Center for Energy and Environment

Actual Savings and Performance of Natural Gas Tankless Water Heaters

Prepared for Minnesota Office of Energy Security

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Contents

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Water heating is the second largest energy use in residential homes in the USA. It is also a very inefficient use of energy, with typical equipment efficiencies around 60%. The Center for Energy and Environment with funding from the Minnesota Office of Energy Security ran a two year field monitoring project to determine if high efficiency tankless water heaters could be part of the solution to this large inefficiency.

A 37% savings of water heating energy per household was found for replacing a typical natural draft storage water heater with a tankless one. However, this savings was not enough to offset the high incremental cost resulting in paybacks from 20 to 40 years.

Tankless water heaters saved energy and provided homeowners with acceptable hot water service at a reduced monthly cost without increasing total hot water consumption. Tankless water heaters have achieved about 5% of the new water heater market despite the long paybacks. Improving the payback could increase installations and a significant amount of energy could be saved.

INTRODUCTION

Water heating is the second largest end use of natural gas in homes in the United States, accounting for 24% of residential use (D&R International 2006). Water heating is also typically one of the least efficient end uses, since the federal minimum efficiency (Energy Factor) is only 0.59 (for a typical 40 gallon water heater). More efficient water heating technology thus has the potential to provide large natural gas savings.

The federal rating (DOE 2001) for water heaters is a laboratory rating that is similar to efficiency. It is determined by measuring the heater’s performance over a simulated daily usage pattern. The Energy Factor (EF) is the ratio of the energy in the hot water output from the water heater divided by the energy into the water heater, in this case in natural gas. The usage pattern consists of six equal draws, at 3 gallons per minute for 216 seconds. The draws are at one hour intervals with a total volume of 64.3 gallons followed by a 19 hour period with no draws. The inlet and outlet water temperatures, water volume, and energy input are recorded and used to compute the EF.

A large fraction of the total energy used by conventional storage water heaters (StWHs) goes to make up standby losses from the approximately 92% of the day (estimate based on

(Mayer and Deoreo 1999) when no hot water is being used. Tankless water heaters (TWHs), which are widely used outside the U.S., store little or no hot water and so eliminate much of this standby loss, offering one potential strategy to improve water heating efficiency. In addition, they typically have intermittent ignition, whereas conventional storage water heaters typically have a standing pilot light. The typical federal energy factor (DOE 2001) of non-condensing tankless water heaters (NTWHs) on the U.S. market ranges from 0.78 to 0.85, while that of condensing tankless water heaters (CTWHs) ranges from 0.91 to 0.96 (AHRI 2010). However, their installed cost is also 2 to 6 times that of conventional StWHs. Moreover, there is very little data on their real-world energy use and the actual savings they provide relative to StWHs.

Field data are important to determine whether actual savings are comparable to those estimated based on laboratory tests and federal efficiency ratings. Hoeschele and Springer's (Hoeschele and Springer 2008) field testing, based on a total of only 48 days of data for two water heaters (one StWH and one NTWH), showed a significant difference between field performance and Energy Factor (EF) and, perhaps more important, indicated that the difference in performance between StWHs and TWHs might not be accurately captured by the EF test. Differences between field and rated performance occur because the EF draw profile is not representative of actual draw patterns or total hot water use in homes. A 30 home study in Ontario, Canada found that 44 gallons per day was the average hot water consumption for single family residences (Thomas 2008). A US Environmental Protection Agency (Environmental Protection Agency 2005) study found that real usage patterns are considerably different from those assumed by the EF test procedure. The study, which monitored the hot water usage of twenty homes in the Northwestern United States, found that the average draw length was 70 seconds and that typically there are only one or two large draws per day, with over 95 percent of draws less than two gallons.

The EF is a figure of merit and, as such, was not intended to characterize actual hot water energy use in homes, but to provide a means to compare the relative performance of different water heaters. However, with new technologies emerging the draw profile used in the federal test procedure may result in EFs that do not accurately reflect the relative real world performance of various types of water heaters.

TWHs do not have continuous standby heat losses but when hot water is called for they must bring the heat exchanger back up to temperature before they can deliver hot water. The input required to re-heat the heat exchanger greatly reduces efficiency on short draws. StWHs have large stand-by losses, but when hot water is called for it is immediately available at the heater outlet. The impact of these differing modes of operation on energy use can only be accurately assessed using realistic draw patterns.

Other issues that affect the relative energy use of TWHs include electrical energy consumption and potential changes in water use habits. TWHs use electricity for controls, ignition, draft fans, and freeze protection. Electricity must be accounted for in energy savings calculations and will offset some of the natural gas savings. The EF test procedure takes electrical consumption for normal operation (controls, ignition and draft fans) into account, but does not include any conditions that would trigger freeze protection. Unlike StWHs, which can run out of hot water if the rate of hot water use exceeds the combined storage volume and recovery capacity, TWHs can provide endless hot water at a fairly high flow rate, since they have maximum firing rates three to five times as high as StWH input rates.

There are also outstanding questions about qualitative aspects of TWH performance, such as increased time required for the water heater to produce hot water, minimum flow rate required to activate the burner, and “cold water sandwiches,” which occur when hot water remains in the pipes from a previous draw when a new draw is initiated. The hot water in the pipes comes through first, and then cold water as the heat exchanger heats up, before more hot water comes through. These performance issues could affect energy use as well as user satisfaction. Delays in getting hot water, for example, could encourage people to walk away from fixtures while waiting for hot water. Minimum flow rates to activate the burner could cause people to operate fixtures at higher flow rates. Cold water sandwiches could encourage people to leave a shower running between users or to leave a faucet running when rinsing dishes. On the other hand, the fact that low flow draws do not activate the burner may save energy if people don’t switch to higher flow rates. THWs could encourage people to use the cold water tap for more short or low flow uses, which would also save energy.

Finally, some utilities have raised questions about the potential impact of TWHs on gas distribution systems. Their concern is that, since TWH inputs are typically three to five times that of StWHs, they could create problems in areas with limited distribution capacity.

These issues were addressed through a field study in the Minneapolis/St. Paul, Minnesota metropolitan area. Two or three different water heaters were installed in each of ten homes and were alternated monthly for a year to evaluate energy use, hot water use, efficiency, qualitative aspects of water heating performance and occupant satisfaction for each heater. The water heaters were instrumented to collect data continuously on hot water flow, inlet and outlet water temperatures, gas and electricity input, time required for hot water to reach fixtures, and other parameters. These data were supplemented with homeowner surveys that assessed occupant satisfaction with various aspects of water heater performance.

Laboratory tests were performed on each water heater to learn more about TWH performance. The EF test was performed on each unit to determine the EF for the specific unit tested in the field. A full matrix of steady state and cyclical tests were run on each heater to define a performance map that could be used to model the energy use for any arbitrary draw pattern. The full test matrix would give a large range of test to determine whether or not a small subset of tests could be used to develop the energy use model.

BACKGROUND

Two important aspects of domestic water heating were addressed in the field portion of this study: in-situ water heater performance for different types of water heaters, and domestic hot water draw patterns and usage by fixture. These are both high interest areas in energy efficiency policy and research but little monitoring has been done in actual homes.

This section reviews the current market for TWHs, past field and laboratory studies comparing TWH and StWH energy use and economics, data on customer satisfaction with TWHs and utility incentive programs for TWHs. In addition, it summarizes previous research on hot water usage patterns.

Current Market for Tankless Water Heaters

Many NTWH and CTWH units are available for residential use. Almost all such units have modulating burners with electronic controls to maintain constant outlet temperatures despite variations in hot water flow rate or inlet water temperature. Supplementing AHRI data (AHRI 2010) with information from manufacturers’ literature, residential TWHs have minimum inputs ranging from 11,000 to 20,000 Btu/hr and maximum inputs ranging from 117,000 to 199,900 Btu/hr. Models are available with energy factors up to 0.95 and flow rates at a 77°F temperature rise up to 5 gallons per minute (gpm).

Nationally, annual sales of natural gas TWHs are 254,600 units (DOE 2008). This represents a little more than 5% of the total water heater market of 9.8 million gas water heater shipments annually (DOE 2008), and is five times more than a 2003 estimate (Sachs et al. 2004) and twice as much as a 2004 estimate (Sachs et al. 2004) , suggesting that sales of TWHs are on the rise.

In discussions with manufacturers' representatives, distributors and contractors the TWH market has been described as consumer-driven, with two major users of TWHs and two minor users. The majority of TWH users are individuals or families dedicated to energy efficiency and green building or users that require endless hot water for large families or luxury bath fixtures. The two smaller groups of TWH users are those who need these water heaters for physical space savings or for use in a summer or part-time home.

There are many manufacturers of TWHs in the U.S. but of these, only five appear to be significant players in our region at this time. These are Takagi, Rinnai, Noritz, Rheem/Ruud (Paloma), and Bosch. Noritz, Rinnai and Takagi appear to have the biggest market shares, although the exact breakdown is not clear. Noritz and Rinnai factory contacts both mentioned each other as their biggest competitor in the U.S., but did not mention Takagi. However, the local manufacturer's representative for Rinnai said that both Noritz and Takagi were his biggest competitors. In addition, the Takagi factory thought that in the Midwest Takagi had roughly one-third of the business without mentioning competitors by name. The Rheem/Ruud and Bosch brands appear to have smaller shares of the regional market, but are still active players.

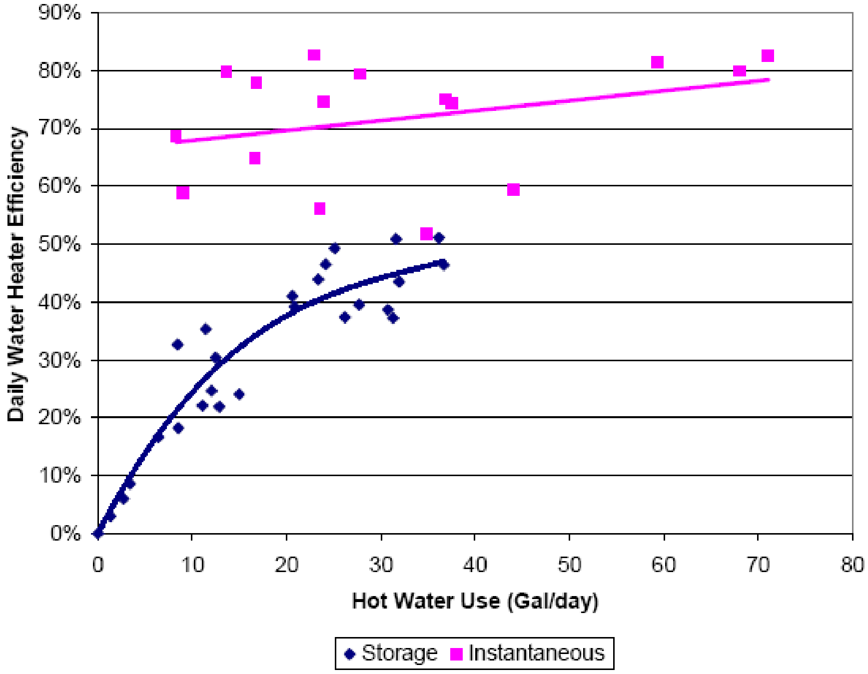
Most of these manufacturers produce both non-condensing and condensing units. In addition to the manufacturers previously listed, Navien has begun to gain a share of the market. The Navien CTWHs are noteworthy due to their low cost and the option of a small (0.5 gallon) buffer tank that eliminates some of the hot water delivery and performance issues.

Previous Studies of TWH Energy Use

Various sources estimate 20 to 50% savings for tankless water heaters relative to conventional storage water heaters. Energy savings stem primarily from the fact that tankless heaters have minimal standby losses (although there is some heat loss from the small volume of water that is in the heat exchanger of a tankless water heater between cycles). Additional savings come from higher combustion efficiencies and the fact that most tankless units do not have pilot lights.

Only one previous field study has measured the energy efficiency of a tankless water heater (EF 0.82) and a storage water heater (EF 0.69) in a side-by-side comparison (Hoeschele and Springer 2008) Unfortunately this study was of short duration (29 days of data on the tank-type unit and 19 days of data on the tankless). Figure 1 shows efficiency as a function of total daily hot water volume for the two heaters.

Figure 1. Field Measurements of Gas Storage and Tankless Water Heater Performance



Source: (Davis Energy Group 2007)

This study showed that the efficiency of both StWHs and TWHs varied broadly based on the actual load, (Table 1).

Table 1. Water Heater Efficiency as a Function of Load in a Single Family Residence (Davis Energy Group 2007)

	Daily Load	**Load Dependent EF StWH (Rated EF = 0.62)**	**Load Dependent EF TWH (Rated EF = 0.82)**

Minimum Load	10 Gallons/Day	0.24	0.68
Average Load	53.2 Gallons/Day	0.46	0.75
Maximum Load	60 Gallons/Day	0.52	0.76

The researchers found that maximum efficiency was achieved when hot water use was concentrated into a small number of high volume draws. Efficiency decreased for shorter draws at lower flow rates. Additionally, uses that were well spaced from other uses had lower efficiencies because energy was needed to heat up the thermal mass of the water heater itself.

The authors used the regression curves in Figure 1 to calculate “load dependent energy factors” for each water heater type over a range of daily hot water use volumes. These load dependent energy factors were used in conjunction with the Title 24 method[1] (California Code of Regulations 2007) to estimate annual energy use for a typical single family residence. Based on this methodology, annual savings for TWHs were estimated at 102 therms or 39%.

Hoeschele and Springer offer several caveats about this estimate. First, it is most relevant to new construction rather than retrofit because monitoring was done in new construction and because of the assumptions in the Title 24 method. Second, the field data on which the estimate is based may underestimate savings due to two issues: the tank-type water heater had an EF of 0.62 which is on the high end of what’s available; and monitoring took place in August when standby losses on the tank-type water heater were lower than a more representative seasonal average (Davis Energy Group 2007).

