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WATER HEATING ENERGY USE REDUCTIONS FROM EPA WATERSENSE LAVATORY PLUMBING FITTINGS

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ABSTRACT

Hot water savings from water-efficient lavatory fittings lead to reductions in water heating energy consumption, and ultimately to decreases in carbon emissions. This paper characterizes existing and proposed approaches used to estimate hot water savings and carbon emissions reductions stemming from the U.S. Environmental Protection Agency's WaterSense program. Also described are refinements that improve the accuracy of residential hot water use percentage estimates of lavatory fittings. The authors conclude that (1) hot water percentages for showers and faucets calculated using up-to-date, publicly available national data are consistent with those found by regional studies and household-level models of water use; (2) the accuracy of heating energy savings estimates attributable to WaterSense-labeled lavatory products, as well as associated emissions reductions, can be refined by modifying the existing energy factor/uniform energy factor (EF/UEF)-based estimation approach with available data. The refined approach accounts for more nuanced conditions than the EF/UED-based approach but depends on data not always available; and (3) the approaches described and intermediate outputs can be generalized for other water conservation programs or estimating purposes.

Keywords: Hot water, Residential water use, WaterSense, Water conservation, Water heating

Word count: 6763

1 INTRODUCTION

All water contains energy that is used to extract, transport, treat, and deliver both potable water and wastewater. A 2013 report from the Electric Power Research Institute (EPRI) found that U.S. public drinking water systems consumed roughly 39.2 billion kWh for this purpose, while municipal wastewater treatment systems consumed 30.2 billion kWh per year. These uses combined represent roughly 2 percent of the total electricity use in the U.S. annually (EPRI, 2013) and can be as much as 13 percent of total U.S. annual electricity use with water end uses included (Griffiths-Sattenspiel and Wilson, 2009). What is more, higher energy intensity sources and treatment strategies (such as desalination or reclaiming wastewater for new purposes) currently represent small but growing portions of the overall treatment profiles. The trends indicate that these values will rise both nominally from increases in population and development, and proportionally from increased use of high intensity sources and treatment (EPRI, 2013).

Hot water-using fittings and appliances can have additional energy consumption at the point of use in the form of hot water; resulting in a substantial economic impact on consumers with U.S. households spending an average of $300 USD annually on energy to heat water (U.S. EIA, 2015a). Consumers typically use hot water from a range of water-using appliances and fittings, including those found in the kitchen, lavatory, and laundry room.

The amount of energy embedded in water from transport, treatment, and heating, along with the volume of water needed to support thermoelectric cooling during power generation (Dieter *et al*., 2018), have driven an increased focus on the connection between water and energy in recent years. It has also led to increased interest in reducing hot water use as a strategy for energy savings. An analysis found that showerheads and faucets (taps for both kitchen and lavatories) could save a cumulative total of 63.6 and 60.3 million metric tons of CO_2 through the year 2050 from reductions in water heating loads.[1] This ranks faucets and showerheads fifth and sixth highest in potential carbon savings among the 27 different appliance/end uses assessed, placing a larger potential carbon savings on showerheads and faucets than on traditional energy efficiency targets such as air conditioners, refrigerators, and freezers (ACEEE, 2020).

The desire to maximize energy and carbon savings has driven an increase in interest in capturing the relationship between water and energy, and the energy savings that water efficiency may offer. One such use case that can provide helpful data to others facing similar goals for quantification is the U.S. Environmental Protection Agency (EPA)'s voluntary WaterSense program. EPA estimates savings associated with labeled water-efficient fittings (as well as other products) that have been third-party certified to meet both the efficiency and performance requirements of WaterSense specifications. Current WaterSense-labeled residential products that use hot water are showerheads and lavatory faucets (also called lavatory fittings or taps). As hot water use is reduced, energy savings increase and carbon emissions are further lowered.

Reductions in the amount of hot water used by water-using fittings and appliances can be expressed as gallons, as energy (kWh or kJ), as financial impacts quantified from consumer water and energy bills, and as greenhouse gas emission impacts quantified as carbon by applying EPA carbon dioxide multipliers. A full and accurate accounting of the program's impact on water and energy use, and associated carbon savings, is considered vital to properly monitor the success of the program and report its impacts. This requires the considered selection of inputs. Several publicly available datasets include some of these inputs, while others must be modeled or estimated from best available data. Data points that the authors were not able to find in publicly available

[1] These numbers are based solely on water heating load reductions and exclude the embedded energy and associated carbon savings that are realized from reduced extraction, treatment, and conveyance. The actual savings could be even higher.

datasets and had to be modeled from other source data are discussed in this paper. The authors recognize that water-using products and consumer water use may vary significantly between countries. However, given the paper's focus on the water and energy savings assessment of U.S. EPA's WaterSense program, the studies cited and conclusions made are specific to the United States as a study sample of the methods discussed. Additionally, unlike other countries, the United States has no regular national survey or accounting of water demand by end use. Due to the lack of water-specific national surveys and regularly conducted field metering studies in the United States, authors employed existing studies and considered data availability limitations in developing their approach.

The WaterSense program employs several analytical models to estimate the change in water use attributable to the improved efficiency of labeled products (Schein *et al.*, 2019). This paper focuses on several refinements to inputs used in these analytical models needed to accurately estimate the total energy and carbon savings associated with the demonstrated water use savings. It explores existing and proposed methods of (1) creating a nationally representative picture of the likely mix of hot and cold water in residential plumbing fittings at the point of use, (2) establishing the heating energy savings associated with hot water savings from more efficient fittings, and (3) calculating resulting carbon emission reductions. Section 2 of this paper summarizes the approach used to estimate the hot water percentage of lavatory fitting total water consumption that incorporates geographical temperature differences into the calculation of hot water saved by the WaterSense program (or water use savings in general). Section 3 describes two approaches for estimating total hot water energy savings from the WaterSense program, one using water heater energy factors/uniform energy factors (EF/UEF) and the other employing the Water Heater Analysis Model (WHAM), and compares results. The authors conclude that the latter is the preferred method, but that currently available data on water heating technology limits its use at scale. Section 4 describes the approach for determining associated carbon emission reduction estimates, and Section 5 discusses results before proposing future possibilities for model amendments.

2 LAVATORY FITTING HOT WATER PERCENTAGE AND USE

EPA regularly evaluates its WaterSense program impacts using models that require readily available, nationally representative data. Approximations and assumptions must be made to available data because actual household water use data are not regularly gathered, are not apt to be nationally representative, and may not include critical model inputs. The authors propose an approach that employs nationally representative data from the Energy Information Administration (EIA) and Housing and Urban Development (HUD) to improve the accuracy of evaluating the hot water percentage used in lavatory fittings over time.

2.1 Field data for hot/cold water mix values

The percentage of hot water used by lavatory fittings is crucial in determining heating energy savings associated with more efficient fittings. In the absence of data from direct measurement and metering of hot water consumption in a representative sample of households, this percentage has conventionally been estimated using point values from publicly available studies. For the last 20 years, residential hot water use has been disaggregated into end uses. Prior to 2000, hot water usage studies for Canada and the United States reported total residential hot water for medium to small numbers of homes in limited geographic areas (Perlman and Mills, 1985; Merrigan, 1988; Becker and Stogsdill, 1990; Abrams and Shedd, 1996). In the late 1990s, residential studies disaggregated hot water end use using a variety of approaches: attaching thermocouples onto hot water pipes and conducting flow-trace analyses according to “flow signatures" (Lowenstein and Hiller, 1998; DeOreo and Mayer, 2000). More recent figures on hot water use suggest the effects of a decrease in household members and an increase in water-efficient fittings (Hendron *et al.*, 2010; Evarts and Swan, 2013; Parker *et al.*, 2015; Escriva-Bou *et al.* 2015). See Chen *et al.* (2020) for more discussion of these studies.

