other faucets: 12.5 + 4.16(bedrooms). Aggregate total= 30.0 + 10(Bedrooms) * Fmix.

This equation is based on analysis by Burch and Christensen of NREL using measured inlet water temperature data for multiple locations. (Burch and Christensen 2007). Practically, however, if seasonal accuracy is not needed, the annual average is equal to the average mains water temperature, which is generally found to be the average annual air temperature + 2 F).[7] The average annual temperature is available from the source TMY3 data for relevant locations in North America..

The fraction of the water use for bathing, showers and faucet is is based on F_{mix} which is determined as follows:

$$F_{mix} = 1 - [(T_{set} - T_{mix}) / (T_{set} - T_{mains})]$$

Fixture Gallons per Day + CWgpd + DWgpd

A study of 127 homes with electric resistance water heaters in Central Florida (Parker, 2002) showed that audited hot water set temperature averaged 127 F (Std. Dev: 11.5 F). In Central Florida, where T_{amb} averages 75, so that the variables going into the model are:

Tmix:	105 F
Tset:	127 F
Tmains:	77 F

Under these parameters, F_{mix} is 0.560, total daily hot water use for a three person home would be:

Fixture hot water	=	33.6 gallons/day
Total hot water	=	Fixture Gallons per Day + CWgpd + DWgpd:
Total hot water	=	33.6 gallons/day + 4.0 + 4.0 = 41.6 gallons/day

In Duluth, Minnesota, with an annual average T_{amb} of 39 F, the value for F_{mix} would be 0.744 and the fixture hot water use would climb to 44.7 gallons/day yielding total hot water consumption of 53.0 gallons/day. In San Francisco, with an average annual temperature of 57, the value for F_{mix} would be 0.676 and total consumption would be 48.9 gallons/day.

In 1992, the Energy Policy Act of 1992 went into effect, although the market changed by 1997-1998 (Selover, 2012). This limited showerheads to 2.5 gpm and faucets to 2.2 gpm, If the home was built (or not remodeled and using pre 1997 plumbing fixtures), it would be reasonable to increase the fixture gallons by approximately 10% based on the Aquacraft (2005) data which showed older fixtures lead to increased consumption, particularly for showers and faucets.

Hot Water Waste

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[7] It is useful to note that for analysis of water heating systems with strong seasonality in performance, such as solar or heat pump water heaters, it is probably useful to consider the seasonal variation in water heating loads since the performance of such systems is lower in months where water heating loads are highest.

In most homes, a substantial quantity of hot water is wasted to flush the hot water from the lines to reach the point of service for showers, baths and hand washing. In reality, this is a complex phenomenon that depends on the distance from the tank to the point of service, the size of the lines and the branch structure as well as the number of uses where hot water must be drawn (may be modified by the consumption associated with recent users). This has been studied by Lutz (2005 and 2011) with estimates of wasted hot water to be 20-30% of hot water use. For the purposes of our estimates, in order to be conservative, we assume the lower value.
Currently, we assume that the amount of hot water wasted in this fashion is a factor of:

- Distance to the showers used by occupants
- Distance to the point of other temperature sensitive end-uses
- Frequency of draws where lines must be cleared to obtain hot water
- Plumbing size and layout
- Frequency of use and utility of warm water between draw events

The way in which these factors interact is complex and somewhat probabilistic depending on the way and frequency with which fixtures are used.

A proposed preliminary model suggested by Klein (2012) considers the above factors.

- Characteristic plumbing length (CPL): The square root of the house floor area is use as an estimate for the length of the hot water line run to which is added + 10 feet for each story of house height given the fact that bedrooms are often located upstairs. Although the location of the hot water supply and the furthest shower or bath is uncertain, the number of such draws with wasted water in the day can be more than one. There are also complications based on the time between draw events (with the utility of the still warm water) and the plumbing arrangement vs. the characteristic length. If the distance to the longest plumbing run to a shower in the home can be measured, it is suggested this be used. Otherwise:

  CPL= Measured distance from supply to most distant shower or:
  Conditioned floor area^0.5 + [(No. Stories-1) * 10]