National Grid (formerly Keyspan Energy), a Northeast U.S. gas utility, conducted an informal field comparison between two StWHs and one TWH in a condominium (Halfpenny 2010). Savings for TWHs were measured between 25 and 30%, although these results were said to be only preliminary because the study was short in duration due to various issues with the StWHs.

Okaloosa Gas District, a Florida gas utility, conducted a side-by-side laboratory test on a gas TWH, an electric StWH, and a gas StWH (Exelon Services Federal Group 2002). The three water heaters were operated for 30 days each, with identical quantities of water drawn in a simulated residential usage pattern. The researchers fixed the 30-day quantity of water, and then simulated the draw pattern by making hot water draws every half hour between 7 AM and 3 PM

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[1] The Title 24 method for calculating water heater energy use correlates hot water use with floor area.

on weekdays with additional draws on weekends. The average draw volume was 5 gallons and the average flow rate was 3 GPM. The total load averaged 85.2 gallons per day, much higher than the 64.3 gallons per day used in the DOE test procedure (DOE 2008). Results are summarized in Table 2. Operating costs for the gas TWH were about 37% than for the gas StWH. 47% less than for the electric StWH. The high total flow volume and the absence of small volume or low flow rate draws may account for the fact that the measured EFs are close to the rated EFs.

Table 2. Summary of Lab Tests for TWHs and StWHs (Exelon Services Federal Group 2002)

	Gas TWH	Gas StWH	Electric StWH
Tank Capacity	N/A	40 gallon	40 gallon
Rated EF	0.82	0.55	0.88
Measured EF	0.85	0.55	0.87
30-Day Electric Consumption (kWh)	0.6	N/A	332.9
30-Day Gas Consumption (therm)	11.3	17.9	N/A
30-Day Total Energy Consumption (site kBtu)	1,130.55	1,793.74	1,136.29
Electrical Energy Costs ($) at $0.06327/kWh	$.04	N/A	$21.06
Natural Gas Costs ($) at $0.9885/therm	$11.21	$17.73	N/A
Total Energy Cost ($)	$11.25	$17.73	$21.06

Gas TWHs use electricity for controls, for draft fan operation and for freeze protection. Electrical energy use is not included in the DOE Energy Factor test for gas water heaters. Electrical wattages are listed in Table 3 for the most common sizes of residential TWH from each manufacturer.

Table 3. Wattage for Electric Use on TWHs

	Wattage
Standby consumption (controls), average	5 W
Consumption during operation (controls and draft fan), average	50 to 80 W
Freeze Protection – Bosch	120 W
Freeze Protection – Noritz	161 W
Freeze Protection – Rinnai	100 W
Freeze Protection – Rheem	182 W
Freeze Protection - Takagi	102 to 111 W

Energy use for freeze protection in particular could be substantial, but no previous field data are available to quantify this. Most freeze protection systems have some sort of sensor which turns on a heater when the temperature at the sensor goes below a preset level (usually between 34 and 42°F). Some manufacturers have more than one heater system. In addition, the exact control strategy varies from manufacturer to manufacturer, as does sensor location. It is unclear how these factors affect electrical use among different products.

The only study found which measured electrical use of a gas TWH during operation is the Okaloosa lab tests. This study measured consumption of 0.6 kWh over 30 days or about 7 kWh per year. It did not measure freeze protection as that system did not operate during the test period.

Economics of TWHs

From interviews with eight local contractors, installed costs for whole-house gas TWHs as a retrofit were estimated from $2,000 to $5,000, with typical price range of $2,500 to $3,400. These costs are considerably higher than estimated by others: $350 to $2,000 according to (Sachs et al. 2004); $1,600 according to ACEEE 2007; and $1,470 to $2,500 according to DOE 2008. The reason for this disparity is not known.

Local contractors' estimates of material and labor costs for TWHs are summarized in Table 4. For comparison, these same contractors estimated the installed cost of a conventional StWH to range from $900 to $1,300 with an average cost of about $1,100. They estimated the installed cost of a power-vented tank-type heater to range from $700 to $2,200 with an average of about $1,600.

Table 4. Estimated Costs for TWHs

	Low Estimate			**High Estimate**		
	Material	**Labor**	**Total**	**Material**	**Labor**	**Total**
1	-	-	-	-	-	-
2	$600	$1,400	$2,000	$1,200	$1,400	$2,600
3	-	-	$2,500	-	-	$3,000
4	-	-	-	-	-	-
5	$1,865	$690	$2,555	$2,000	$1,150	$3,150

6	$1,600	$1,000	$2,600	$1,800	$1,200	$3,000
7	-	-	$2,500	-	-	$5,000
8	$1,000	$2,000	$3,000	$1,200	$2,300	$3,500
Average	$1,266	$1,273	$2,526	$1,550	$1,513	$3,375
Median	$1,300	$1,200	$2,528	$1,500	$1,300	$3,075

Several factors contribute to the higher cost of TWHs. The water heaters themselves have a high cost than StWHs. The installation of TWHs, especially in retrofit applications, adds significantly to the cost. Side wall venting must be planned out and installed, often with expensive venting materials (stainless steel). TWHs are typically installed on exterior walls, which often require relocation of the water heater and modification of the water piping and natural gas lines. In some cases the gas line from the gas meter to the water heater has to be upsized. A 120V electrical outlet is needed near the heater.

Most sources estimate savings potential for TWHs using the DOE EF and the following formula:

$$\text{Energy Use (therms/yr)} = \left[\frac{\text{41,045 Btu/day output}}{\text{EF}} * \text{365 days/year}\right] * \frac{\text{therm}}{\text{100,000 Btu}}$$

NTWHs have EFs that range from 0.78 to 0.85 (AHRI 2010), with 0.82 being fairly typical. CTWHs have EFs from 0.90 to 0.98 StWHs have EFs that generally range from 0.58 to 0.67 (AHRI 2010). Within that range an EF of 0.58 is typical for a standard StWH and an EF of 0.64 is typical for a power-vented StWH. Table 5 summarizes costs, savings and payback estimates for TWHs using the DOE EF.

TWHs are said to have a longer lifetime than StWHs. Manufacturers typically claim about a 20 year life for TWHs, which is longer than the 10-12 year average lifetime of StWHs. However, because there were very few TWHs installed in the U.S. 20 years ago and because TWH design has evolved over that time, there is little relevant data to support or refute these claims.

Table 5. Estimated Costs, Savings and Paybacks for TWHs

	Standard StWH	**Power-Vent StWH**	**NTWH**	**CTWH**
Energy Factor (EF) [1]	0.58	0.64	0.82	0.95
Annual Consumption (therm/year) [2]	258	234	183	158
Annual Gas Cost ($/year) [3]	$248	$225	$175	$150
Annual Savings compared to Standard StWH ($)	N/A	$23	$73	$96
Life Expectancy [4]	13	13	20	20
Lifetime Savings over Standard StWH	N/A	$302	$1,450	$1,930
Installed Cost [5]	$1,100	$1,600	$3,000	$3,500
Price Premium over Standard StWH [5]	N/A	$500	$1,900	$2,400
Payback on Premium (years)	N/A	21.5	26.2	24.9

Sources:
1 – (AHRI 2010)
2 – (DOE 2001)
3 – Gas cost of $.96 per therm
4 – (DOE 2008)
5 – Interviews with eight local contractors who have installed TWHs

Differences in maintenance requirements between TWHs and StWHs could affect both operating costs (for maintenance), efficiency over time and equipment life. Older TWH units required an annual flushing with water and a mild acid flush every five years. If the homeowner is not able to perform this work the contractor visits could add considerably to overall operating costs. However, newer TWHs only require flushing in areas with hard water. One study showed a larger performance drop for TWHs due to scale buildup (PM Engineering 2005). This study used very hard water that exceeds the tolerances of the DOE test procedure and the maximum hardness recommended by the manufacturer for use without a water softener. There have been several reports published in recent years that disagree about how problematic hard water is for tankless water heaters (PM Engineering 2005) (Gregg 2006). Current TWH technology only requires the operator to remove any build up from a small screen at the water heater outlet as long as the water passing though the water heater meets potable water requirements.

Customer Satisfaction with TWHs

National Grid Survey

Keystone Energy (now National Grid) is the only source identified that had completed an evaluation of its Tankless Water Heater Program including customer feedback (Halfpenny 2010). This study surveyed 101 program participants who had recently purchased TWHs, 91 of whom replaced a tank-type water heater and 10 of whom replaced some other type of water heater. Questions included:

- Sources of information on TWHs
- Motivations for purchasing TWHs
- Satisfaction with the performance of and various features of the TWH
- Awareness of regular maintenance requirements for TWHs
- Changes in behavior since installing the TWH
- Demographics

The most common initial source of information on TWHs for people surveyed was a friend, family member, neighbor, acquaintance or co-worker. The second and third most common sources were the gas-company or program website and personal contact with a contractor or plumber. Additional sources of information included radio or television programs, advertisements by a contractor or plumber, bill stuffers, magazine articles, and manufacturer’s advertisements.

The primary motivation for purchasing a TWH was to save energy, followed by saving money. Additional reasons that ranked high included never running out of hot water and saving space.

Participants were very satisfied with the overall performance of their TWHs (Table 6). Respondents were extremely satisfied with the length of time they could use hot water without running out and the amount of hot water they received out of the faucet. In general, they also were satisfied with the ability to use hot water for more than one purpose, though participants were slightly less satisfied with this aspect than the other two.

Table 6. Satisfaction with TWHs (n=101) (Halfpenny 2010)

Characteristic	**Level of Satisfaction**			
	Dissatisfied (0 to 4)	**Neutral or satisfied (5 to 8)**	**Extremely satisfied (9 to 10)**	**Don't Know**
Overall performance of tankless water heater	3	30	67	1
Length of time you can use hot water without running out	2	7	86	6
The amount of hot water that comes out of the faucet	2	18	77	4
The ability to use hot water for more than one purpose	5	32	60	4
The reliability of the tankless water heater	3	15	51	32
Savings on natural gas bill	0	32	29	40
The amount of time it takes for hot water to come out of the faucet	17	62	21	1
The savings on water bills	0	36	26	39

Respondents were less sure of their satisfaction with the savings on their gas bills, the savings on their water bills or the reliability of their tankless water heaters. Thirty to 40% of respondents were unable to rate their level of satisfaction with these characteristics. The authors point out that this is likely due to the relatively short time the homeowners had used the water heaters at the time they were surveyed.

The attribute with which respondents were least satisfied was the amount of time it took for hot water to come out of the faucet, with nearly 20% of respondents expressing dissatisfaction.

The study also found that satisfaction with TWHs may be associated with the distance from the water heater to the primary faucet or appliance. Respondents with TWHs that are either closer to or the same distance from the primary use of hot water as their old water heater were more likely to report being extremely satisfied with the TWH's overall performance. In addition, this subgroup of respondents also appeared to be more satisfied with the amount of time it takes hot water to come out of the faucet, the ability to use hot water for multiple purposes, and the reliability of the TWH. Related to this is the finding that homeowners with their TWHs located in a utility closet, bathroom or hallway are more satisfied overall and more satisfied with the time it takes for hot water to come out of the faucet than were homeowners with their TWHs installed in a basement, garage or attic.

Fewer than 20% of respondents to this survey were aware that their TWHs required regular or scheduled maintenance. Only six of the 101 homeowners surveyed had performed any regular maintenance. The maintenance they performed primarily consisted of cleaning filters or filter baskets.

About 75% of those surveyed believed that they use the same amount of water with their TWH as they did with their previous StWH. Twelve respondents estimated that they use *more* hot water now, citing longer showers and the wait time to get hot water to taps as the most common reasons for this. Conversely, twelve respondents estimated that they use *less* hot water now. Their most common reasons for using less hot water were that they use cold water instead of hot water for some purposes and that they are more likely to turn the water on and off at the kitchen sink while washing dishes, rather than let the hot water run continuously.

Local Homeowner Interviews

Prior to the receiving the OES grant, CEE interviewed 10 local homeowners who currently have TWHs to obtain end-user feedback for our geographic area. These ten represent installations of the following brands:

2 – Bosch (both purchased through the retail market, one of them self-installed)
3 – Noritz
3 – Rheem
1 – Rinnai
1 - Takagi

Five of the installations were done in 2007, three in 2006 and two in either 2006 or 2005. Of the six owners who knew the model numbers, three were models with maximum outputs of around 199,000 Btu/h, two with maximum outputs of around 180,000 Btu/h and one with a maximum output of 117,000 But/h.

Nine of the owners interviewed initiated the TWH option on their own impetus. For the tenth owner, the TWH was recommended by a Green Builder the owner was working with. All but one of the nine who took the initiative on their own did so in part because of an interest in energy conservation, including two who planned to use the TWH in conjunction with a solar water heater. Two of the nine had seen TWHs in Europe and liked the way they worked there.

Most owners had to rely on their memory to estimate costs and only seven came up with a figure. Their estimates ranged from $1800 (for the self-installed unit) to $3,000, with an average of about $2,150.

All of the owners seemed happy with their TWH; most were very satisfied. None reported problems meeting demand, though four reported that it took longer to get hot water than their old system. Five reported issues get hot water with low flow tasks such as shaving and on-off dish rinsing, but all of them said this was not a big annoyance. Three reported problems with getting slugs of cold water in between showers or during times of low water usage ("cold water sandwiches"). Four noticed a need to change behaviors, but they were small changes and usually made to accommodate issues around either water flows too low to activate the heater and/or cold water sandwiches.

Utility Incentive Programs

Twenty-nine U.S. utilities and two Canadian utilities (one with some service territory in the U.S.) were identified that currently offer rebates for gas TWHs. Rebate amounts range from $100 to $500, with a median of $200.

The minimum requirements to qualify for these rebates vary from utility to utility. Some programs have multiple criteria. For example, a utility might have a minimum EF requirement and require the customer to use equipment only from a pre-approved list of manufacturers or a minimum EF requirement and a requirement that the equipment have an intermittent ignition device (IID). Results are summarized in Table 7. A detailed table of utility programs for TWHs is given in Appendix II.

Table 7. Qualifying Criteria for TWH Rebates in the U. S.