Available field data on hot/cold water mix values are sparse. The percent of overall water use that is hot water at various fittings was determined via flow-trace analysis in 10 single-family homes in Seattle (DeOreo and Mayer, 2000); in 20 representative single-family homes in Seattle and the San Francisco Bay Area before and after a retrofit with high-efficiency products (Aquacraft, 2005); and in 94 residences in nine North American locations (DeOreo *et al.*, 2016). Table 3 displays these percentages (section 2.4.2). Alternatively, hot water use in residential buildings varies according to a number of factors: regional climate (which impacts inlet water temperature), water heater setpoint temperature, hot water flow piping configurations from the water heater equipment, installed fittings and appliances, household occupancy numbers, occupant behavior, and household occupant ages (Evarts and Swan, 2013).

Previously, WaterSense models used the point value of 72 percent for hot water percentage for lavatory fittings (Aquacraft, 2005). The rest of this section describes the refined method now used in the WaterSense models to estimate lavatory fitting hot water percentages.

2.2 Determining lavatory fitting hot water use using ANSI-301

The American National Standards Institute (ANSI) 301 standard (ANSI 301-2019) was developed under the Residential Energy Services Network (RESNET) with the goal of providing a "consistent, uniform methodology for evaluating and labeling the energy performance of residences." First published in 2014, the first 301 standard, *ANSI/RESNET/ICC 301-2014, Standard for the Calculation and Labeling of the Energy Performance of Low-rise Residential*

Buildings using an Energy Rating Index, has been amended to include an approach to estimate daily hot water use volumes.

The ANSI-301 hot water draw model, referenced as Equation 4.2-2 in *ANSI/RESNET/ICC 301-2014,* is used in this paper; it permits comparable hot water use estimates for the end uses of interest, lavatory faucets and showerheads, while including related hot water waste. The ANSI-301 model established a method to assess daily hot water gallon use through dishwasher and clothes washer use, a number of climatic conditions, and dwelling characteristics thought to have implications on household size, among other factors. The equation and inputs are shown below.

$$\boldsymbol{HW_{gpd}} = (\boldsymbol{refDW_{gpd}} + \boldsymbol{refCW_{gpd}} + \boldsymbol{F_{mix}} \times (\boldsymbol{refF_{gpd}} + \boldsymbol{refW_{gpd}})) \qquad \textbf{Equation 1}$$

Where:

HW_{gpd} = gallons per day of hot water use,

$refDW_{gpd}$ = reference dishwasher gallons per day,

= $(0.7801 \times Nbr) + 1.976$,

Nbr = number of bedrooms in the rated home, not to be less than 1,

$refCW_{gpd}$ = reference clothes washer gallons per day

= $(0.6762 \times Nbr) + 2.3847$,

F_{mix} = $1 - \frac{(T_{setTemp} - T_{mix})}{(T_{setTemp} - T_{inletTemp})}$; see Section 2.4.1 for description of these temperatures,

$refF_{gpd}$ = reference climate-normalized daily fixture water use in Energy Rating Reference Home (in gallons per day)

= $14.6 + 10.0 \times Nbr$, and

$refW_{gpd}$ = reference climate-normalized daily hot water waste due to distribution system losses in Energy Rating Reference Home (in gallons per day)

$$= 9.8 \times Nbr^{0.43}.$$

Employing ANSI-301 allows estimates of hot water use to approximate occupancy differences without requiring data on operational characteristics and demography. Using readily available national representative data allows WaterSense program estimates to remain current as both water use trends and the make-up of the housing stock continue to change over time.

2.3 Determination of inputs

This section summarizes the inputs used to estimate hot water use and percentage of hot water per unit volume of water.

2.3.1 Regional differences and bedroom number

ANSI 301-2019 relies on publicly available data of number of bedroom counts by housing unit vintage (American National Standards Institute, 2014) instead of data on household age groups or number of occupants, which may not be consistently available. Two studies assert that the amount of residential hot water use correlates to the number of household members (Parker *et al.*, 2015; Lutz, 2005). Parker *et al.* (2015) demonstrated that even though home occupant age and number are better predictors of hot water use in individual homes, a reasonable substitute is the home's bedroom count.

The ANSI 301-2019 method using the home's bedroom count as an indicator of household occupancy allows for estimation of hot water use when other household characteristics are not available (as is the case for home energy ratings and building code calculations). Using EIA's Residential Energy Consumption Survey (RECS 2015) data as the input for number of bedrooms allows regional adjustments to total household water use and hot water use by appliance or fitting with improved accuracy (U.S. EIA, 2015a). Because ANSI 301-2019 uses number of bedrooms to approximate household size (number of occupants), the authors examined the relationship between household size and number of bedrooms using several nationally representative datasets; see

American National Standards Institute (2019) and Chen *et al.* (2020) for more detail. The authors find that with a robust sample size, both RECS 2015 and HUD's American Housing Survey (AHS 2017) data show a strong linear and positive correlation between the numbers of bedrooms and household size for single-family homes, with little variability (U.S. HUD, 2017). Based on this analysis, the authors conclude that the number of bedrooms is a reasonable proxy for household size.

2.3.2 Water heater setpoint temperature

In the field, the water heater setpoint temperature ($T_{setTemp}$) varies by household, but to the authors' knowledge, apart from a regional study of 127 homes with electric resistance water heaters in Central Florida (Parker, 2002) showing that audited setpoint temperature averaged 52.8°C and field measurement studies in California (Lutz, 2012) showing an average setpoint temperature of 50.6°C, no national household dataset reporting setpoint temperatures exists. Therefore, instead the authors use 51.7 ºC (125ºF) based on ANSI 301-2019 (ANSI, 2019) for tank setpoint temperature. It is worth noting that the tank setpoint temperatures do not necessarily match outlet water temperatures or account for temperature drift within a storage water heater, but are used here as the best available proxy.

2.3.3 Inlet water temperature

Water inlet temperature influences the energy impact of hot water-using plumbing fittings both by affecting the required temperature rise to the water heater setpoint and by influencing the temperature of cold side premise plumbing. Colder temperature in the cold water lines can result in a higher percent mix to achieve the user-desired warm water temperature.

Inlet water temperature can be estimated from either air or groundwater temperature as prior studies have shown. An ANSI 301-2019 equation calculating cold water inlet temperatures was first referenced by Hendron *et al.* (2004) and is based on Burch and Christensen (2007). The ANSI 301-2019 equation for cold water inlet temperature is lengthy and not repeated here for space considerations (ANSI, 2019) but can be simplified by using the annual average outdoor temperature ($T_{airTemp}$) plus 3.3ºC (6ºF) offset, assuming that the ground water temperature is slightly warmer than air temperature.