- Internal water volume: (IWV) Pipe size: ¾" pipe is used as the default pipe size to compute the gallons of water contained in each lineal foot of piping (0.025 gals/lineal foot) from the hot water supply to the point of service. The following volumetric values can be used for differing pipe sizes:

  - IWV: Gallons/lineal foot:
    - ¾" pipe: 0.025
    - ½" pipe: 0.012
    - 1" pipe: 0.043
    - 1.25" pipe: 0.065

Wasted Hot Water Per Occupant (WHW) = CPL * IWV *2

For instance, 2000 sqft single story home with ¾" piping: 2.24 gallons per day added to the per occupant consumption number (WHW) to reflect hot water waste to reach the point of end-use. Note that this waste is not subject to Fmix, since it represents hot water line draw to move heated water to the point of service—a fact shown in detail by instrumented results obtained by Lutz (2011) where hot water is drawn (and wasted) until hot water reaches a shower/bath end use point.

While demand recirculation systems can reduce this waste, estimates from Ally et al. (2002) and Burr-Rosenthal (2005) and show that realized savings are behavioral and are generally lower than the potential. Until better empirical data is available, these two studies, particularly that in the five Palo Alto Homes would suggest that savings of 50% can be realized in application.

Analysis

We undertook an analysis of the 92 homes for which we had measured long-term hot water use of a recent vintage. Not all of the data were consistent relative to some parameters, notably hot water setting, inlet water temperatures and age distribution of the occupants. In particular, not having the demographic data on the occupants is limiting, as will be shown.

For instance, if we include all the homes, we get this:

```
. reg dhw_gpd occpts

      Source |       SS       df       MS              Number of obs
=      92
-------------+------------------------------           F(  1,    90)
=   71.92
       Model |  27423.8094     1  27423.8094           Prob >
F      =  0.0000
    Residual |  34317.0298    90  381.300332           R-
squared     =  0.4442
-------------+------------------------------           Adj R-squared
=  0.4380
       Total |  61740.8392    91  678.470761           Root
MSE      =  19.527

-----------------------------------------------------------------------------
-
     dhw_gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+---------------------------------------------------------------
-
      occpts
|   12.49502   1.473353     8.48   0.000     9.567952     15.4221
       _cons
|   12.50515   4.577406     2.73   0.008     3.411333    21.59896
-----------------------------------------------------------------------------
-
```

But if we drop the Ottawa homes where we don't have the demographic data on occupants, we only get slightly changed results:

```
. reg dhw_gpd occpts if obs<57

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  1,    54)
=   52.38
       Model |  24167.4983     1  24167.4983           Prob >
F      =  0.0000
    Residual |  24917.2005    54  461.429638           R-
squared     =  0.4924
-------------+------------------------------           Adj R-squared
=  0.4830
       Total |  49084.6988    55  892.449069           Root
MSE      =  21.481

-----------------------------------------------------------------------------
-
     dhw_gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+---------------------------------------------------------------
-
      occpts
|   12.79797   1.768389     7.24   0.000      9.25256    16.34337
       _cons |   10.20643   6.283384     1.62   0.110    -
2.390999    22.80385
-----------------------------------------------------------------------------
-
```

A three person household will predict about 50 gallons of consumption per year—which is similar to recent studies cited above. This seems to indicate the data are not intrinsically different without the Ottawa set. A regression, did show, as suspected, that the inlet water temperature is important and with a negative sign. The warmer the inlet water temperature to the system, the lower will be the amount of hot water used since many of the end-use are sensitive to the mix temperature to reach approximately 105 F.

Given the indicated importance of occupant demographics from ANOVA tests to the individual variables we use data from the first 56 homes where we have good data. A stepwise regression method is used with variables removed to yield the most simple, yet powerful explanation of the variation in our data:

```
. sw reg dhw_gpd occpts adult child youth senior if obs<57, pr(0.2)
                      begin with full model
p = 0.2783 >= 0.2000  removing senior
p = 0.5177 >= 0.2000  removing adult

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  3,    52)
=   43.79
       Model |  35165.1853     3  11721.7284           Prob >
F      =  0.0000
```

```
    Residual |  13919.5135    52  267.682953           R-
squared     =  0.7164
-------------+------------------------------           Adj R-squared
=  0.7001
       Total |  49084.6988    55  892.449069           Root
MSE      =  16.361

------------------------------------------------------------------------------
-
     dhw_gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+----------------------------------------------------------------
-
      occpts
|   13.70517    2.85715     4.80   0.000     7.971881    19.43846
       youth
|   10.27785   3.729809     2.76   0.008     2.793445    17.76226
       child |  -8.062202   3.503486    -2.30   0.025    -15.09246   -
1.031944
       _cons |   5.731131    6.04389     0.95   0.347   -6.396821    17.85908
------------------------------------------------------------------------------
```