Number of Utilities Using this Criterion	Main Criterion	Additional Criteria
18	Minimum EF = 0.80	1 also requires pre-approved mfgrs. 2 also require IID
1	Minimum EF = 0.81	
7	Minimum EF = 0.82	6 also require IID
1	Minimum EF = 0.84	
1	Pre-approved mfgrs.	
3	No criteria specified	1 also requires that the gas TWH be replacing a water heater using a different energy source or be the second gas water heater for the home. 1 also has pilot program that requires pre-approved mfgrs.

Note: This table adds up to more than 29 utilities because two utilities offer one incentive criterion (the EF) in one part of their service territory and a different incentive criterion in another part of their territory.

Most of the utilities offer some sort of contractor training as part of their programs (either directly or through a coalition), although what constitutes training varies considerably from utility to utility. For example, some utilities partner with manufacturers who bring tankless units to central locations for day or half-day training sessions. This is particularly done at the beginning of incentive programs to make sure contractors are familiar with the equipment that is being promoted, learn which distributors they can purchase the equipment through, and meet a factory representative who can offer ongoing product support. Other utilities do not consider technical training part of their responsibility, but do educate contractors by giving them information on their programs and incentives, and by providing marketing materials to help them inform customers of the same.

Most utilities provide no education to their customers on how best to use TWHs. Education is usually limited to brochures, bill stuffers, web site materials and trade show contacts, which typically provide information on the incentive program but not on the technology itself except in the broadest sense. Yet industry experts as well as local contractors and end-users who were interviewed all seemed to concur that some education was important in order to ensure appropriate use of TWHs and maximum customer satisfaction.

Program contacts usually considered their TWH programs to be successful, although few formal evaluations have been done, or are available externally if they are done. Managers of programs were measuring success by the number of rebates, the participation of contractors and manufacturers in their programs and the heightened level of customer interest in tankless technologies. Most also felt their TWH programs were cost-effective, but a number of utilities expressed a desire to know more definitively what actual savings are from this technology. All contacts who knew the methodology behind their program savings estimates indicated that they were based on Energy Factors and assumed hot water use, not on measured field data.

When asked, most utility contacts were not concerned about TWHs causing huge gas demand problems in their systems. A few have concerns about low pressure in certain areas of their distribution system, but noted that if they have had any problems it has been rare and in limited areas.

Water Usage and End Use Disaggregation

There is a wide diversity of water usage in homes across the U.S. Diversity comes in both volume and usage patterns. Understanding how domestic hot water is consumed plays a large role in understanding and rating water heater performance. A few previous studies have looked at water usage. Several different methods have been used in these studies resulting in several different types of usage data.

Total Water Use by Fixture

The American Water Works Association Research Foundation conducted a study of 1188 single family homes in twelve different locations across North America (Mayer and Deoreo 1999). This study collected data at each house for two weeks in the summer and two weeks in the winter. Though this is by far the largest study of residential water use we identified, it did not differentiate between hot and cold water usage. Total water flow was measured at the whole house water meter for each site at 10 second intervals. The characteristics of a hot water end use, such as volume, flow rate and length define a fixtures flow trace signature. A flow trace was determined for each fixture. Data was then analyzed to assign each water draw event to a specific fixture. For example, the toilet in a home uses the same volume of water at the same flow rate each time it is flushed. Data processing can assign all draws with a volume and flow rate matching the toilet's flow trace to the toilet. Using this method a very high percentage of the total water volume can be assigned to specific fixtures.

The AWWA study discovered many interesting things about how residents use water in their homes. It established a strong relationship between total daily indoor water use and number of residents with a mean daily indoor use of 69.3 gallons per capita. Fixture usage was also analyzed, resulting in household usage characteristics. For example, study-wide, 1.98 showers were taken per household per day. This type of data is important because water heaters perform differently under long high volume draws than short low volume draws. Therefore the more showers there were in a day, the higher the daily water heating efficiency.

Hot Water Use by Fixture

In 2005 the Environmental Protection Agency conducted a study to determine the actual water savings from low flow fixtures (Environmental Protection Agency 2005). A total of 96 homes in Seattle, WA, the East Bay are of California, and Tampa, FLA were monitored, collecting baseline water use data for two weeks. Each home was then retrofit with low flow toilets, clothes washers, showerheads and faucets. A second two week monitoring period was conducted one month after the retrofit. The same type of flow trace analysis used by Mayer and Deoreo (Mayer and Deoreo 1999) was used to assign the flows to different fixtures. In additional to monitoring total water flow, the EPA study also monitored flow into the water heater for 20 of the homes, allowing all draws to be split into hot and cold water usage.

In addition to the primary findings on water savings from low flow fixtures (average savings of 39% of total water usage per home) the data collected provided insight into hot water use. The 20 homes in this study used 55 gallons per day (gpd) of hot water prior to the retrofits and 44 gpd after the retrofits.

Tiller et al. developed a different protocol for disaggregating domestic hot water consumption by fixture (Tiller et al. 2004). This protocol used a flow measurement at the inlet to the water heater and temperature sensors at each fixture. Temperature rises at each fixture were correlated back to the flow measurements to assign each draw to a fixture. This method allowed 93.7% of events and 99.7% of the hot water volume to be assigned to specific fixtures.

METHODOLOGY

Water Heater Selection

A total of twenty-four water heaters were installed in ten homes. A single popular StWH model from one of the largest manufacturers was used as the base case system and was installed in eight of the homes. Only one model was selected because heaters of this type have similar properties and performance. This standing pilot, natural draft unit had a 40 gallon nominal storage capacity, a 40,000 Btu/hr nominal firing rate and an Energy Factor (EF) of 0.60. Three-quarters of the 40 gallon residential gas water heater models on the U.S. market today are natural draft units with standing pilots, and these models probably represent an even greater percentage of total units sold. The EFs of this type and size of heater range from 0.59 to 0.63, with median and modal EFs by model of 0.59 (AHRI 2010). The firing rate of the StWH units used was initially measured at 24,000 to 30,000 Btu/h so the burner orifices were changed to achieve input rates of 34,000 to 36,000, closer to the nominal input[2]. Because non-condensing tankless water heaters are relatively new in the U.S. and different models use different control strategies and freeze protection schemes, units were installed from several manufacturers that have a significant

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[2] StWHs fired often fire below their rated input rate. Several factors contribute to the reduced fire rate, water heater orifices are sized for a particular natural gas heating value and elevation. Changes to these valuable require a change if the burner orifice size to reach the nameplate rating.

share of the NTWH market, either in the U.S. as a whole or in Minnesota. Ten NTWHs were obtained, two of a given model from each of five different manufacturers (Bosch, Noritz, Rheem, Rinnai, and Takagi). These units had a variety of characteristics but all had EFs between 0.82 and 0.84. The median and modal EF of NTWH models currently on the market in the U.S. is 0.82. Eight condensing tankless water heaters were purchased, two of a given model from two manufacturers and two each of two models from a third manufacturer. The CTWHs had EFs from 0.89 to 0.95. One model, Navien CR-240A, had a lightly insulated 0.5 gallon buffer storage tank intended to allow hot water output for any size flow and to reduce the time delay in hot water delivery. Table 8 lists the characteristics of the water heaters installed in the study.

Table 8. Characteristics of Tested Water Heaters

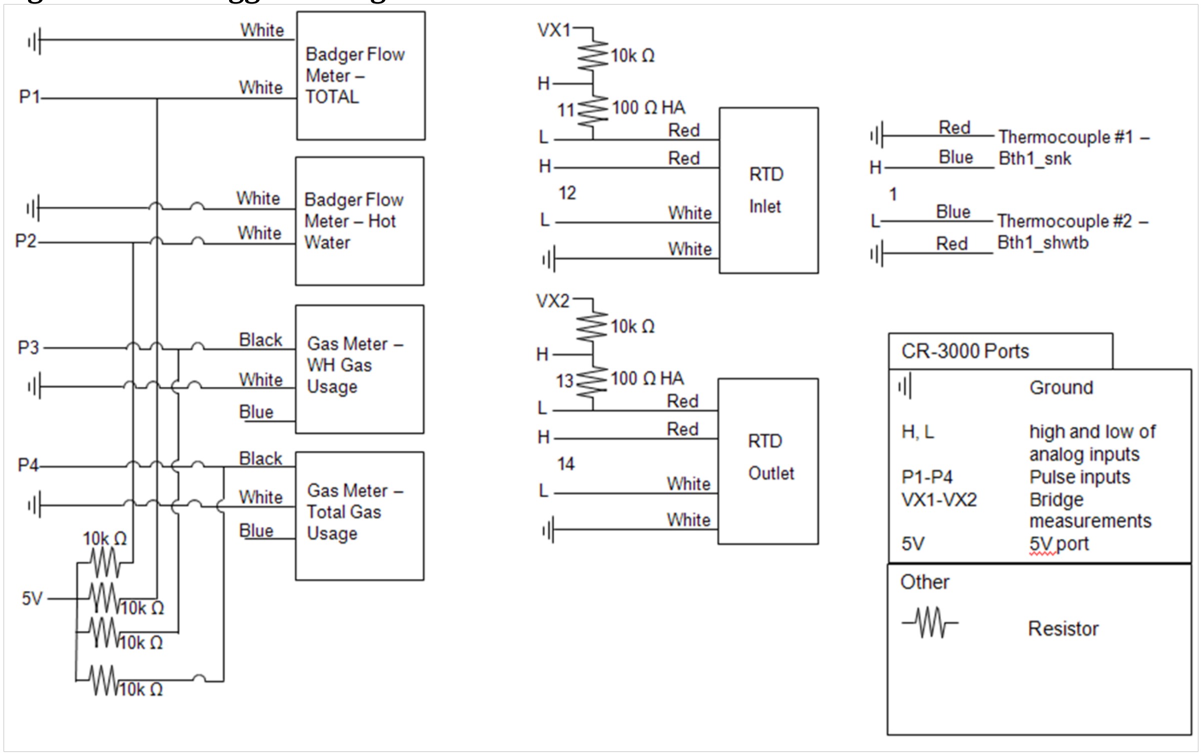
Make	Model	Input Rate, kBtu/hr	Min. Flow Rate to Start, gpm (lpm)	Max. Flow Rate at 70°F (21°C) Temp Rise, gpm (lpm)	Max. Flow Rate at 35°F (2°C) Temp Rise, gpm (lpm)	DOE EF
AO Smith	GCV40	40	N/A[1]			0.60
Rinnai	R75Lsi	15-180	0.6 (2)	4.2 (16)	7.5 (28)	0.82
Takagi	TK-3	11-199	0.5 (1)	5.0 (19)	5.5 (20)	0.84
Bosch	GWH 715ES	19-199.9	0.65 (2)	4.7 (18)	9.2 (34)	0.81
Rheem	RTG66 DV	11-180	0.5 (1)	4.2 (16)	8.4 (31)	0.82
Noritz	N0751 MCDV	12-199.9	0.66 (2)	4.8 (18)	9.8 (37)	0.82
Navien	CR-240A	17-199	N/A[2]	6.0 (23)	11.1 (42)	0.95
Navien	CR-210	17-175	0.5 (1)	5.3 (20)	9.8 (37)	0.95
Noritz	N0841 MCDV	11-199.9	0.5 (1)	4.8 (18)	10.2 (38)	0.91
Bosch	GWH c800 ES	19.9-199	0.65 (2)	5.0 (19)	10.1 (38)	0.89

1. No min. start flow rate; water heater has a 40 gal tank
2. No min. start flow rate; water heater has a 0.5 gal tank
3. Sources: (Rinnai 2008) (Takagi 2009) (Bosch 2008) (Noritz 2009) (Navien 2009) (Rheem 2009) (Bosch 2009) (Noritz 2008)

Instrumentation

Each home was equipped with two water meters, a total house water meter and a meter mounted on the inlet of the water heaters. The water meters were nutating disc, positive displacement water meters with reed switch pulse outputs of 198.4 pulses per gallon from Badger meter (model M25) (Badger Meter 2006). American Standard diaphragm meters were used for gas measurements. These meters (AC-250) were fitted with IMAC systems domestic meter pulsers to give a resolution of 40 pulses per cubic foot (Elster American Meter 2008) (IMAC 2008). These meters and pulsers were laboratory calibrated to make measurements accurate to 0.03% of the reading. Two gas meters were also installed in each house, a total house gas meter and a separate meter that measured the gas consumption of the water heaters only. A watt transducer, from Ohio Semitronics, was used to measure the electric consumption of each water heater. These watt transducers, model GW5-005B, measure true power with an accuracy of 0.2% of the reading (Ohio Semitronics 2010). Matched immersion resistance temperature detectors (RTD) were installed at the inlet and outlet of each water heater to measure temperatures. The RTDs were model P-M-1/10-1/8-3-0-P-25 from Omega Engineering and are 1/10 DIN which means an accuracy of +/- 0.03°F at 32°F (Omega Engineering 2010). Surface mount thermocouples were adhered to the hot water distribution pipes as close as possible to each hot water fixture. Thermocouples were stuck to the pipe with an adhesive sticker and then a 2 inch piece of pipe insulation was wrapped and secured around the thermocouple to isolate it from ambient air temperatures. In homes where some fixtures were unable to be isolated a remote wireless logger (HOBOloggers) were used. Remote loggers collected temperature information at one minute intervals. The HOBO data was used with one second data collected from a sensor on the nearest branch to assign end uses. Table 9 shows the important characteristics of the data collection apparatus. All monitoring equipment was wired to Campbell Scientific data loggers. The data loggers, model CR-3000, took measurements once a second and uploaded data to a central server every evening. All instrumentation was hard wired to the data logger at each site. Each logger had two water meters, two gas meters, two RTDs, a watt transducer, and up two fourteen thermocouples for end use disaggregation. Figure 2 shows the schematic for wiring the data logger at each site.