Using the relationship between the annual average groundwater temperature and the annual average outdoor air temperature based on Yoshitake *et al*. (2002), which reports the relationship between groundwater temperature and annual average temperature, the resulting equation is:

$$\boldsymbol{T^{°F}_{inletTemp} = T^{°F}_{airTemp} + 6\ °F = \frac{\left(T^{°F}_{gwt} - 12.1\right)}{0.83} + 6\ °F}$$

$$\boldsymbol{T^{°C}_{inletTemp} = T^{°C}_{airTemp} + 3.33\ °C = \frac{\left(T^{°C}_{gwt} + 11.06\right)}{0.83} - 14.44}$$

Equation 2

Where:

$T_{inletTemp}$	= water inlet temperature,
$T_{airTemp}$	= annual average outdoor air temperature,
T_{gwt}	= average annual ground water temperature.

Groundwater temperatures vary over geographic areas, as do cold water inlet temperatures (see Table 1). The previous estimate for temperature delta (water heater minus cold water inlet) used by EPA's WaterSense program was 41.7ºC (75.0ºF). The results of the analysis presented here support employing a temperature delta value of 35.8ºC (64.5ºF), calculated via subtracting the weighted average of cold water inlet temperature across Census divisions using the RECS 2015 data of 15.8ºC (60.5ºF) (see section 2.4.1 for more details) from the water heater setpoint temperature of 51.7ºC (125.0ºF).

Table 1: Distribution of Hot Water Use Percentages by Census Division Calculated from RECS 2015 Data and Study Comparisons *(proposed values bolded)*

Census Division	Population	Groundwater temperature from RECS 2015 (°C, °F)	Inlet water temperature (°C, °F)	Hot water percentage for showerheads	Hot water percentage for lavatory faucets
1	5,628,844	8.2, 46.8	8.8, 47.8	74.0	66.2
2	15,377,694	9.9, 49.8	10.8, 51.4	72.7	65.0
3	18,094,391	9.6, 49.2	10.4, 50.7	73.0	65.3
4	8,277,344	10.3, 50.6	11.3, 52.4	72.3	64.7
5	23,474,851	18.2, 64.7	20.8, 69.4	62.6	56.0
6	7,197,189	16.6, 61.9	18.9, 66.0	65.6	58.7
7	13,769,934	19.9, 67.9	22.9, 73.2	61.0	54.6
8 (North)	4,246,877	8.0, 46.4	8.5, 47.3	74.2	66.3
8 (South)	4,266,870	17.6, 63.6	20.1, 68.1	64.1	57.3
9	17,874,256	15.6, 60.1	17.7, 63.8	66.7	59.6
Weighted average		**14.1, 57.4**	**15.8, 60.5**	**67.8**	**60.7**
Aquacraft (2005)[a]				72.0	72.0
DeOreo *et al.* (2016)[b]				66.2	57.0

[a] Values are from post-retrofit stage of the study, and faucets encompassed all faucets, not only lavatory faucets.
[b] Faucets in this study encompassed all faucets, not only lavatory faucets.

2.3.4 Temperature mix for shower and lavatory faucet use

Based on ANSI-301, warm water temperatures *(T_{mix})* for showers are 40.6ºC (105ºF). Faucet hot water use is adjusted given that people use faucet hot water differently from showerhead hot water (*e.g.,* faucet hot water may be mixed into cold water when people shave or face wash but not during hand washing or teeth brushing.) The authors assumed that faucet use includes hot water for 89.4 percent of overall use based on the average ratio of hot water use by faucets and showerheads weighted by number of sample households in field studies. [2]

[2] DeOreo et al. (2000) showed a ratio of 0.995; Aquacraft (2005) had a ratio of 1; and DeOreo et al. (2016) showed a ratio of 0.861. Note that these studies looked at all indoor faucets (were not limited to lavatory faucets).

2.4 Results

This section shows results using the inputs determined in section 2.3 for determining the percentage of lavatory fitting use that constitutes hot water and for estimating the amount of hot water used by lavatory fittings.

2.4.1 Hot water percentages for lavatory fitting use

Hot water percentages for showerheads and lavatory faucets *(F_{mix})* are calculated using water heater setpoint, water inlet, and temperature mix (fitting/user target temperature) and assume no volumetric measurement, which can be interpreted as the assumption that consumers may not wait for the water to come up to a desired temperature. See Equation 3 based on ANSI 301-2019. The temperature for the water heater setpoint is assumed to be 51.7°C (125ºF), explained in Section 2.3.2. Adjusted RECS 2015 household data are used for cold water inlet temperature. The temperature for showerheads and faucets is represented by T_{mix}, 40.6°C (105ºF).

$$\boldsymbol{F_{mix} = 1 - \frac{(T_{setTemp} - T_{mix})}{(T_{setTemp} - T_{inletTemp})}} \quad \textbf{Equation 3}$$

Where:

F_{mix}	= percentage of hot water for shower event and lavatory faucet usage,
$T_{setTemp}$	= water heater setpoint temperature,
T_{mix}	= fitting/user target temperature.

.

Table 1 shows showerhead and faucet hot water percentages by Census Division, with findings from other studies included for comparison. The hot water by end use estimation includes the percentages given in Table 1.

2.4.2 Average hot water use volume per day for lavatory fittings

Hot water from a water heater may be used intentionally by a consumer (*e.g.*, by taking a hot shower), or unintentionally, as hot water may not always reach the end-use in time to be used by the consumer. (The water waste volume can be as much as 25 percent of hot water use according to ANSI 301-2019.)

Three assumptions were made for the intentional hot water use estimation: (1) no hot water use for hand-washing clothes for households without clothes washers, (2) no hot water use in the dish pre-washing step for older dishwasher models, and (3) faucet and showerhead flow rates are at the federal standard, noting that this value will fluctuate across households. See Table 2.

Table 2: Inputs for Lavatory Fitting Use Calculations

Input	Kitchen faucets	Lavatory faucets	Showerheads
Minutes per person per day	5[a]	3[a]	5[a]
Liters per minute (U.S. Gallons per minute)	8.3 (2.2[b])	8.3 (2.2[b])	9.5 (2.5[b])

[a] Baumann *et al.* (1998)
[b] Energy Policy Act (1992), Federal Standard from EPACT 1992 https://www.govinfo.gov/content/pkg/CHRG-106hhrg58509/html/CHRG-106hhrg58509.htm

The ANSI 301-2019 equation gathers together all fitting hot water use. The authors distinguished different fitting hot water use percentages using the average minutes of use for each fitting type. For the showerhead hot water percentage, total fitting hot water volume is multiplied by the ratio of shower use in minutes over all fitting use in minutes. On average, shower use is assumed to be 88 percent of total shower and bath water use, based on DeOreo *et al.* (2016). For faucet use between kitchens and lavatories, a ratio of minutes for each fitting type is multiplied by total fitting hot water volume. Table 3 compares the estimated hot water use percentage developed in this study to those from selected studies.