A stepwise regression was run with a p>0.2 required to keep statistically significant independent variables in the model. The stepwise regression drops adult and senior as not significantly different from occupants in general. However, youth and child counts are highly significant-- as seen from early review of the CA data alone. Youths (13-23, inclusive) are much different than adults-- they use approximately 10 gallons more per day. By way of balance, children use less. We also note that the coefficient of determination, R-squared, increases dramatically from 0.49 to 0.72 within the same dataset. Once we consider occupant demographics we do much better at predicting hot water loads. What would the above model indicate for the following three occupant households?

```
Three adult occupants, no kids:       47.0 gpd
Two adults; one child:                38.7 gpd
One single parent: two children:      30.7 gpd
Two adults: one youth:                57.1 gpd
One single parent; two youths:        67.4 gpd
Three college kids in a rental:       77.7 gpd
```

Even ignoring the three college kids scenario, we see greater than a 2:1 difference from the demographics of the household. Household demographics appear to matter quite a bit for estimating site specific hot water consumption. Of course, across buildings and over their useful life, these factors fall out.

Making Improvements to the Building America Model

Examination of the data shows a differing form of the relationship of gallons to occupants than seen in the Building America model which is correlated based on bedrooms (BR).

Current is 30 + 10(BR) * FMIX

Data on the 56 sites in FL, MN and CA shows greater variation with occupancy and a lower fixed amount.

Gallons = Fixed Amount + 19.8 (Occupants * Fmix)

Practically, we can assume the fixed amount is the estimate for clothes washer and dishwasher end-uses.

Fmix is the fraction of occupancy uses that is hot based on water inlet temperatures. We created a new variable OccNom, which is the occupancy times the Fmix value computed for that location.

```
. reg gpd OccNom

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  1,    54)
=   58.91
       Model |  25610.3572     1  25610.3572           Prob >
F      =  0.0000
    Residual |  23474.3416    54   434.71003           R-
squared     =  0.5218
-------------+------------------------------           Adj R-squared
=  0.5129
       Total |  49084.6988    55  892.449069           Root
MSE      =   20.85

------------------------------------------------------------------------------
-
         gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+----------------------------------------------------------------
-
      OccNom
|   19.79138   2.578505     7.68   0.000     14.62178    24.96097
       _cons |   6.187041   6.428863     0.96   0.340    -
6.702053    19.07613
------------------------------------------------------------------------------
-
```

Fmix averaged 0.77 across the sites where most of the inlet water temps were measured.

Example: three occupants and Fmix= 0.77.

Std. clothes washer and dishwasher with three occupants = 8.0 gallons per day.

Old model:

8.0 gallons + (30 + (3*10))*Fmix= 46.2 = 54.2 gallons

New model from the data:

8.0 gallons + (19.8 * 3 * Fmix) = 53.7 gallons

What at first seems like good agreement between the two models is not true when occupancy differs, however. To illustrate:

2 occupants:
6.9 gals for CW & DW

Old model: 45.4 gals
New model: 37.4 gals

4 occupants

9.7 gals for CW & DW

Old model: 63.6 gals
New model: 70.7 gals

How well do the two models replicate the actual data? On average, both do well. But for specific cases the new model is much more successful at capturing the real-world variation in hot water consumption:

The old model, regressed against the actual data:

```
. reg gpd total

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  1,    54)
=   58.72
       Model |   25569.424     1   25569.424           Prob >
F      =  0.0000
    Residual |  23515.2748    54  435.468052           R-
squared     =  0.5209
-------------+------------------------------           Adj R-squared
=  0.5121
       Total |  49084.6988    55  892.449069           Root
MSE      =  20.868

-----------------------------------------------------------------------------
-
         gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+---------------------------------------------------------------
-
       total
|   1.714347   .2237259     7.66   0.000     1.265803     2.16289
       _cons |   -39.7226   12.11992    -3.28   0.002    -64.02157   -
15.42363
-----------------------------------------------------------------------------
-
```