Figure 2. Data logger wiring schematic



All instrumentation was calibrated or had calibration verified before being installed in the field. The total and water heater flow meters were tested in series. Four test draws were run through each meter in series and then into a weighable bucket. Two low volume draws at less than half a gallon per minute and two high volume draws at one and a half gallons per minute were run through the set of flow meters for each site. The duration and water weight of each draw was also recorded and then checked against the measured volume and duration from each flow meter. All readings were within the manufacturer-specified calibration. A similar process was performed with each set of gas meters, whole house and water heater. Instead of running natural gas through the meters, air was forced through with a known flow rate. During this calibration check it was discovered proper performance of the pulsers on the gas meter dials was highly sensitive to placement. Pulsers had to be carefully placed so that the axis of rotation matched the dial on the gas meter.

The inlet and outlet immersion RTDs were matched in the laboratory before installation. Each set was placed in an ice bath for five minutes. The readings for this five minute period were then used to determine an offset constant to match each set of RTDs at 32 °F. After matching constants were applied, RTDs were check by placing them in an ice bath and then in a hot water bath at about 120°F. Warm up curves were checked for the set of RTDs to verify calibration and matching.

Flow and gas meters readings were verified in the field as well. After installation at each site a series of hot water volumes were drawn. A low flow draw at about 0.75 gpm and a high flow draw at about 3 gpm were taken at each site. During these draws hot water was run into a bucket at the fixture and weighed for comparison and gas meter dial revolutions were counted. The measurements taken by the data monitoring system were checked against these manual measurements.

Figure 3 shows the installation diagram for a three water heater site. The diagram shows the basic layout of the site with three-way water and gas valves and shut off valves to allow water heaters that are not operating to be shut off from the water and gas supplies. The matched RTDs were installed so that the same two RTDs could be used to measure the temperatures for all three water heaters. The inlet temperature was measured at one location for all three heaters. This measurement was made just before the water lines branched off for each water heater. The distance from the inlet RTD to the water heater varied from site to site but was typically only about two feet. A single outlet RTD was rotated from water heater to water heater depending on which heater was active. It was placed about six inches from the outlet of the active heater. Water piping distances, from the water heater outlet to the outlet RTD and from water heater outlet to the common distribution line were matched within one inch for all water heaters at a site. An equal distance for hot water distribution from each water heater was important to compare the performance of the water heaters in delivering hot water to the fixtures. For example, if the distance from water heater #1 to the connection at point “A” in Figure 3 was longer for the StWH, the homeowner would notice an increased hot water delivery time for the StWH that was a function of the distribution system, not the water heater.

Figure 3. Three water heater installation diagram

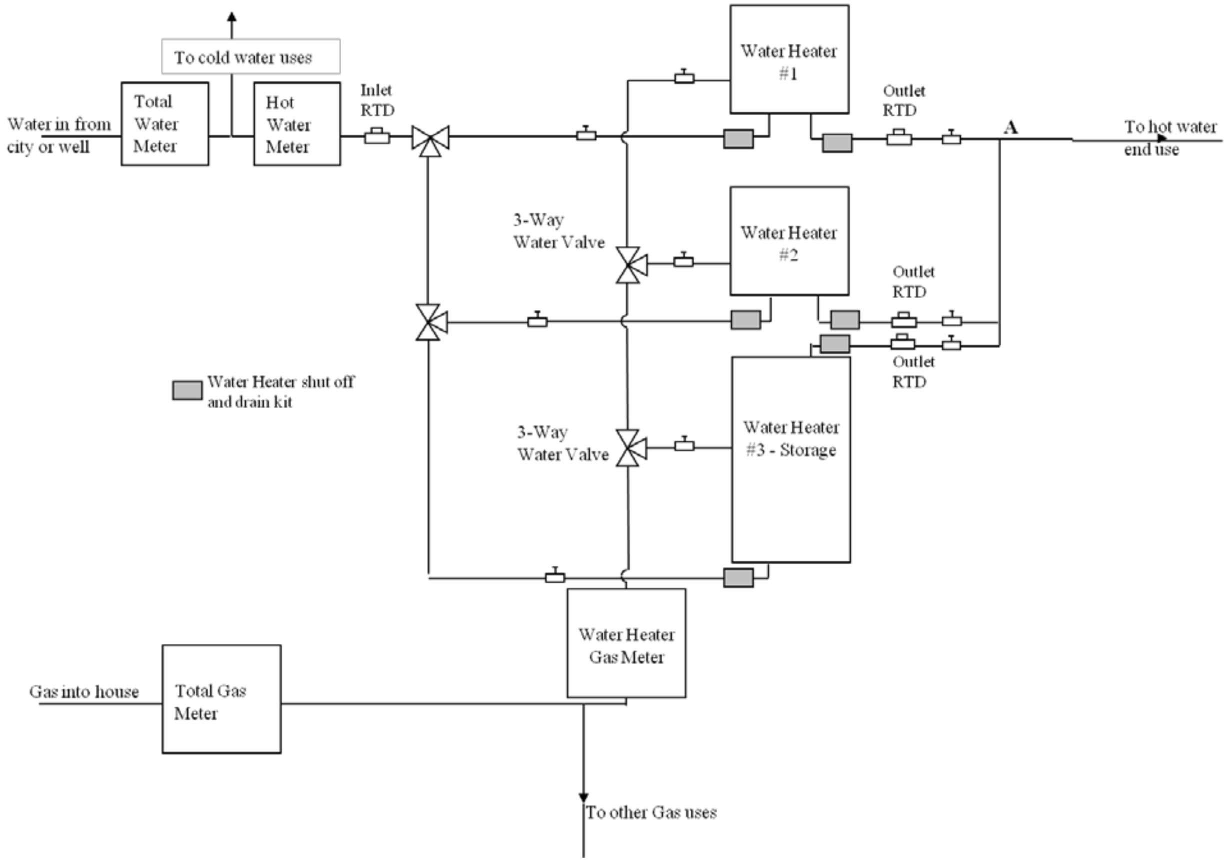


Table 9. Key Instrumentation Specifications

Instrument	Parameter Measured	Resolution	Precision	Range
Water Meter (positive displacement)	Total and water heater water volumes	198.4 pulses/gal	2% of Reading	0.5 to 25 gpm
Gas Meter	Total and water heater natural gas volumes	40 pulses/cubic foot	0.3% of reading	0 to 250 cfm
Watt Transducer	Water heater electrical consumption		0.2% of reading	0 to 500 W

Immersion RTDs	Water heater inlet and outlet temperatures		1/10 DIN	-148 to 752°F

Site Selection and Water Heater Installation

A convenience sample of ten sites was selected with a mix of household sizes matching that of the single family detached housing in the 2000 United Stated Census for Minnesota, space to install at least two water heaters, and sufficiently accessible piping to enable the hot water pipe temperature at each fixture to be monitored.

Data from the 2000 Census was used to determine the breakdown of occupancy for single family detached homes in Minnesota. 18% of homes were occupied by one person, 35% were occupied by two people, 17% by three people, 18% by four people, and 12% of homes by more than four people (US Census Bureau 2000). The ten sites for field monitoring were broken down using these percentages so that two homes had single residents, three homes had two people, two homes had 3 residents, 2 homes had four residents, and one home had more than four residents (it had 5)[3].

Homes were selected that had sufficient space for water heaters and monitoring equipment. This required space above the StWH to mount temperature sensors and the water heater flow meter. Space on an exterior wall was required to mount and properly vent one or more TWHs and the temperature sensors to collect inlet and outlet temperature data. Additionally, at least partially unfinished basements were preferred because of the access they allow to the plumbing distribution system.

Sites with city water were given preference over sites with private wells. The city water in the Minneapolis/St. Paul area leaves the water treatment plants with hardness below the maximum levels recommended by TWH manufacturers. Water from private wells in the metro area is quite hard, which requires that homeowners consistently maintain their own water softening equipment to keep hardness below recommended maximums. Water heaters were sized based on manufacturers' and plumbers' sizing guidelines and installed in conformance with

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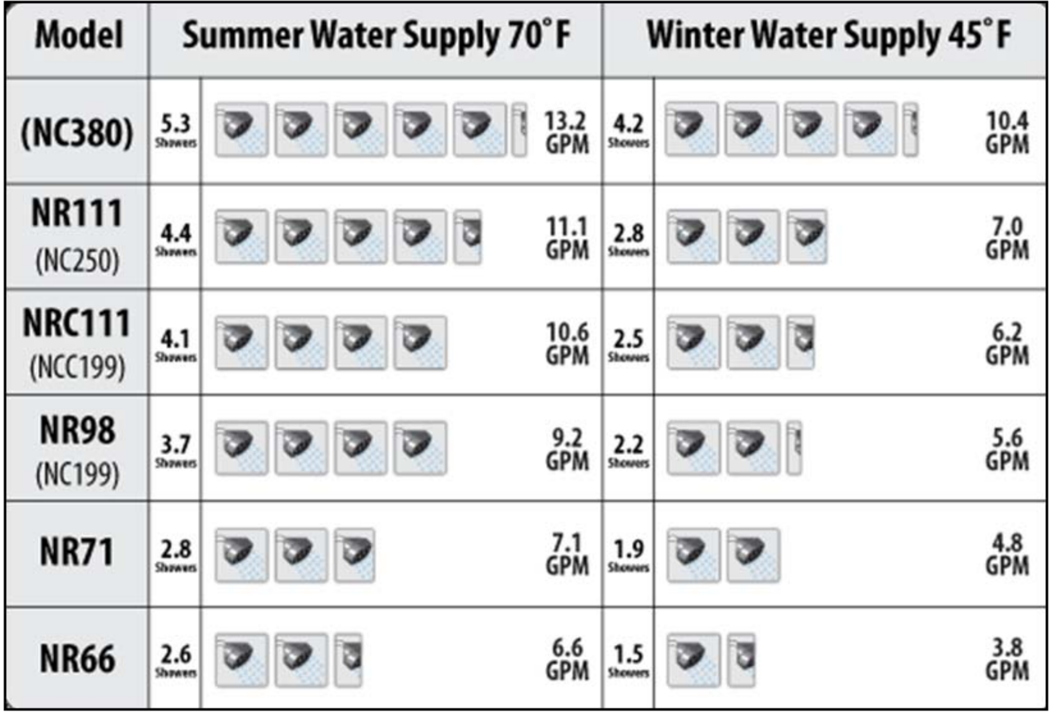
[3] Site 8 had one occupant moved out in November of 2009 reducing occupancy from four to three. Sites 1 and 9 had a college age child move in May and move out in August of 2009.

manufacturers' requirements. The sizing guidelines used are based on the size of the homes and the number of fixtures, rather than the current number of occupants. This practice prevents the possibility of an undersized water heater when the home is sold.

Manufacturer's sizing recommendations, for TWHs, are usually based on inlet water temperature and a usage component, such as number of end uses. Recommendations are typically provided for two conditions, northern or cold climates where the inlet water temperature drops below 50°F and southern or warm climates where the inlet temperature is typically above 70°F. Models are then listed for their appropriate usage condition. Some manufacturers use number of major and minor fixtures, using 2 gallons per minute as the dividing point between major and minor uses, and others use number of showers or bathrooms. Figure 4 shows a sample of one such sizing chart.

The majority of the TWHs that were installed had maximum inputs between 190,000 and 199,000 Btu/hr. The Rinnai and Rheem NTWHs had maximum inputs of 180,000 Btu/hr and the Navien CR-210 had a maximum input of 175,000 Btu/hr. These smaller units were installed in one bathroom homes with no dishwasher, because they were not in danger of exceeding the maximum flow rate ratings of the smaller water heaters. Table 10 shows the breakdown of installations.

Figure 4. Sample sizing chart for a TWH manufacturer



Model	Summer Water Supply 70° F		Winter Water Supply 45° F	
(NC380)	5.3 Showers	13.2 GPM	4.2 Showers	10.4 GPM
NR111 (NC250)	4.4 Showers	11.1 GPM	2.8 Showers	7.0 GPM
NRC111 (NCC199)	4.1 Showers	10.6 GPM	2.5 Showers	6.2 GPM
NR98 (NC199)	3.7 Showers	9.2 GPM	2.2 Showers	5.6 GPM
NR71	2.8 Showers	7.1 GPM	1.9 Showers	4.8 GPM
NR66	2.6 Showers	6.6 GPM	1.5 Showers	3.8 GPM

Source: (Noritz 2010)

Data were collected between December 2008 and June 2010. An alternating mode test procedure was employed. Valves were set at each site so that gas and water would only flow to one water heater at a time. Each site alternated modes, or changed water heaters, every month. This test method allowed data to be collected for each water heater under similar entering water temperature conditions and seasonal usage patterns. The schedule for water heater changeover was monitored and adjusted at each site so that every heater operated over the full spectrum of incoming water temperatures and outdoor air temperatures. At changeover the heater being brought on line was flushed and refilled and the period required to bring StWHs back to temperature was discarded from the dataset.

Installations were slightly staggered and data collection was terminated at different times for each site. An average of 363 useful days of data was collected at each home. Each water heater had at least 90 days of monitoring, including enough seasonal variation to characterize performance over the entire year. Some days were determined to be unusable due to artificially introduced draws, water heater or monitoring equipment maintenance, or a forced change in monitoring conditions. After deleting these days, the average number of days monitored per heater was 150.

Table 10. Water heater installations by site

Site	Household Size, No. of People	No. of Bath-rooms	No. of Showers and tubs	Dish-washer	StWH	NTWH	CTWH
1	3	3	2	Yes	AO Smith	Takagi	Navien 240A
2	4	2	2	No	AO Smith		Noritz
3	3	1.5	1	Yes		Rinnai	
4	2	1	1	No	AO Smith	Rheem	Navien 210
5	1	1	1	No	AO Smith	Rinnai	
6	5	2	2	Yes	AO Smith	Noritz	Noritz
7	2	2	2	Yes		Takagi	Navien 240A
8	4	2	2	Yes	AO Smith	Noritz	Bosch
9	1	2	2	No	AO Smith	Rheem	
10	2	1.5	1	No	AO Smith	Bosch	Bosch

All water heaters were initially set to match the temperature setting of the water heater that existed in each home prior to the study. This setting was determined by measuring the water temperature at the fixture closest to the water heater for a full-flow hot draw. After the new water heaters were installed the setpoints were adjusted until the temperature at the same fixture matched the measurement for the original water heater.