Table 3: Estimates of Percentage of Showerhead and Faucet Hot Water Use

<table>
<tr><th colspan="2"></th><th>Lowenstein and Hiller (1998)</th><th>DeOreo and Mayer (2000)</th><th>Escriva-Bou et al. (2015)</th><th>DeOreo et al. (2016)</th><th>Using ANSI 301-2019 and RECS 2015 Data</th></tr>
<tr><td colspan="2">Location</td><td>Unspecified</td><td>WA</td><td>CA</td><td>AZ, CO, FL GA, ON, TX, and WA</td><td>National</td></tr>
<tr><td colspan="2">Sample size</td><td>14</td><td>10</td><td>>700</td><td>94</td><td>5,686</td></tr>
<tr><td colspan="7">Percent of total residential hot water use, by end use (%)</td></tr>
<tr><td colspan="2">Showers</td><td>41.6</td><td>25.1</td><td>41</td><td>39.1</td><td>34.8</td></tr>
<tr><td rowspan="2">Faucets</td><td>Kitchen</td><td rowspan="2">--</td><td rowspan="2">34.3</td><td rowspan="2">39</td><td rowspan="2">33.8</td><td>27.5</td></tr>
<tr><td>Lavatory</td><td>16.5</td></tr>
</table>

3 DETERMINATION OF LAVATORY FITTING ENERGY SAVINGS

More water-efficient showerheads and lavatory faucets also save energy from a reduction in the hot water used. One approach to calculate the amount of energy saved from a hot water usage reduction can employ a time series of annual stock-weighted EF and UEF for both electric and gas water heaters; the stock of water heaters obtained based on the combination of shipments and the survival function; time series of annual water savings; the percentage of houses using gas or electric for water heating; and the percentage of hot water used by lavatory fittings. A second approach adds inputs including recovery efficiency, standby loss coefficient, and rated power to provide a more detailed profile of the water heater used. The first method relies on water heater EF, determined based on the amount of hot water produced per unit of fuel consumed over a typical day, while the second method uses the WHAM equation (Lutz *et al.*, 1999); see Section 3.3 for more detailed description of the latter. Because most homes in the United States use electric-resistance water heaters or natural gas water heaters, saving estimates are confined to those energy forms.

3.1 Determination of the hot water energy savings equation

For WaterSense, energy savings ($Q_{savings}$) have been calculated based on the amount of water saved ($Vol_{WS\_savings}$), the percentage of the saved volume that constitutes hot water ($HW_{per\_fitting}$), the ratio of water heaters using either natural gas or electricity to total residences with plumbing systems, and the energy required to heat a unit volume of water (Q_{HW_vol}). (Section 2 describes the method used to estimate the percentage of hot water for showerheads and lavatory faucets.) Equation 4 shows the EF/UEF-based method used to estimate water heating energy savings from WaterSense-labeled lavatory fittings.

$$\boldsymbol{Q_{savings,WH\_fuel} = Vol_{WS\_savings} \times HW_{per\_fitting} \times \frac{Houses_{WH\_fuel}}{Houses_{total}} \times Q_{HW\_vol,fuel}} \qquad \textbf{Equation 4}$$

Where:

$Q_{savings,\ WH\_fuel}$ = heating energy savings (from electricity or natural gas water heater) from WaterSense lavatory faucets or showerheads, kWh/year,

$Vol_{WS\_savings}$ = total lavatory faucet or showerhead water savings from WaterSense lavatory faucets or showerheads, L/year (gal/year),

$HW_{per\_fitting}$ = percentage of water use that is hot water (see Section 2 for calculation),

$WH\_\ fuel$ = fuel type of water heater used, electric or natural gas,

$Houses_{WH\_fuel}$ = number of households using electric or gas storage water heaters (from AHS data),

$Houses_{total}$ = number of households with electric or gas water heaters (from AHS data), and,

$Q_{HW\_vol,fuel}$ = heating energy (electricity or natural gas) required per unit of water volume with ambient temperature, kWh/L (kWh/gal).

Note that the "total number of households" denominator ($Houses_{total}$) ideally should include households using fuel types other than natural gas or electricity for their storage water heaters and other water heater types. Insufficient data exist, so the authors made the conservative assumption that the water heating energy consumption for these water heaters is similar to that of electric and natural gas ones; the impact on water heating energy savings estimates should be minor.

3.2 Estimating energy savings per unit volume of heated water based on EF/UEF

The energy required per unit volume of water ($Q_{HW\_vol,fuel}$) is the key input to estimate the energy saved by WaterSense showers and lavatory faucets shown in Equation 4. This section describes EPA's WaterSense program EF/UEF-based approach for calculating $Q_{HW\_vol,fuel}$.

To estimate the energy savings per unit volume of hot water, since 2006 EPA's WaterSense program has used either EF (EPCA, 1975) or assumptions for overall efficiency (based on the most recent estimates available from U.S. Department of Energy [DOE] water heater analyses). EF is defined in the previous federal water heater test procedure (U.S. DOE, 2015); see Equation 5.

$$EF = \frac{0.001 \times vol_{tp} \times den_{tp} \times C_{p,tp} \times (T_{tank,tp} - T_{in,tp})}{Q_{in} \times 3600} \qquad \textbf{Equation 5}$$

Where:

EF = energy factor, unitless,

0.001 = m^3 to Liter,

vol_{tp} = 243.4 L, volume of hot water drawn in 24 hours during the previous federal test procedure (DOE 2015), L/day,

den_{tp} = density of water during the previous federal test procedure (DOE 2015), kg/m^3,

$C_{p,tp}$ = specific heat of water during the previous federal test procedure (DOE 2015), kJ/(kg × C) (Btu/lb × °F)),

$T_{tank,tp}$ = 57.2°C (135°F), the water heater setpoint value during the previous federal test procedure (DOE 2015),

$T_{in,tp}$ = 14.4°C (58°F), the inlet water temperature during the previous test procedure (DOE 2015), *3600* = kJ to kWh conversion, and

Q_{in} = total water heater energy consumption, kWh/day.

Based on Equation 4 and accounting for a range of EF values according to stock, energy savings per unit volume of water for year *y* can be determined in Equation 6.

$$Q_{HW_{vol},fuel} = \frac{0.001 \times den \times C_p \times (T_{tank} - T_{in})}{EF_{stock} \times 3600} \qquad \textbf{Equation 6}$$

Where:

$Q_{HW_{vol},fuel}$ = energy (electricity or natural gas) required per unit of water volume with ambient temperature, kWh/L (kWh/gal), and

EF_{stock} = average energy factor of the stock.

Assuming a Weibull distribution for the retirement function and an average retirement age of 13 years (DOE, 2014), EF minimum requirements from an ENERGY STAR market report (DOE, 2010b), and water heater shipments from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI, 2019), the weighted average EF is calculated and used in the equation for water heater energy use. See Figure 1.