Note that the intercept is strongly negative and the total has a large multiplier.

```
. reg gpd newtotal

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  1,    54)
=   58.69
       Model |  25563.3407     1  25563.3407           Prob >
F      =  0.0000
    Residual |  23521.3581    54  435.580705           R-
squared     =  0.5208
-------------+------------------------------           Adj R-squared
=  0.5119
       Total |  49084.6988    55  892.449069           Root
MSE      =  20.871

------------------------------------------------------------------------------
-
         gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+----------------------------------------------------------------
-
    newtotal
|   1.002188   .1308201     7.66   0.000     .7399091    1.264466
       _cons |  -.0571318   7.183465    -0.01   0.994    -
14.45911    14.34485
------------------------------------------------------------------------------
-
```

Here the coefficient is unity to two decimal places and there is essentially no intercept. The simple model, also explains 52% of the measured variation in site to site hot water use.

One can argue that the BA model is solely meant for bedrooms and not occupants, but in that case it is incorrect in aggregate unless one adjusts for the relationship of occupants and bedrooms in single family homes.[8] Relationship of occupants to bedrooms:

```
. reg occupants bedrooms if SF==1

      Source |       SS       df       MS              Number of obs =
8693
-------------+------------------------------           F(  1,  8691) =
1001.94
       Model |  2097.62684     1  2097.62684           Prob > F      =
0.0000
    Residual |  18195.2155  8691  2.09356984           R-squared     =
0.1034
-------------+------------------------------           Adj R-squared =
0.1033
       Total |  20292.8423  8692  2.33465742           Root MSE      =
1.4469
```

[8] Variable TYPEHUQ in the RECS database is as follows: 1: Mobile Home, 2: SF Detached
3: SF attached, 4: Apt: 2-4 units, 5: Apt 5+ unit

```
------------------------------------------------------------------------------
-
   occupants |      Coef.   Std. Err.      t    P>|t|     [95% Conf.
Interval]
-------------+----------------------------------------------------------------
-
    bedrooms |   .5396171   .0170477    31.65   0.000     .5061996
.5730346
       _cons |   1.094259   .0567196    19.29   0.000     .9830749
1.205443
------------------------------------------------------------------------------
-
```

Thus, for the purposes of using the relationships shown above, the assumed occupancy would be (important to use decimals):

2 BR: 2.2
3 BR: 2.7
4 BR: 3.2
5 BR: 3.8

Since occupancy doesn't differ a lot with bedrooms, some of the fixed nature of the Building America model will reappear in any version of the calculations focused solely on bedrooms rather than occupancy. However, the resulting influence on potential accuracy is important—most of the predictive ability of any estimation of daily hot water use will depend on numbers of occupants and their ages and not on bedrooms which is a poor predictor.

The new relationship is steeper relative to occupancy as the old Building America definition was focused on bedrooms instead.

Finally, the demographic model includes variables for the number of children and no. of youths (13 - 23) that make up the occupants. *After adding them we can predict 73% of the variation in hot water consumption for our available sample:*

```
. reg gpd newtotal child youth

      Source |       SS       df       MS              Number of obs
=      56
-------------+------------------------------           F(  3,    52)
=   46.79
       Model |  35815.7906     3  11938.5969           Prob >
F      =  0.0000
    Residual |  13268.9082    52  255.171312           R-
squared     =  0.7297
-------------+------------------------------           Adj R-squared
=  0.7141
       Total |  49084.6988    55  892.449069           Root
MSE      =  15.974

------------------------------------------------------------------------------
```

```
-
         gpd |      Coef.   Std. Err.      t    P>|t|     [95% Conf. 
Interval]
-------------+----------------------------------------------------------------
-
    newtotal 
|   .9612795   .1860795     5.17   0.000     .5878836    1.334675
       child |   -6.15009    3.00462    -2.05   0.046     -12.1793    -
.120879
       youth 
|   11.56864   3.350554     3.45   0.001     4.845264    18.29202
       _cons |  -1.676968   6.951229    -0.24   0.810    -
15.62563    12.27169
------------------------------------------------------------------------------
-
```