Homeowners were allowed to adjust the temperature settings over time for their comfort and were asked to track any changes they made on a log attached to each water heater. It was learned through the course of the study that the outlet water temperature of a StWH (which all ten homes had as their existing water heaters) varies considerably and cannot be accurately characterized by measuring the temperature of a single draw. Thus the new water heaters may have been matched improperly to the pre-existing setpoints, leading to a greater number of temperature adjustments by the homeowners. Nine of the ten sites made at least one temperature setting adjustment during the monitoring period. A more detailed breakdown of set point temperatures is reported in the results section.

TWHs were set digitally and temperature settings were set at the start of each monitoring period to match the set point from the end of the previous monitoring period for the same heater. The StWHs had dials to set the temperature. These dials had to be turned to a special setting to light the pilot at the start of a monitoring period and were then returned as closely as possible to the dial setting from the prior period.

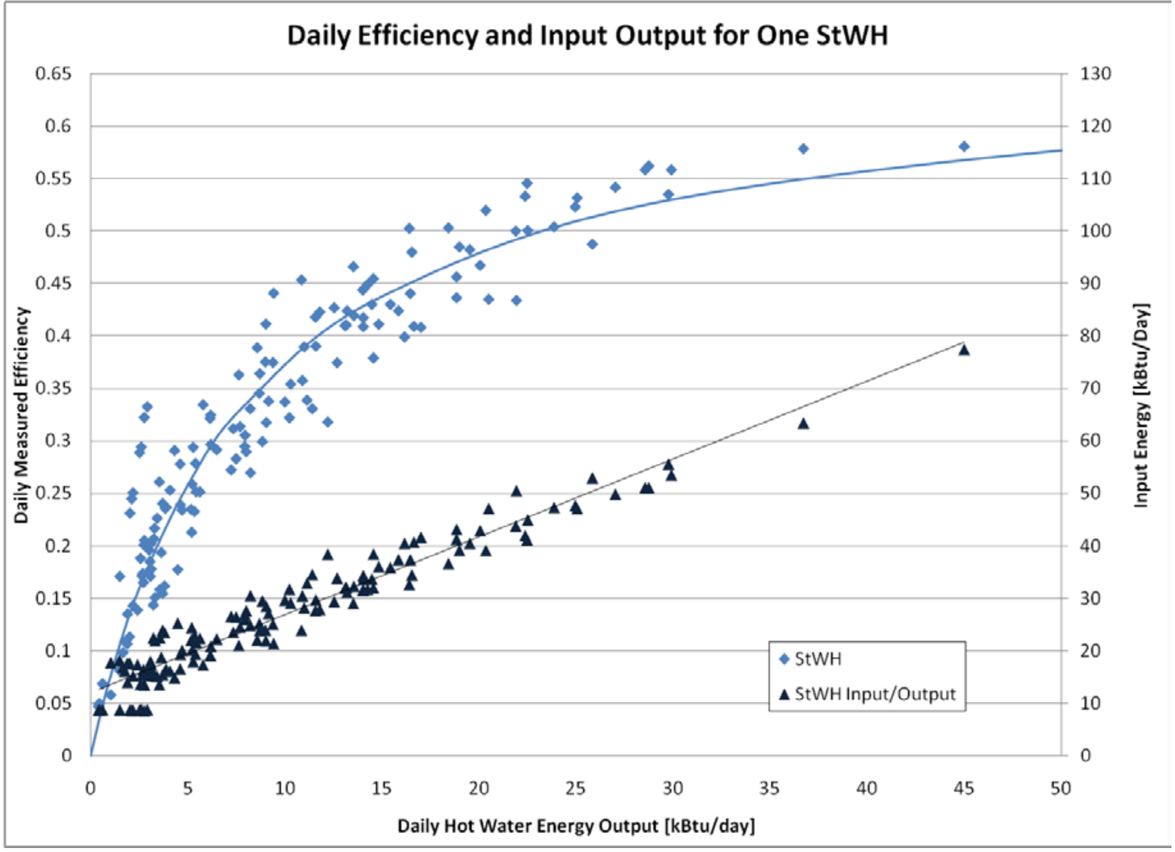
Residents at each test site were asked to complete a survey at the end of several monitoring period for each water heater. The surveys consisted of two sections. The first section addressed the acceptability of six aspects of hot water performance. The second section addressed the residents' likelihood of purchasing or not purchasing the water heater given the heater's performance on each of these attributes. The six performance attributes addressed were: delay time until hot water arrives at a fixture, the need to increase flow for low flow draws to receive hot water, the consistency of water temperature for single draws, the amount of hot water produced before running out, the consistency of water temperature for multiple simultaneous draws, and any reduction in flow rate for multiple simultaneous draws. Appendix III contains copy of the survey questions and the responses from each homeowner for each water heater.

Data Analysis

Annual natural gas use and efficiency were estimated through a two-step process. In the first step the relationship between daily output and daily input was determined, and in the second step this relationship was used, together with output data taken over the course of the 15 month study, to determine annual energy use and efficiency. The same procedure was used to determine electricity consumption related to hot water output. Electricity consumption due to freeze protection was treated separately.

Analysis of the data verified a strong linear relationship between daily natural gas input and daily hot water energy output (see Figure 5 for an example) for the range of data collected. This is consistent with results reported previously for commercial boilers (Hewett 2005), commercial water heaters (Bohac et al. 1991) residential dual integrated appliances (Butcher, Celebi, and Wei 2006) and commercial gas cooking equipment (Horton and Caron 1994). These linear input-output relationships with non-zero intercepts produce typical efficiency curves when plotted in the form of efficiency vs. output (see Figure 5 for an example). The slope of the input-output line can be thought of as something similar to the inverse of recovery efficiency and the y-intercept can be thought of as the energy input required to offset stand-by losses. For StWHs the y-intercept closely approximates the energy input required to keep the heater warm on a day with no draws. Except for the unit with the buffer tank, the TWHs do not keep themselves warm, so the y-intercept does not predict energy consumption for a day with no draws, which would in fact be close to zero. Rather, it reflects the energy required to make up for typical daily transient losses. These transient losses occur due to heating and cooling of the TWH's thermal mass when cycling in response to draws. The y-intercept for the input/output plot of the TWHs does not represent the energy usage with no hot water draws. It represents the ramp up losses associated with the water heater "warming up" during the start of a draw. Actual energy usage for a no draw day would by the electric standby consumption (about 0.6 kBtu/day).

Figure 5. Daily efficiency and energy input and output for one StWH



When individual draws (rather than daily averages) are plotted on an input-output graph for TWHs, some non-linear effects are seen for draws with very small outputs, due to the input required to bring the mass of the water heater itself up to temperature, but over the course of a day the transient losses apparently are either relatively constant from day to day or perhaps vary linearly with daily output, so that the daily input-output plots do not show non-linearities other than the discontinuity right at zero output. Thus the linear input-output relationship accurately captures water heating energy use for any practical daily draw volume when the homeowner is in residence, but does not accurately capture energy use for days when the homeowner is away.

The input-output lines for StWHs have more scatter (r^2 = 0.91 to 0.98) than those for TWHs (r^2=0.97 to 1.00). Examination of the intervals at which StWHs fire when on standby and the length of standby fires suggests that much of the scatter is due to the varying amounts of energy stored in the tank at the end of each day. Another factor is that the StWH set point is set by a dial and it was not possible for the technician to return the dial to precisely the same point after relighting the pilot for the start of each StWH test period. Controlled experiments conducted in one of the homes after the primary monitoring period confirmed that different set point temperatures correspond to different stand-by losses and therefore different y-intercepts. For all water heaters analysis of subsets of the data and other side experiments showed that different inlet water temperatures, water heater setpoint temperatures and ambient air temperatures created slightly different linear relationships. However, the change in these linear relationships was small enough over the ranges observed at the ten sites monitored that very high r-squared values were computed for regressions of data aggregated across variations in these variables.

Because the relationship between input and output is linear, the mean energy use for any period can be computed directly from the mean heater output. Hot water energy output, in turn, varied linearly with the temperature of the cold water coming into the house (referred to here as the “main temperature”). This relationship has been shown previously in Minnesota (Hancock and Bohac 1996). It may reflect both greater energy input required to heat colder water to a given set point and increased hot water volume used due to the need to blend more hot water with the colder cold water for a given shower or bath water temperature, or perhaps taking warmer showers or baths in colder weather.

Main temperatures were calculated by looking at all hot water draws in a day that were over three minutes. It was assumed that after the first minute of a draw all water that had been in the pipes between the inlet of the home and the water heater, i.e., all water which had been warmed by the ambient room conditions, had passed through the water heater. This allowed an average main temperature to be calculated from the average temperature at the water heater inlet over the remaining duration of the draw. These long-draw temperatures were averaged over each day and defined as the daily main temperature. Mean annual main temperatures were computed for each site by averaging the daily main temperatures over the course of a year.

The main temperature varied with season and depended on the water source. Eight sites were supplied by city water from surface sources. The main temperature for these homes ranged seasonally from 37 °F to 72°F. One site had city water from a municipal well. Its main temperature ranged from 47°F to 57°F. Another site relied on a private well and its main temperature ranged from 47°F to 52°F. The two homes with well water sources did not have a large enough variation in main temperature to produce a statistically significant correlation between hot water energy output and main temperature.

Day to day hot water energy output varied considerably due to variations in water use activities in the home. Weekly average output was much less variable and so better suited to analysis of seasonal variations in output. In order to determine whether hot water energy output was statistically different for different heaters at the same house, weekly output was regressed on main temperature with the water heater used as a dummy variable. Because of the linear relationship between the hot water energy output and the main temperature, the mean output can be computed directly from the mean main temperature. If the water heater dummy variable was not significant, the same mean output was used for each heater. If the dummy variable was significant, the water-heater-specific mean output was used. These output values were then used with the linear input-output relationships for each heater to compute mean annual energy use.

In cold northern climates, such as Minnesota, an TWH heat exchanger could be damaged if standing water were allowed to freeze inside the unit. Under some venting and usage scenarios cold air can enter the units through the combustion air supply or exhaust. Manufacturers provide freeze protection to prevent this. If temperature sensors inside the water heater drop below a manufacturer-determined level, electric heaters inside the unit are triggered. The run time of the electric heaters and the power draw required during freeze protection vary

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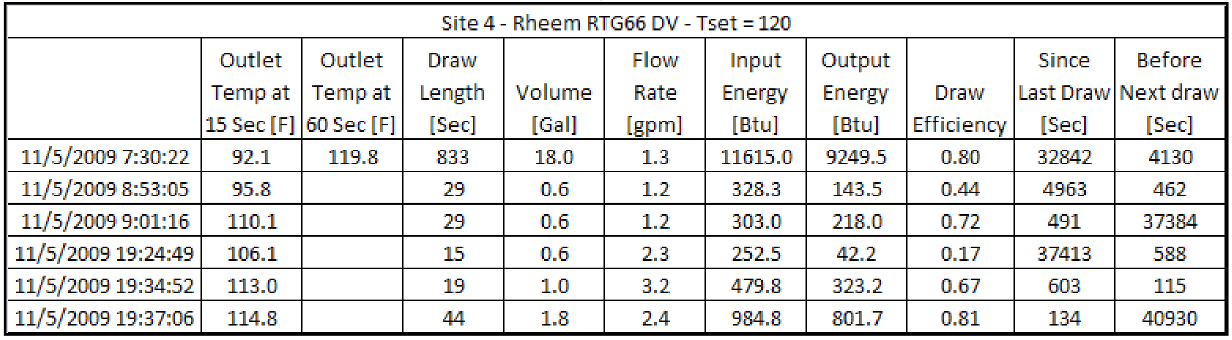
from heater to heater. A reference temperature for each TWH was defined as the daily average outdoor temperature below which electrical consumption for freeze protection was observed. Electricity consumption for freeze protection increased linearly with decreasing average daily outdoor temperature below the reference temperature. Any electrical consumption for freeze protection was included in the energy use and savings calculations for TWHs.

In addition to the energy use and savings analysis, hot water draw pattern and end use analyses were also performed. The draw pattern study analyzed all draws out of the water heaters to determine overall hot water usage patterns. The end use analysis looked at hot water draws by fixture to determine usage patterns for each hot water end use in the home.

The analysis of all hot draws was performed to determine overall characteristics of the hot water usage in a home. The one second data from each site were processed to generate a list of hot water draws and their characteristics, such as length, volume, flow rate, energy input, energy output and temperature. The analysis was performed by using the hot water flow meter pulses as an on off switch. One flow meter pulse is about 0.6 fluid ounces and the data is logger at one second intervals. The high resolution of the water meter allows it to be used to indicate the beginning and ending of a draw. The summation of draw characteristics begins any time the hot flow meter pulse rate goes from zero to one or greater per second and concludes when the pulse rate drops back to zero. Draws that lasted less than three seconds were excluded, to eliminate draws that may result from leaks in the distribution system or fixtures as well as spurious draws that may result from slight changes in water pressure at the flow meter. Table 11 shows a sample of the data processed with this method at one site. These data can be used to determine the frequency of draws for the different characteristics recorded. For example, how many draws with a NTWH are less than 30 seconds in length?