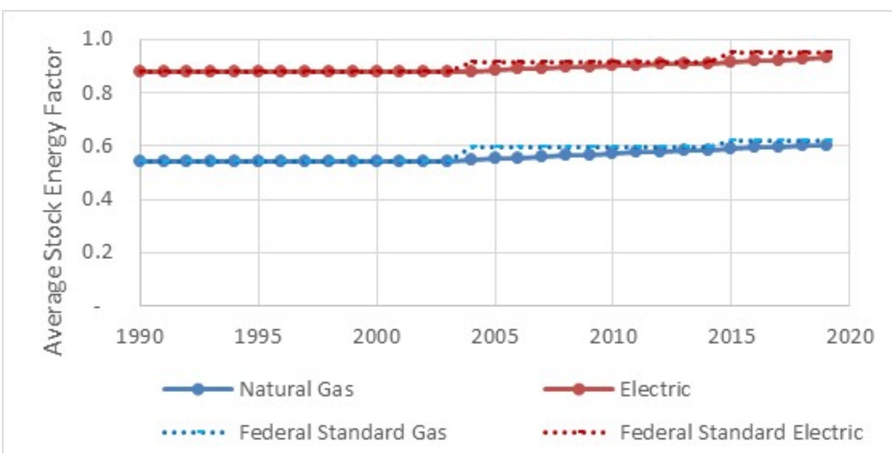

Figure 1: Average Shipment-Weighted Energy Factor per Stock Year (1990–2019) for Electric and Natural Gas-fired Water Heaters

3.3 Estimating energy savings per unit volume of heated water using a WHAM-based method

This section describes a second approach to estimate the energy savings per unit volume of water (presented in section 3.2) based on the WHAM. For demonstration purposes, the authors have used recovery efficiency values from the 2010 DOE final rule technical supporting documents (DOE, 2010c).

The WHAM is an equation for calculating the energy consumption of storage type residential water heaters under different operating conditions (such as daily draw volume, thermostat setpoint temperature, inlet water temperature, and ambient air temperature), different water heater characteristics, and accounting separately for recovery and standby energy use.

The WHAM equation was developed under the assumption that the amount of energy consumed by a storage water heater (Q_{in}) is equal to the sum of the energy consumed to heat the water drawn from the water heater (Q_{recov}) plus the energy due to standby (Q_{stdby}), see Equation 7. Standby in the WHAM equation is defined as the time when the water heater is not heating water to recover from a draw, so the time when the burner is firing or the elements are energized to make up for standby heat losses is included in the hours of standby.

$$\boldsymbol{Q_{in} = Q_{recov} + Q_{stdby}} \qquad \textbf{Equation 7}$$

Where:

Q_{in} = total water heater energy consumption, kWh/day,

Q_{recov} = energy consumed to heat the water drawn from the water heater, kWh/day, and

Q_{stdby} = energy to make up for standby energy loss, kWh/day

The WHAM equation then uses federal water heater test procedure (U.S. DOE, 2015) definitions and parameter inputs to estimate Q_{recov} and Q_{stdby} while continuing to use the energy factor as defined in the prior DOE test procedure; see Equation 8 (U.S. DOE, 2009). The new federal test procedure became effective July 13, 2015, changing the water heater efficiency metric from EF to uniform energy factor. Note that the WHAM equation has not been validated or modified to be used with the uniform energy factor (see Lutz, et al., 1999 for a complete discussion of the equation, including seasonal considerations).

$$\boldsymbol{Q_{in} = \frac{Q_{out}}{RE} + H_{stdby} \times UA \times (T_{tank} - T_{amb})} \qquad \textbf{Equation 8}$$

Where:

Q_{in}	= total water heater energy consumption, kWh/day,
Q_{out}	= heat content of the water drawn from the water heater (subtracting for standby power heat content), kWh/day,
	= $vol \times den \times C_p \times (T_{tank} - T_{in})$,
vol	= volume of hot water drawn in 24 hours, L/day (gal/day),
RE	= recovery efficiency, %,
H_{stdby}	= hours of standby per day, h/day,
	= $24 - \frac{Q_{recov}}{P_{on}}$
Q_{recov}	= daily energy consumed to heat the water drawn from the water heater, J/day (Btu/day),
P_{on}	= rated input power, J/hr (Btu/hr),
UA	= standby heat loss coefficient, kW/°C (kW/°F),
T_{tank}	= water heater thermostat setpoint temperature, °C (°F),
T_{amb}	= ambient air temp around water heater, °C (°F).

For the WaterSense model, it is unnecessary to determine the 24-hour energy consumption from water heating given that only the hot water savings from using more efficient WaterSense products is relevant to EPA. Instead, the authors calculate the energy consumption per unit water volume ($Q_{HW\_vol,fuel}$), which is then multiplied by the total hot water volume savings to determine the corresponding amounts of energy and carbon savings. Note that heat loss during a water heating event is considered minimal given the short time durations of the usage and therefore is not accounted for in this approach.

As the authors assumed that all WHAM equation parameters were the same with the exception of hot water volume, the resulting hot water energy savings calculation from using more-efficient WaterSense showerheads and lavatory faucets for year y ($Q_{savings,y}$) is shown in Equation 9. Given the objective is to only characterize the fitting event energy savings, the expression related to the 24-hour standby energy use in Equation 8 cancels out because this parameter does not vary with changes in hot water use.

$$Q_{savings,y} = \frac{0.001 \times vol_{savings,y} \times den \times C_P \times (T_{tank} - T_{in})}{RE_{stock,y} \times 3600} \times \left(1 - \frac{UA \times (T_{tank} - T_{amb})}{P_{on}}\right) \qquad \textbf{Equation 9}$$

The subsequent expression for energy savings per unit water volume ($Q_{HWvol,\ fuel\_WHAM,y}$), or $Q_{savings,y}$ divided by $vol_{savings,y}$, is described by Equation 10.

$$Q_{HW_{vol},fuel_{WHAM},y} = \frac{0.001 \times den \times C_P \times (T_{tank} - T_{in})}{RE_{stock,y} \times 3600} \times \left(1 - \frac{UA \times (T_{tank} - T_{amb})}{P_{on,stock,y}}\right) \qquad \textbf{Equation 10}$$

3.4 Site energy savings results

Based on the 2019 inputs, the EF/UEF-based method of calculating energy savings per unit of hot water by lavatory fittings estimates 249.7 kJ/L (69.35Wh/L, 895.8 Btu/gal) for gas-fired water heaters and 44.78 Wh/L (169.5 Wh/gal) for electric storage water heaters. Estimates using the WHAM equation with the same inputs show 194.7 kJ/L (54.09 Wh/L, 698.7Btu/gal) and 42.24 Wh/L (159.9 Wh/gal), respectively.

Figure 2 shows the evolution from 2007–2019 of site heating energy saving estimates resulting from the two methods for lavatory faucets and showerheads. The WHAM-based approach provides more conservative estimates for both electricity and gas savings compared to the EF/UEF-based approach. The difference of saving estimates for gas-fired water heaters is greater than the electric water heaters for three reasons: 1) the difference of magnitude of EF for gas-fired and electric water heaters, 2) the introduction of RE in the WHAM approach, and 3) the role EF and RE play in the two equations. The impact of introducing RE on the final energy savings estimates (in the WHAM-based approach) is greater for gas-fired water heaters than for electric ones, because the EF for electric water heater is close to 1 while the EF for gas-fired water heater is close to 2/3. The difference between RE and EF is greater for gas-fired water heaters (~0.15) than for electric (~0.05), and in the EF/UEF-based method, the EF appears in the denominator only, while in the WHAM equation, the RE has multiple appearances in both the denominator and the numerator.