Total daily hot water gallons = previous estimate + 11.6 * (youths) – 6.2(children)
The new model as shown below: *Newtotal* is the value predicted for the relationship in the stepwise regression above plus the estimate for wasted hot water per occupant (WHW)

NewModel (HW_GPD)

The new model assumes that the wasted hot water was already intrinsically included in the coefficient from the previous regression (approximately 19.5 gallons * Fmix) and is therefore subtracted out to prevent over-prediction while still preserving an estimate of wasted hot water from draws to move hot water to point of service.

HWdem_GPD = CWgpd + DWgpd +17(Occp) * Fmix +11.6(Youth) – 6.2(Child) +WHW (Occp)

Where:

CWgpd: 4.0
DWgpd: 4.0
Occp (Occupants): 3
VintageFR: 1.00
Youth: No. of occupants aged 13-23 yrs
Child: No. of occupants that are 0-6 yrs in age
Fmix: 0.77
WHW: Wasted hot water

And Wasted Hot Water Per Occupant (WHW) = CPL * IWV

No youths or children are part of the household. The building floor area is 2000 sqft in a two story home with ¾" piping. WHW= 2.736. House was built in 1999 so that all fixtures are newer vintage.

HW_dem_GPD= 55.5 gallons per day.

If one of the household was a Youth, estimated consumption would be 67.1 gallons; if one was a child instead it would be 49.1 gpd.

The alternative model has no information on the age distribution of occupants. It is more simple, but can be expected to do more poorly with its estimates for a specific household, particularly when there are children or teenagers in the mix of the household occupants:

HWavg_GPD = CWgpd + DWgpd +17(Occp) * Fmix * VintageFR +WHW (Occp)

Where:

CWgpd: 4.0
DWgpd: 4.0
Occp (Occupants): 3
Fmix: 0.77
VintageFR: 1.00 (1.10- 0.10*Fraction of fixtures post 1996 or meeting EPACT 1992.)
WHW: Wasted Hot Water per occupant

Note that if bedrooms, rather than occupants are to be used with the relationship, the following values should be substituted into the variable Occp based on the preceding analysis of occupancy vs. bedrooms.

Bedrooms	Avg. No. of Occupants
2 BR:	2.2
3 BR:	2.7
4 BR:	3.2
5 BR:	3.8

It must be noted, however, the ability of this relationship to predict hot water consumption will be considerably worse than either of the above two forms where actual occupant number and their ages are important to accurate prediction.

Summary

A new hot water prediction model has been described. The model takes into account, consumption due to occupancy. It also considers the following significant factors:

- Number of household occupants and location dependent inlet water temperature can explain about 50% of the variation in observed variation in hot water consumption
- Age-related distribution of the occupants appears to explain about further 25% of the occupancy related variation. Teenagers use more hot water and young children use less.
- How bathing and faucet hot water consumption varies with climate and seasonality to reach the optimal temperature for skin sensitive uses (~105 F).
- We can approximate the quantity of hot water wasted to enable the water to reach the point of end use at a satisfactory temperature.
- Machine-related consumption from clothes washers and dishwashers is included.

Our results show that occupancy—and particularly, the age of the occupants—are major factors influencing site specific consumption. All other factors held equal, young adults and teenagers use considerably more hot water than other occupants. The model is able to explain approximately 73% of the variation in measured hot water consumption from three empirical data sets where daily hot water use was directly measured.

The explanatory power is much, reduced, however, when only data on occupancy is available—or even less optimally when only data on number of bedrooms is considered. In such cases, only about 25% of the observed variation in consumption can be explained. Of course from a policy perspective a building will undergo a changing age distribution of its occupants as well as the number of occupants itself. Accordingly, building related models, focused on the number of bedrooms will be large unable to account for observed variation in hot water use—an artifact of the loose relationship between occupants and bedrooms.

There remains stochastic variation in occupancy related variation that cannot be readily accounted for in a prediction model. As human behavior is involved, such models will likely always be approximate. However, studies cited here do show that other physical factors—particularly fixture leakage may account for some of the remaining variation.

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