Table 11. Sample of data processed for analysis of hot water draw profiles



Site 4 - Rheem RTG66 DV - Tset = 120

	Outlet Temp at 15 Sec [F]	Outlet Temp at 60 Sec [F]	Draw Length [Sec]	Volume [Gal]	Flow Rate [gpm]	Input Energy [Btu]	Output Energy [Btu]	Draw Efficiency	Since Last Draw [Sec]	Before Next draw [Sec]
11/5/2009 7:30:22	92.1	119.8	833	18.0	1.3	11615.0	9249.5	0.80	32842	4130
11/5/2009 8:53:05	95.8		29	0.6	1.2	328.3	143.5	0.44	4963	462
11/5/2009 9:01:16	110.1		29	0.6	1.2	303.0	218.0	0.72	491	37384
11/5/2009 19:24:49	106.1		15	0.6	2.3	252.5	42.2	0.17	37413	588
11/5/2009 19:34:52	113.0		19	1.0	3.2	479.8	323.2	0.67	603	115
11/5/2009 19:37:06	114.8		44	1.8	2.4	984.8	801.7	0.81	134	40930

The hot water end use draw patterns were determined using the measured fixture temperatures and the flow meter readings. Surface mount thermocouples had been mounted on the "twig" for each fixture. A twig is a section of piping that supplies water to only one fixture. Local minimums and maximums of the derivative with respect to time of each of these end use temperatures can be used as indicators of hot flow to each fixture. This method was developed for ASHRAE Research Project 1172 (Tiller et al. 2004). Figure 6 shows a single shower draw with a StWH. This figure also plots the water heater's outlet temperature, the temperature at the active fixture (bath1 shower) and the temperature at a typical non-active fixture (laundry sink). Both of the outlet and active end use temperatures increase shortly after flow is registered, while there is no increase in the non-active end use temperature. There is a delay between the increase in the outlet temperature and the increase in temperature at the active fixture because the hot water takes time to flow through the distribution system. Figure 7 shows the same draw, but instead of the end use temperatures this plot shows the derivatives of the running sixty second backward regressions of each end use temperature curves. The large spike in the bath1 shower derivative and the lack of such a spike in the laundry sink derivative can be used as an indicator that the shower is in use and the laundry sink is not. After each draw is assigned to a fixture in this manner, all draws for each fixture can be analyzed to characterize the draw profiles for each end use.

Figure 6. Flow rate, water heater outlet water temperature and end use temperature for a single shower draw with StWH

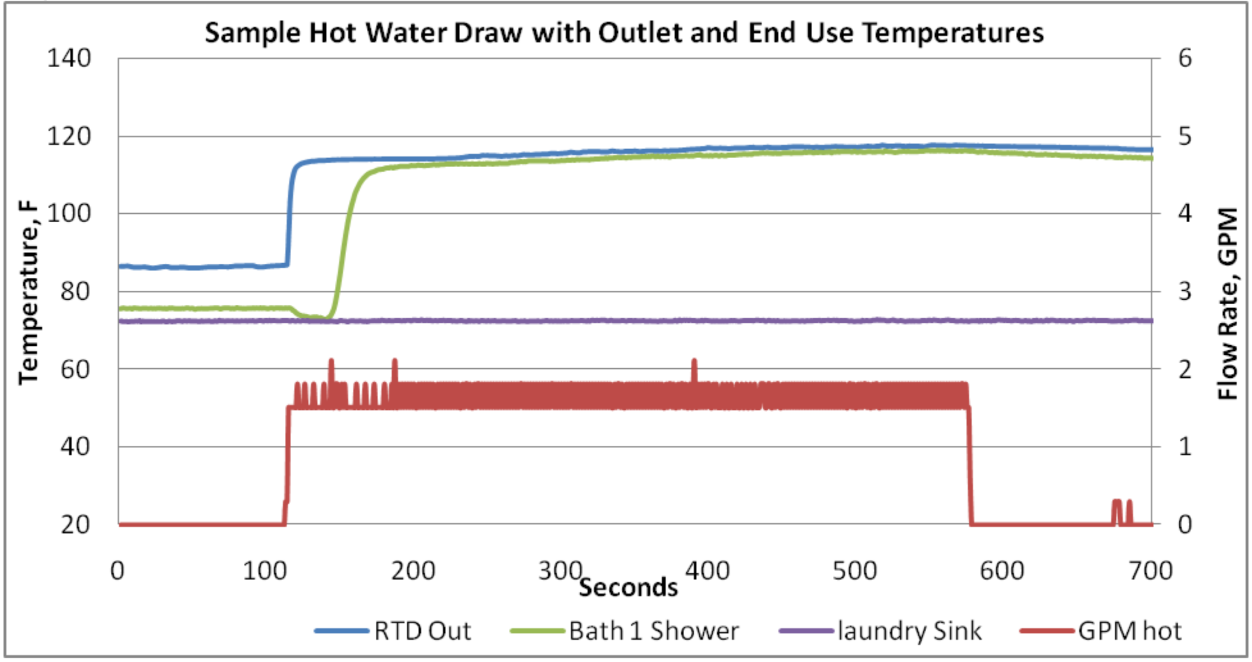
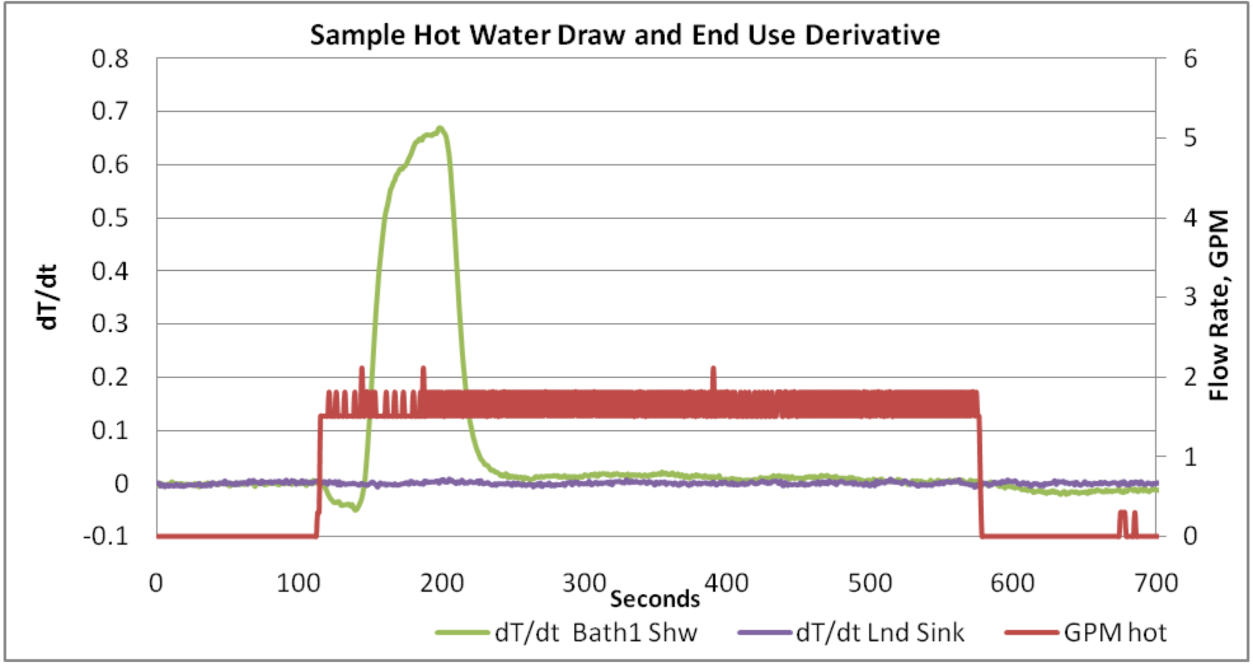


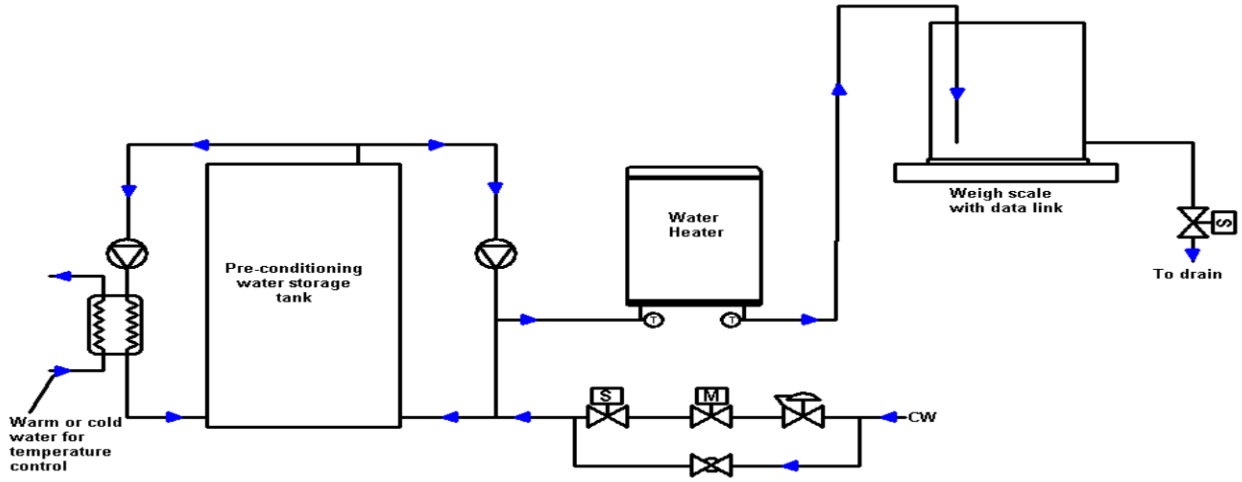
Figure 7. Flow rate and end use time derivatives for draw shown in Figure 6



Laboratory Testing

One unit of each model of water heater installed in the field was tested in the laboratory at Brookhaven National Laboratory. Each water heater was tested using the apparatus shown in Figure 8. Natural gas input to the water heaters was measured using a diaphragm gas meter with a pulse output sensor. The sensor had a resolution of 1000 pulses/ft^3. Total pulses per second were counted on a pulse logger. An “in-line” gas chromatograph measured gas composition and relevant properties periodically. Energy output was measured using inlet and outlet thermocouples and a weigh scale which communicates with the lab’s measurement and control system. The scale is located on the second floor balcony of the lab and drains down during the periods between hot water draws under control of the lab’s central system. Draining of this tank is stopped 15 seconds before each draw and for a 15 second period after the end of the draw to allow readings to stabilize. Temperatures and scale mass are recorded at 5 second intervals. For some very short draw tests, a 1 second temperature measurement interval was used. A 40 gal (151 L) preconditioning tank was used to heat or cool the inlet water. Inlet and outlet thermocouples were located 4 inches from the appliance.

Figure 8. Water heater laboratory test apparatus



Each water heater tested underwent a series of tests. The test matrix (Table 12) included steady state tests at various inlet water temperatures from 40 to 70°F and outlet temperatures from 105 to 133°F. Steady state draws also covered a range of flow rates from the minimum flow rate required to maintain steady burner fire to the maximum flowrate of the water heater. The test matrix also included a wide range of cyclical tests designed to replicate the range of draws found in the field. Draw characteristics varied in the protocol include flowrate, total volume, time between draws, inlet and outlet temperatures, and inlet water temperature. The DOE EF test was also performed on each unit and a test to measure to water volume inside the water heater.

Cyclic testing was done under computer control. A series of cyclic test conditions were defined in an input file and this typically contained combinations of draw patterns with the total test period as long as 20 hours. For each specific test, 3 to 20 draw/idle cycles were imposed at the same condition. Short draws required more cycles for repeatability. During these cyclic tests all data were recorded in multiple files and these were analyzed later to determine average conditions and results for each pattern.

Table 12. Laboratory test matrix listing test conditions to be applied to each water heater

CYCLIC TESTS							
Test No.	Volume	Volume	T cold in	T cold in	T out	T out	Idle time
	gal	L	F	C	F	C	min
Cyclic Tests at 2.0 gpm							
1	1	3.8	60	15.6	133	56.1	2
2	1	3.8	60	15.6	133	56.1	4
3	1	3.8	60	15.6	133	56.1	45
4	2	7.6	60	15.6	133	56.1	2
5	2	7.6	60	15.6	133	56.1	4
6	2	7.6	60	15.6	133	56.1	45
7	3	11.4	60	15.6	133	56.1	2
8	3	11.4	60	15.6	133	56.1	4
9	3	11.4	60	15.6	133	56.1	45
10	4	15.1	60	15.6	133	56.1	2
11	4	15.1	60	15.6	133	56.1	4
12	4	15.1	60	15.6	133	56.1	45
13	5	18.9	60	15.6	133	56.1	2
14	5	18.9	60	15.6	133	56.1	4
15	5	18.9	60	15.6	133	56.1	45
16	10	37.9	60	15.6	133	56.1	2
17	10	37.9	60	15.6	133	56.1	4
18	10	37.9	60	15.6	133	56.1	45
Cyclic Tests at less than 1 gpm							
19	2	7.6	60	15.6	133	56.1	2
20	2	7.6	60	15.6	133	56.1	4
21	2	7.6	60	15.6	133	56.1	45
22	10	37.9	60	15.6	133	56.1	2
23	10	37.9	60	15.6	133	56.1	4
24	10	37.9	60	15.6	133	56.1	45
Cyclic Tests at 4 gpm							
25	2	7.6	60	15.6	133	56.1	2
26	2	7.6	60	15.6	133	56.1	4
27	2	7.6	60	15.6	133	56.1	45
28	10	37.9	60	15.6	133	56.1	2
29	10	37.9	60	15.6	133	56.1	4
30	10	37.9	60	15.6	133	56.1	45
STEADY STATE TESTS							
	Flow	Flow	T cold in	T cold in	T out	T out	
	gal/min	L/min	F	C	F	C	
31	1.5	5.7	60	15.6	133	56.1	
32	2.5	9.5	60	15.6	133	56.1	
33	max	max	60	15.6	133	56.1	
34	2	7.6	60	15.6	133	56.1	
35	2	7.6	60	15.6	105	40.6	
36	2	7.6	60	15.6	115	46.1	

37	2	7.6	60	15.6	125	51.7	
38	2	7.6	40	4.4	133	56.1	
39	2	7.6	70	21.1	133	56.1	

RESULTS

Hot Water Energy Output

As described in the Methods section, daily water heater energy input is a strong linear function of daily hot water energy output. Total annual energy input can be estimated to a high degree of accuracy by combining this linear input-output relationship with information on annual average hot water energy output. Hot water energy output, in turn, is a linear function of main water temperature (Hancock and Bohac 1996).