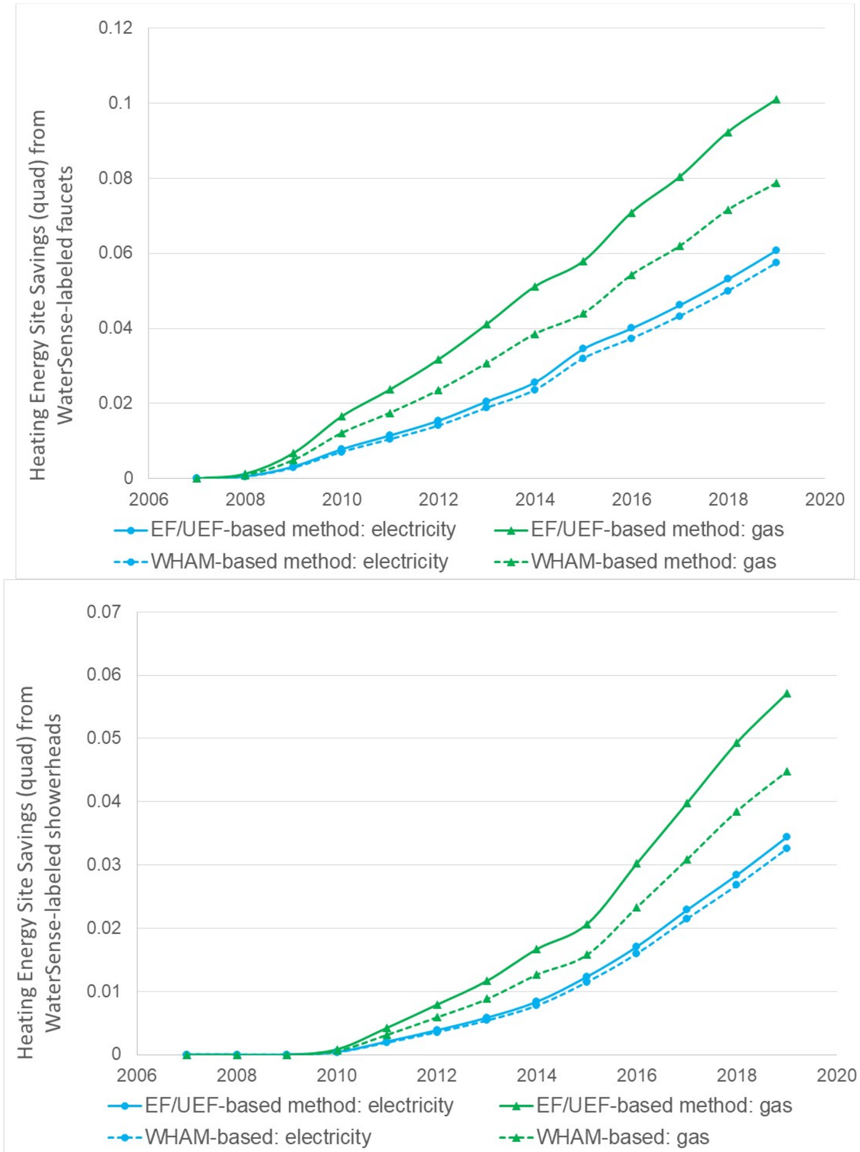

Figure 2: Heating energy site savings estimates (2007-2019) for WaterSense-labeled faucets (top) and showerheads (bottom) resulting from EF/UEF-based method and WHAM-based approach

4 DETERMINATION OF CARBON EMISSION SAVINGS

The U.S. EPA estimates site CO_2 emission savings attributable to WaterSense products. The CO_2 emission savings are evaluated from the reduced load on water heaters used to bring water to a warmer temperature at the showerhead or lavatory faucet and from the reduction in energy from the treatment and delivery of drinking water, as well as from the treatment and distribution of wastewater. Site emissions of CO_2 are estimated using emissions intensity factors from an EPA publication (Greenhouse Gases Equivalencies Calculator, 2019) based on a marginal analysis. The carbon emissions estimates account for the line losses for electricity,[3] yet do not encompass the upstream component (full-fuel cycle factor).

The calculation to estimate CO_2 emissions reduction uses the estimates of embedded energy from annual water savings ($Vol_{WS\_savings}$, $elec_{PW}$, and $elec_{WW}$) from the water and wastewater utility, energy from annual hot water savings ($Q_{savings}$) using the WHAM-based method, metric tons of CO_2 per kWh ($CO2_{kWh}$), and metric tons of CO_2 per kilojoule ($CO2_{kJ}$). Equation 11 shows the calculation of carbon emissions reductions.

$$\boldsymbol{Mt_{CO_2} = \left(\left(\left(Vol_{WS_{savings}} \times (elec_{PW} + elec_{WW})\right) + Q_{savings_{elec}}\right) \times CO2_{kWh}\right) + \left(Q_{savings_{gas}} \times CO2_{MJ}\right)}$$

Equation 11

Where:

$Vol_{WS_{savings}}$ = volume of water saved by WaterSense showerheads and lavatory faucets,

$elec_{PW}$ = energy required to convey potable water, kWh/unit of water,

$elec_{WW}$ = energy required to treat wastewater, kWh/unit of water,

$Q_{savings}$ = energy savings from annual hot water savings (electricity and natural gas),

$CO2_{kWh}$ = metric tons of CO_2 per kWh,

$CO2_{MJ}$ = metric tons of CO_2 per MJ (per therm).

[3] Because the distance between the point of use and point of generation for electricity is usually substantial, a reduction in kWh also results in a reduction in emissions from generation that would have had to cover the line losses. This explains why line losses were accounted for in the electricity CO_2 emission estimate. By contrast for natural gas, fuel is transported a long distance but energy generation occurs very close to the point of use. So while that's not to suggest that 100% of the natural gas put into a pipe is actually combusted, reductions in the demand for natural gas do not necessarily result in additional reduction of emissions. Therefore, no line loss was assumed in the corresponding carbon emission estimates.

In Table 4, the emission savings estimates from 2019 for lavatory fittings resulting from the two approaches mentioned above are compared. The embedded energy savings (potable and wastewater) are equal for the two methods given the same amount of water savings (Table 4 Part 1). The second and third parts of the table show energy savings from electric and gas water heaters respectively, while the fourth part is a sum of electricity savings for both embedded and water heater electricity and gas savings for water heater energy. The last two parts show the corresponding carbon dioxide savings estimates. Critical distinctions between the two calculation methods can be found in Part 2 and Part 3 of the table. Heating energy savings estimates are larger for gas water heaters compared to heating energy savings estimates for electric water heaters because of the role of EF and RE in the calculations (See Section 3.4.). Estimate differences in Parts 4 through 6 are rooted in Parts 2 and Part 3, and differ according to the addition of embedded electricity savings or emissions multipliers.

Table 4: Summary of Carbon Emissions Savings Results for 2019

Part 1: Embedded annual electricity savings[a] (quad)			
	EF/UEF-based method	WHAM-based method	
Faucet	0.0056		
Showerhead	0.0029		
Part 2: Heating energy savings from electric water heater (quad)			
	EF/UEF-based method	WHAM-based method	% difference
Faucet	0.0608	0.0574	5.6%
Showerhead	0.0345	0.0326	5.5%
Part 3: Heating energy savings from gas water heater (quad)			
	EF/UEF-based method	WHAM-based method	% difference
Faucet	0.1009	0.0787	22.0%
Showerhead	0.0572	0.0448	21.7%
Part 4: Total energy savings from heating energy and embedded electricity savings (quad)			
	EF/UEF-based method	WHAM-based method	% difference
Faucet	0.17	0.14	15.3%
Showerhead	0.09	0.08	15.1%
Part 5: Emission reduction from heating energy savings (million metric tons)			
	EF/UEF-based method	WHAM-based method	% difference
Faucet	18.0	16.1	10.5%
Showerhead	10.2	9.1	10.2%
Part 6: Emission reduction from all energy saved (million metric tons)			
	EF/UEF-based method	WHAM-based method	% difference
Faucet	19.1	17.2	9.9%
Showerhead	10.8	9.7	9.7%

[a] Energy that would have been required to convey potable water and treat wastewater for the water saved by WaterSense products.