In order to determine the energy required to provide hot water to the home, it was therefore necessary to characterize the hot water energy output (HWEO) at each site and determine whether it was a function of the particular water heater being used.

Hot water energy output varies with season. In colder months with lower main temperatures more hot water energy is used, as seen in **Error! Reference source not found.** and similar figures for all sites in Appendix VI. The amount of seasonality depends on the range of main temperatures and the amount of seasonality in the homeowner’s water use habits. Table 13 lists the range of daily main temperature for each site over the entire monitoring period. Site 1 had a private well, which reduced the variation in main water temperatures to less than 2 degrees. Site 9 received water from a municipal well. Though the groundwater temperature is likely constant, there was a small (9°F) range in main temperature at this site, probably because water travelling from the well to the site is affected by ground temperatures. Because the main temperature ranges were small at these two sites there was no correlation between hot water energy output from the water heater and the main temperature. At sites 1 and 9 there was not a significant difference in average consumption between the different heater types so the HWEOs from all water heaters were analyzed together. At the other eight sites’ main temperatures varied seasonally by about 30 to 35°F.

Figure 9. Seasonal variance in hot water energy usage for all data at Site 10

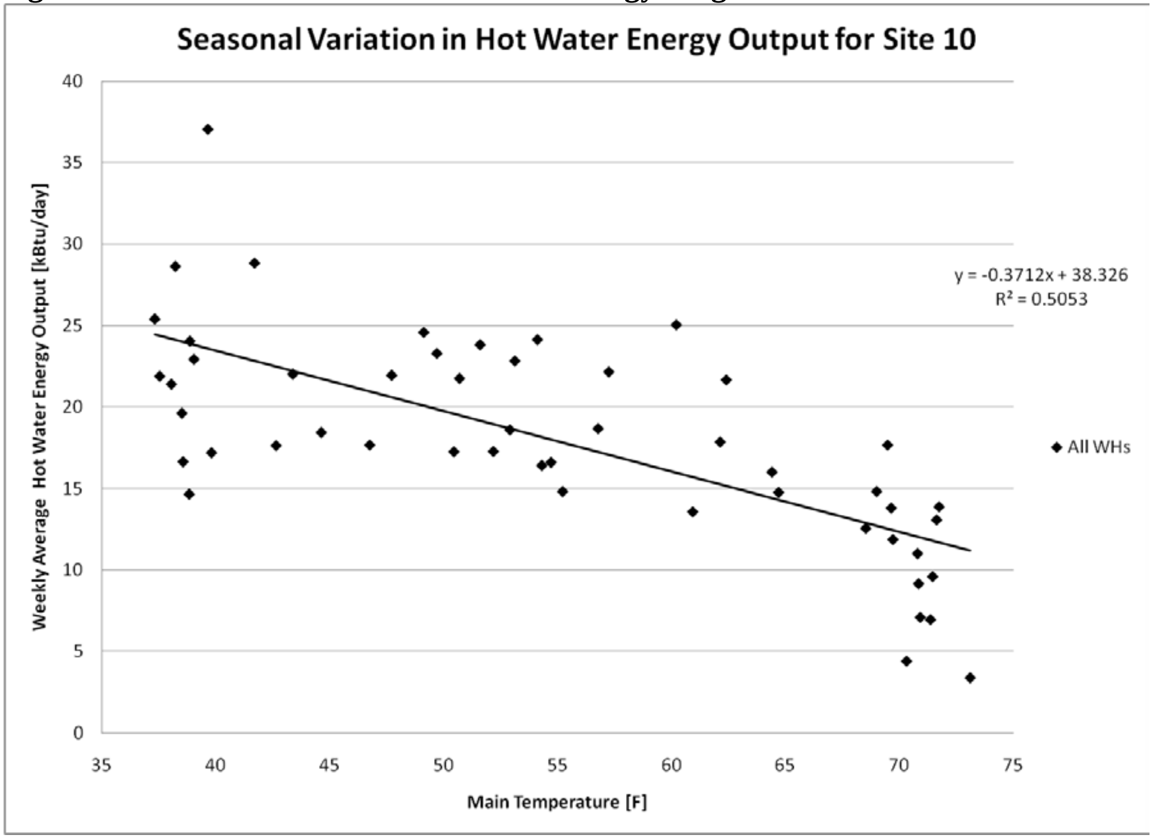


Table 13. Main temperature ranges and hot water energy outputs over that range

Site	Main Min.	Main Max.	Range	HW Energy Output at 40 F	HW Energy Output at 70 F	
	F	F	F	kBtu/day	kBtu/day	
1	49.3	51.2	1.9			
2	37.4	72.1	34.7	42.6	19.0	55%
3	36.9	71.0	34.1	29.2	16.4	44%
4	38.9	70.7	31.8	17.9	9.7	46%
5	37.9	68.7	30.8	12.8	6.6	49%
6	37.8	71.6	33.8	40.6	24.9	39%
7	38.0	67.8	29.8	24.3	14.4	41%
8	37.9	69.9	32.0	29.1	25.6	12%
9	46.5	55.5	9.0			
10	37.3	71.7	34.4	23.5	13.5	43%

Output as a function of main temperature could depend on which water heater is being used, either because of differences in the output characteristics of the heater or because of changes in occupant behavior in response to those differences. As an example of the former, if a StWH delivers hot water more quickly than a TWH, each of the short draws that occur in the course of a day or year may contribute more energy output when using a StWH than when using a TWH. As an example of the latter, the ability of a TWH to provide endless hot whater might induce the homeowner to take longer showers.

The effects of the water heater on HWEO were determined by comparing the relationship between hot water energy output and main water temperature for different heaters. For this analysis weekly data intervals were used, in order to reduce some of the variation that occurred in daily data due to different showering patterns or clothes and dish washing that was typically on a more weekly than daily schedule. Data was presented as a daily average for the week to keep consistent units. A test of significance was applied to the slope, intercept and correlation coefficient of this relationship for each pair of water heaters (Wuensch 2007) (Fisher 1921). Figure 10 shows the relationship of hot water energy output to main water temperature for site 10, for example. For this site the small difference in the relationship between the StWH and the TWHs is not significant due to the scatter in the data. For sites with no significant difference, output data from all the water heaters was grouped together and regressed on main temperature, as shown in Figure 9.

Figure 10. Hot water energy output as a function on main water temperature with no statistical difference between water heaters

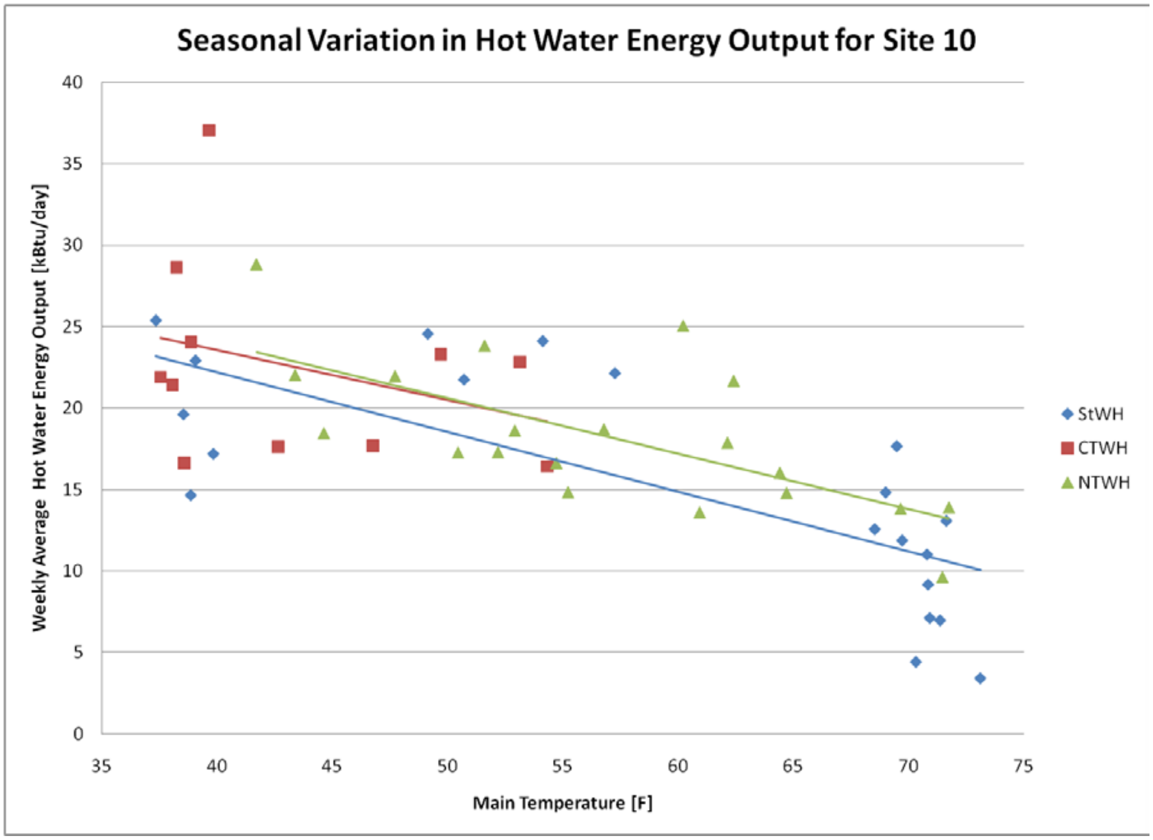


Table 14 shows the relevant statistical parameters and associated critical values for each pair of water heaters at all ten sites. Differences between heaters were determined to be statistically significant if the magnitude of the parameter computed to compare their slope, intercept, or correlation coefficient (t_m, t_b or z, respectively) was greater than the corresponding critical value (t_m_t, t_b_t or z_t). The only sites where any water heaters differed significantly are the two sites where the main temperature range was less than 10 °F (Site 1 and 9) and seasonal effects were disregarded. For all other sites output from all water heaters was grouped together and regressed against main temperature, as shown in Figure 9. Table 15 lists the regression parameters for the seasonal variation of energy output of all water heaters grouped at each site. R-squared values are very low at sites 1 and 9 because there is no seasonal variation at these sites. There was not a strong fit at site 8 because occupancy changed during the course of the study, adding to the variability in weekly output. The change in occupancy was abrupt and unexpected, thus cold weather data for the storage water heater had a higher occupancy (and higher outputs) than that of the TWHs.

Table 14. Statistical parameters and critical values for comparison of hot water energy output vs. main temperature for each pair of heaters at each site

	StWH vs. NTWH						StWH vs. CTWH						NTWH vs. CTWH					
	z	z_t	t_m	t_m_t	t_b	t_b_t	z	z_t	t_m	t_m_t	t_b	t_b_t	z	z_t	t_m	t_m_t	t_b	t_b_t
1	-0.3	2.0	-0.6	2.0	0.6	2.0	-1.5	2.0	1.2	2.0	-1.1	2.0	-1.1	2.0	2.2	2.1	-2.2	2.1
2							0.6	2.0	-0.1	2.0	0.0	2.0						
3																		
4	-0.3	2.0	0.7	2.1	-0.5	2.1	-0.4	2.0	-0.4	2.1	0.2	2.1	-0.2	2.0	-1.0	2.1	0.3	2.1
5	-0.5	2.0	0.0	2.0	0.2	2.0												
6	1.9	2.0	-1.2	2.1	1.1	2.1	0.8	2.0	-0.2	2.0	0.2	2.0	-1.2	2.0	1.0	2.0	-0.9	2.0
7													1.1	2.0	-1.0	2.0	1.2	2.0
8	-0.5	2.0	0.1	2.1	1.5	2.1	-0.6	2.0	0.1	2.1	1.9	2.1	-0.1	2.0	0.0	2.1	0.5	2.1
9	-1.3	2.0	-0.7	2.0	2.6	2.0												
10	0.6	2.0	0.1	2.0	-0.3	2.0	1.6	2.0	-0.1	2.1	0.0	2.1	1.1	2.0	-0.1	2.0	0.2	2.0

Note: There are three comparisons for each site; coefficient of correlation (z), slope (m), and intercept (b). If the magnitude of the value from the computed parameters (z, t_m, t_b) is greater than the critical (table) value (z_t, t_m_t, t_b_t) than the two regressions are statistically different. The parameters that differ significantly and their critical values are shaded in gray.

Table 15. Regression parameters for the hot water energy output vs. main temperature relation at each site

	HW Energy Out vs MAIN Temp			Average Main Temp	HW Energy Output
Site	Slope	Intercept	R^2		
1[1]	-2.88	172.53	0.03	49.8	28.8
2	-0.79	73.99	0.50	56.7	29.5
3	-0.43	46.33	0.49	53.1	23.6
4	-0.27	28.91	0.37	54.6	13.9
5	-0.21	21.22	0.68	54.0	9.9
6	-0.53	61.69	0.49	54.7	23.9
7	-0.33	37.49	0.34	52.5	20.1
8[2]	-0.12	33.75	0.03	54.0	27.4
9[1]	0.51	-15.88	0.08	51.1	9.8
10	-0.33	36.90	0.49	53.7	18.9

1. In Site 1 and 9 had well water and no hot water energy output correlation with season
2. Site 8 had a change in occupancy during the study and the seasonality was lost.

For each site mean main temperatures were computed using daily main temperatures measured over the year of monitoring, then the average daily hot water energy output corresponding to this main temperature was determined (for all heaters together, as described above). At sites 1, 8, and 9 where the seasonal variation in HWEO as a function of main temperature was insignificant the average HWEO was taken over the measured daily values for a full year of monitoring data. Table 15 shows the average main temperatures and average daily HWEOs for each site.