5 DISCUSSION

This study sought to establish a nationally representative estimate of the mix of hot and cold water for two WaterSense-labeled residential products that use hot water: showerheads and lavatory faucets. Analysis including 2015 RECS microdata improves upon values previously used in the EPA WaterSense model, which had relied on regional studies with small sample sizes. Use of RECS microdata, with its large sample size, enables a more accurate estimation of hot water percentage by incorporating temperature differences across the nation, establishing a nationally representative picture of the mix of hot and cold water usage for each product. Further, the proximity of these results to those found through two regional studies corroborate these findings.

The EPA WaterSense program saves not only water by reducing per-unit consumption from individual fittings, but also energy from avoided water heating associated with that use. This study proposed an alternative to the EF/UEF-based approach, which relied solely on EF, by using the modified WHAM-based approach with both EF and RE to account for hot water energy savings per unit volume. The modified WHAM-based approach updates the energy content calculation to include only heated water savings volumes and exclude standby energy use, which leads to a more conservative estimate of the savings that may occur in practice.

Figure 2 shows the estimated hot water savings based on the EF approach in comparison to the modified WHAM equation. Employing the WHAM-based approach reduces estimated energy savings per unit volume by 22 percent for gas-fired and 5.7 percent for electric water heaters. These revised estimates are more conservative and were calculated using a more detailed profile of the water heaters used. In the case that more granular annual average water heater profile data become available, the WHAM-based approach would provide more conservative and technically accurate estimates of the heating energy saved plus the corresponding emissions reduction. Importantly, the refinement of the hot water percentage and savings saw changes to the carbon emissions savings associated with the efficiency improvements of the WaterSense program.

In this study, the authors not only solicited more up-to-date usage information to inform the total water consumption that directly affects hot water consumption estimates, but also reviewed the assumptions and the core methodology for assessing the heating energy required per unit of hot water. Given water efficiency improvements achieved over time due to DOE appliance standards and labeling programs, frequent review of the estimation tool is necessary to achieve more realistic and robust estimates of energy consumption outcomes resulting from potential policy scenarios. The workflow presented here could easily be adapted for heating energy usage estimations of other appliances and fixtures as a decision guide or usage monitoring tool for various stakeholders, such as water utilities, water conservation programs, appliance standards, and government regulation programs.

6 CONCLUSION AND FUTURE WORK

This paper discusses refinements to two inputs in the calculation of both heating energy savings and carbon emissions reduction attributable to hot water-using residential products of the EPA WaterSense program. The first input discussed is the hot water percentage of lavatory fitting flow volume, which can show variability in temperature due to geographic location. The second input is the calculation of the energy content of lavatory fitting hot water. Based on the literature review conducted, (1) a nationally representative publicly available dataset can closely approximate regional field study values for hot water percentages for lavatory fittings. While increased precision can be achieved with the WHAM energy use equation, (2) reasonably approximate values can be obtained using shipment-weighted energy factors when more precise data are not available. (3) The approach described in this paper is generic and can be used to quantify potential water heating energy savings as well as the carbon emission reductions for similar water conservation programs.

As new data become available, the WaterSense models' structure permits updates to these inputs to reflect the most up-to-date assessment of energy savings possible. The method used to estimate the percentage mix of hot water usage for both lavatory faucets and showerheads can be updated with RECS 2020 data once available. Further, the WHAM equation uses the federal water heater test procedure definitions and input parameters to establish several key inputs. This test procedure undergoes periodic updates and revisions. As such, future assessments of emissions savings from the reduction in water heating energy use for WaterSense-labeled products could use the most recent test procedure and be updated accordingly. Additional improvements to further refine the CO_2 emissions savings estimates include expanding this model to incorporate upstream energy savings from energy utilities. The estimate could also include other emissions savings such as Hg, NO_x, SO_2, CH_4, and N_2O by using their associated emission factors, and projections of future emission savings could be refined by using a forecast of these factors.

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7 REFERENCES

Abrams, D. W., Shedd, A. C., 1996. Effect of seasonal changes in use patterns and cold inlet water temperature on water-heating loads. ASHRAE Transactions 103: 1038–1053.

Air-Conditioning, Heating, and Refrigeration Institute, 2019. Residential automatic storage water heaters historical data. http://ahrinet.org/Resources/Statistics/Historical-Data/Residential-Storage-Water-Heaters-Historical-Data (accessed 1 March 2021).

Aquacraft, 2005. Water and energy savings from high-efficiency fixtures and appliances in single-family homes. Prepared for U.S. Environmental Protection Agency. http://www.aquacraft.com/wp-content/uploads/2015/09/EPA-Combined-Retrofit-Report.pdf (accessed 1 March 2021).

American National Standards Institute, 2014. ANSI/RESNET/ICC 301-2014 addendum A-2015, domestic hot water systems. https://www.resnet.us/wp-content/uploads/ANSIRESNETICC-301-2014-Addendum-A-2015-Domestic-Hot-Water-Systems-January-15-2016.pdf (accessed 1 March 2021).

American National Standards Institute, 2019. ANSI/RESNET/ICC 301-2019 standard for the calculation and labeling of the energy performance of dwelling and sleeping units using an energy rating index. http://www.resnet.us/blog/resnet-consensus-standards/ (accessed 1 March 2021).

Baumann, D. D., Boland, J. J., Hanemann, W. M., 1998. Urban water demand management and planning. New York: McGraw Hill. Pp. 254.

Becker, B., Stogsdill, K., 1990. A domestic hot-water use database. *ASHRAE Journal* 96(2): 422–427.

Burch, J., Christensen, C., 2007. Towards development of an algorithm for mains water temperature [online]. National Renewable Energy Laboratory. Available at https://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/AlgorithmForMainsWaterTemperature.pdf (accessed 1 March 2021).

Chen, Y., Fuchs, H., Schein, J., Franco, V., Stratton, H., Burke, T., Dunham, C., 2020. Calculating average hot water mixes of residential plumbing fixtures: Using the ANSI 301-2019 hot water draw model and national residential data to estimate hot water use in showerheads and lavatory faucets, Lawrence Berkeley Laboratory. https://escholarship.org/uc/item/9m90p3qh (accessed 1 March 2021).

DeOreo, W. B., Mayer, P. W., 2000. The end uses of hot water in single-family homes from flow trace analysis. https://www.researchgate.net/publication/252083793_THE_END_USES_OF_HOT_WATER_IN_SINGLE_FAMILY_HOMES_FROM_FLOW_TRACE_ANALYSIS (accessed 1 March 2021).

DeOreo, W. B., Mayer, P. W., Dziegielewski, B., Kiefer, J., 2016. Residential end uses of water, version 2. Water Research Foundation. https://www.waterrf.org/research/projects/residential-end-uses-water-version-2 (accessed 1 March 2021).

Electric Power Research Institute (EPRI) and Water Research Foundation, 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Water Research Foundation. https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/electricity_use_and_management_in_the_municipal_water_supply_and_wastewater_industries.pdf

ENERGY STAR, 2016. What else should I look for when buying a dishwasher? https://www.energystar.gov/products/appliances/dishwashers?qt-consumers_product_tab=2#qt-consumers_product_tab (accessed 1 March 2021).

Escriva-Bou, A., Lund, J. R., Pulido-Velazquez, M., 2015. Modeling residential water and related energy, carbon footprint and costs in California. Environmental Science & Policy 50: 270–281. https://doi.org/10.1016/j.envsci.2015.03.005 (accessed 1 March 2021).

Evarts, J. C., Swan, L. G., 2013. Domestic hot water consumption estimates for solar thermal system sizing. Energy and Buildings 58: 58–65. https://doi.org/10.1016/j.enbuild.2012.11.020 (accessed 1 March 2021).

Griffiths-Sattenspiel, B. and Wilson, W., 2009. The Carbon Footprint of Water. River Network funded by The Energy Foundation. http://www.solaripedia.com/files/1332 (accessed 1 March 2021).

Hendron, R., Engebrecht, C., 2009. Building America research benchmark definition. NREL-TP-550/47246. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy10osti/47246.pdf (accessed 1 March 2021).

Hendron, R., Anderson, R., Christensen, C., Eastment, M., Reeves, P., 2004. Development of an energy savings benchmark for all residential end-uses. National Renewable Energy Laboratory and Partnership for Resource Conservation. Report No. NREL/BK-610-28044. https://www.nrel.gov/docs/fy04osti/35917.pdf (accessed 1 March 2021).

Hendron, B., Burch, J., Barker, G., 2010. Tool for generating realistic residential hot water event schedules. National Renewable Energy Laboratory. SimBuild 2010, New York, NY. https://www.nrel.gov/docs/fy10osti/47685.pdf (accessed 1 March 2021).

Lowenstein, A., Hiller, C. C., 1998. Disaggregating residential hot water use—Part II. *ASHRAE Transactions* 104: 1852–1863.

Lutz, J. D., 2005. Estimating energy and water losses in residential hot water distribution systems. Lawrence Berkeley National Laboratory, LBNL-57199. https://escholarship.org/uc/item/4nj7m0q6 (accessed 1 March 2021).

Lutz, J. D., 2012. Water and energy wasted during residential shower events: Findings from a pilot field study of hot water distribution systems. Lawrence Berkeley National Laboratory, LBNL-5115E. https://escholarship.org/uc/item/5209d7pf (accessed 1 March 2021).

Lutz, J. D., Dunham, C., Lekov, A. B., Rosenquist, G. J., Winiarski, D. W., 1999. WHAM: Simplified tool for calculating water heater energy use. ASHRAE Transactions, vol. 105, pt.1, pp. 1005-1015, 1999 CH-99-16-1.

Merrigan, T. J., 1988. Residential hot water use in Florida and North Carolina. ASHRAE Transactions 94(1): 1099–1109.

Parker, D. S., 2002. Research highlights from a large scale residential monitoring study in a hot climate. Proceeding of International Symposium on Highly Efficient Use of Energy and Reduction of its Environmental Impact. pp. 108–16. Japan Society for the Promotion of Science Research for the Future Program, JPS-RFTF97P01002. Osaka, Japan. http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-369-02/ (accessed 1 March 2021).

Parker, D. S., Fairey, P. W., Lutz, J. D., 2015. Estimating daily domestic hot-water use in North American homes. ASHRAE Transactions 121(2): 258–270.

http://www.fsec.ucf.edu/en/publications/pdf/FSEC-PF-464-15.pdf (accessed 1 March 2021).

Perlman, M. Mills, B. E., 1985. Development of residential hot water use patterns. ASHRAE Transactions 91(2): 657–679.

Residential Energy Services Network, 2014. RESNET Proposes domestic hot water amendment to its ANSI standard for home energy ratings. https://www.resnet.us/articles/resnet-proposes-domestic-hot-water-amendment-to-its-ansi-standard-for-home-energy-ratings/ (accessed 1 March 2021).

Schein, J., Chan, P., Chen, Y., Dunham, C., Fuchs, H., Letschert, V., McNeil, M. Melody, M., Price, S., Stratton, H., Williams, A., 2019. Methodology for the National Water Savings models—indoor residential and commercial/institutional products, and outdoor residential products. Water Supply 19(3): 879–890. https://doi.org/10.2166/ws.2018.136 (accessed 1 March 2021).

U.S. Department of Energy, 2009. Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air Conditioning, and Water Heating Equipment; Final rule. https://www.govinfo.gov/content/pkg/CFR-2015-title10-vol3/pdf/CFR-2015-title10-vol3-part430-subpartB-appE.pdf (accessed 11 January 2021).

U.S. Department of Energy, 2010a. Energy conservation program: Energy conservation standards for residential water heaters, direct heating equipment, and pool heaters; Final rule: Technical support document. https://www.regulations.gov/document?D=EERE-2006-STD-0129-0149 (accessed 1 March 2021).

U.S. Department of Energy, 2010b. ENERGY STAR water heater market profile. https://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/Water_Heater_Market_Profile_2010.pdf (accessed 1 March 2021).

U.S. Department of Energy, 2010c. Energy Efficiency Standards for Pool Heaters, Direct Heating Equipment and Water Heaters (EE-2006-STD-0129) Technical Support Document. https://www.regulations.gov/document?D=EERE-2006-STD-0129-0170 (accessed 1 March 2021).

U.S. Department of Energy, 2015. 10 CFR 430. Uniform test method for measuring the energy consumption of water heaters. https://www.govinfo.gov/content/pkg/CFR-2015-title10-vol3/pdf/CFR-2015-title10-vol3-part430-subpartB-appE.pdf (accessed 1 March 2021).

U.S. Department of Housing and Urban Development, 2017. American Housing Survey . https://www.census.gov/programs-surveys/ahs/data.2017.html (accessed 1 March 2021)

U.S. Energy Information Administration, 2005. Residential energy consumption survey. http://www.eia.gov/consumption/residential/data/2005/ (accessed 1 March 2021).

U.S. Energy Information Administration, 2009. Residential energy consumption survey. https://www.eia.gov/consumption/residential/data/2009/ (accessed 1 March 2021).

U.S. Energy Information Administration, 2015a. Residential energy consumption survey. https://www.eia.gov/consumption/residential/data/2015/ (accessed 1 March 2021).

U.S. Energy Information Administration, 2015b. Consumption and expenditures technical documentation summary. https://www.eia.gov/consumption/residential/reports/2015/methodology/pdf/2015C&EMethodology.pdf (accessed 1 March 2021).

U.S. Environmental Protection Agency, 2019. Greenhouse gases equivalencies calculator - Calculations and references. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (accessed 1 March 2021).

Yoshitake, I., Nagai, S., Tanimoto, T., Hamada, S., 2002. Simple estimation of the ground water temperature and snow melting process. 11th International Road Weather Conference. January 2002. http://www2.ceri.go.jp/sirwec2002/english/papers/yoshitake.pdf (accessed 1 March 2021).

Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2018, Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, 65 p., https://doi.org/10.3133/cir1441. [Supersedes USGS Open-File Report 2017–1131.]