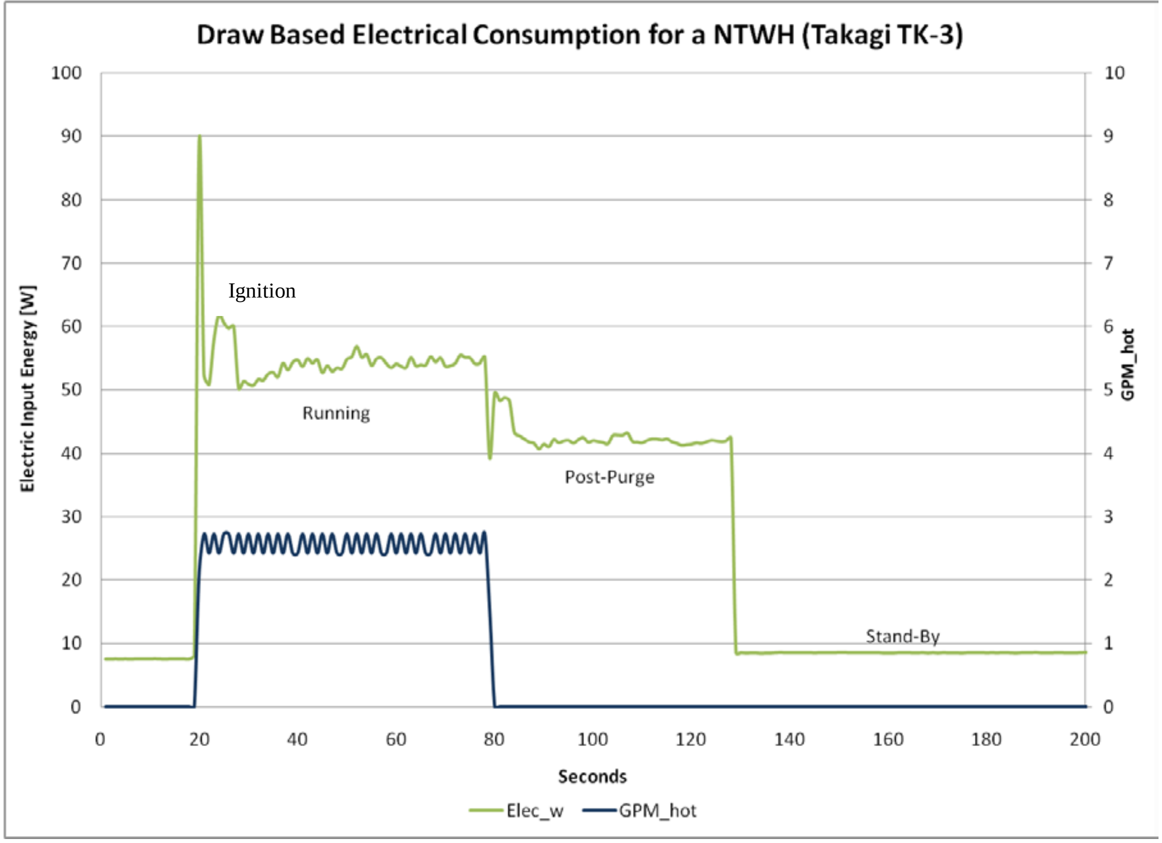
Energy Use, Savings, Costs and Paybacks

The energy input to each water heater as well as the hot water energy output from each water heater was measured and summed on a daily basis. The resulting linear relationship for each water heater was used with the average daily hot water energy output from each site to determine the annual energy consumption for each water heater installed at the site. The input-output relation had very strong R^2 values for all water heaters for natural gas input, draw-related electric input and the combined total energy input. The total energy input versus hot water energy output regressions for each site, for example, have R^2 values greater than 0.90. There are several factors that introduce small non-linearities, as discussed in the Data Analysis section of the Methodology. These non-linearities are small compared to daily energy input and output from the water heater and do not have a significant effect on annual energy use.

Electrical freeze protection could also introduce non-linear effects for some TWHs, by increasing energy input without increasing hot water energy output. Freeze protection energy use was treated separately. There are two ways electricity is used by TWHs, during a hot water event ("draw-related electricity use") and for freeze protection. Draw related electricity use can be broken down into an ignition, draw, and post purge stage, as shown in Figure 11. Standby electricity use is also included in the draw-related electricity use regressed on output. Freeze protection electrical usage is typically used to power ceramic heaters inside the water heater. If temperatures dropped below set levels inside the water heater the ceramic heaters are activated. Freeze protection operation was only observed to any significant extent on 2 NTWHs and 1 CTWH during the monitoring period. The degree to which freeze protection was necessary, if at all, depended not only on water heater characteristics and controls but also on the installation.

Length and design of vent and intake air piping, orientation of vent and intake openings with respect to wind and many other installation specifics all affect the extent to which freeze protection controls are activated. For this reason freeze protection was treated separately from other energy input to the water heaters.

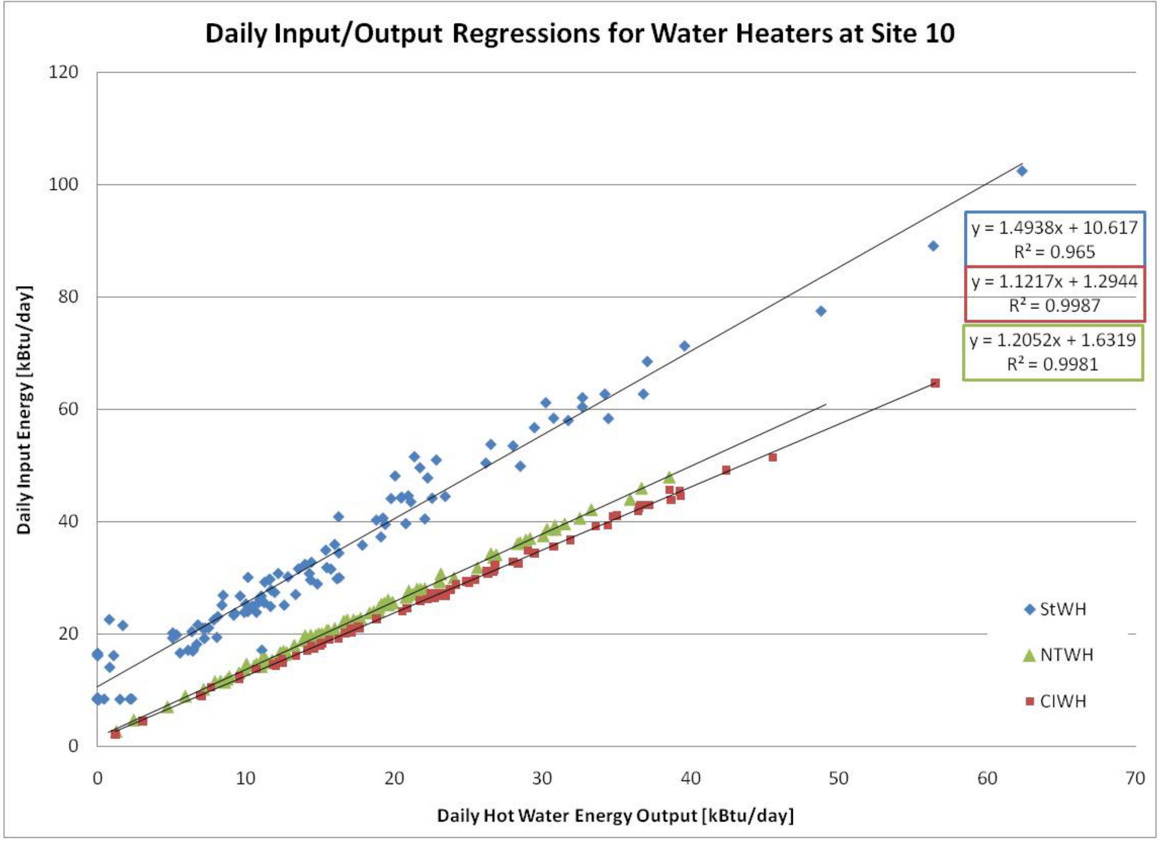
Figure 11. Hot water draw based electrical energy consumption for a sixty second draw on a Takagi TK-3 (NTWH)



Natural gas and (draw related) electrical energy input were regressed against hot water energy output for all water heaters monitored. Figure 12 shows the regressions for site 10. The average daily energy input for any water heater at site 10 can be determined by taking the average hot water energy output, from Table 15, and finding the corresponding energy input from that heater's regression in Figure 12. Figures showing the input/output regressions for all ten sites can be found in Appendix VI. Table 16 shows the regression parameters for all twenty-four water heaters. These regressions all have very high correction coefficients, R^2 between

0.905 and 1.000, demonstrating that non-linear effects are negligible relative to total energy input.

Figure 12. Daily energy input versus hot water energy output for 3 water heaters at Site 10



Average daily natural gas and electricity use determined from the regressions were compared for all heaters at each site to determine the savings for NTWHs and CTWHs. Table 1 and Table 18 shows the annual natural gas and draw-related electric consumption for each water heater at each site and the savings for NTWHs and CTWHs relative to the StWH. A range of savings from 23 to 50% was found for the NTWHs and a range from 32 to 55% for the CTWHs (excluding the Navien CR-240A, discussed separately later). On average switching from a NTWH to a CTWH only increased savings by 3%, which is small compared to the 9% average difference in Energy Factor ratings. Table 18 shows the TWH savings at each site, but does not include any freeze protection energy consumption which was handled separately and is discussed below. At sites 3 and 7, where no StWH was installed, an average input-output relationship from the eight StWHs at the other sites was used together with the hot water energy output at sites 3 and 7 to compute the estimated StWH energy use. All savings calculations are site energy savings and do not account for site to source energy ratios.

Table 16. Regression parameters for energy input versus HWEO (natural gas and draw-related electric input)

				Input as a function of Output, excluding Freeze Protection Input*		
Site	Manuf.	Model	Type	Slope	Intercept	R^2
1	AO Smith	GCV-40-200	StWH	1.355	15.705	0.961
1	Takagi	TK-3	NTWH	1.273	1.600	0.998
1	Navien	CR-240A	CTWH	1.133	10.499	0.986
2	AO Smith	GCV-40-200	StWH	1.401	12.573	0.977
2	Noritz	N-841-DVMC	CTWH	1.138	3.304	0.994
3	Rinnai	r75Lsi	NTWH	1.293	0.590	0.998
4	AO Smith	GCV-40-200	StWH	1.493	15.366	0.932
4	Rheem	RTG-66-DV	NTWH	1.250	0.885	0.999
4	Navien	CR-210	CTWH	1.065	1.511	0.997
5	AO Smith	GCV-40-200	StWH	1.552	9.583	0.905
5	Rinnai	r75Lsi	NTWH	1.206	1.414	0.998
6	AO Smith	GCV-40-200	StWH	1.522	10.238	0.975
6	Noritz	N-751-MCDV	NTWH	1.341	2.440	0.994
6	Noritz	N-841-DVMC	CTWH	1.147	3.349	0.994
7	Takagi	TK-3	NTWH	1.321	0.685	0.985
7	Navien	CR-240A	CTWH	1.215	10.647	0.970
8	AO Smith	GCV-40-200	StWH	1.328	23.212	0.961
8	Noritz	N-751-MCDV	NTWH	1.332	2.950	1.000
8	Bosch	GWH-c800 ES	CTWH	1.130	2.520	0.996
9	AO Smith	GCV-40-200	StWH	1.487	11.957	0.934
9	Rheem	RTG-66-DV	NTWH	1.295	0.661	0.998
10	AO Smith	GCV-40-200	StWH	1.537	11.037	0.957
10	Bosch	GWH-715 ES	NTWH	1.205	1.632	0.998
10	Bosch	GWH-c800 ES	CTWH	1.122	1.294	0.999

*Input is expressed in kBtu. Draw-related electricity consumption (3.412 kBtu/kWh) was combined with gas use (1 kBtu/ft^3) to determine total draw-related input.

Table 17. Natural gas and electric consumption for each water heater

	Natural gas, therms/yr			Draw related elec, kwh/yr		
	StWh	NTWH	CTWH	StWh	NTWH	CTWH
1	199.6	137.1	153.8	0	72.2	103.2
2	196.6		130.6	0		0.0
3	175.8	112.2		0	0.0	
4	131.9	65.2	56.9	0	45.3	80.8
5	91.2	47.6		0	0.0	
6	220.1	166.7	145.9	0	96.1	120.0
7	157.3	93.8	122.0	0	170.6	179.9
8	217.5	138.3	116.8	0	167.5	158.3
9	96.8	47.6		0	31.4	
10	146.5	86.9	79.8	0	68.5	71.5

Table 18. Water heating energy (gas and draw related electric) consumption savings by site

Site	NTWH Saving		CTWH Savings	
	therms/yr*	%	therms/yr*	%
1	60	30%	42	21%
2			62	32%
3	62	35%		
4	65	49%	72	55%
5	42	46%		
6	50	23%	70	32%
7	58	37%	29	19%
8	74	34%	95	44%
9	48	50%		
10	57	39%	64	44%

*1 therm = 100,000 Btu

Significant electricity consumption for freeze protection was observed for one CTWH and two NTWHs. These water heaters had a significant increase in electrical consumption when the average outdoor temperature dropped below freezing. Figure 13 shows the relationship between electrical consumption and outdoor temperature for the NTWH at Site 3, where the freeze protection was significant. Cold outdoor air was entering the water heater, most likely through the combustion air intake or the vent. This reduced the air temperature inside the water heater enough to signal the ceramic heaters near the heat exchanger to fire. Figure 14 shows the electric consumption for two freeze protection events at site 3. This heater (a Rinnai R75Lsi) has a 100 watt ceramic heater. Some TWH control systems run the ceramic heater until the air temperature inside the water heater increases to a specific setpoint, while others run the ceramic heater for a set period of time before turning off. The Rinnai R75Lsi, as shown in Figure 14, turned on the ceramic heater for approximately 16 minutes and then rechecked the air temperature. For the day in the figure, Jan. 2, 2010, when there were no draws, freeze protection ran for about 16 minutes at about 30 minute intervals. Figure 13 shows the typical relationship between freeze protection and outdoor air temperature. For each TWH that had significant freeze protection operation there was an outdoor air temperature (the "reference temperature") below which electrical consumption increased roughly linearly.

Figure 13. Electric energy input to a NTWH vs. average outdoor temperature

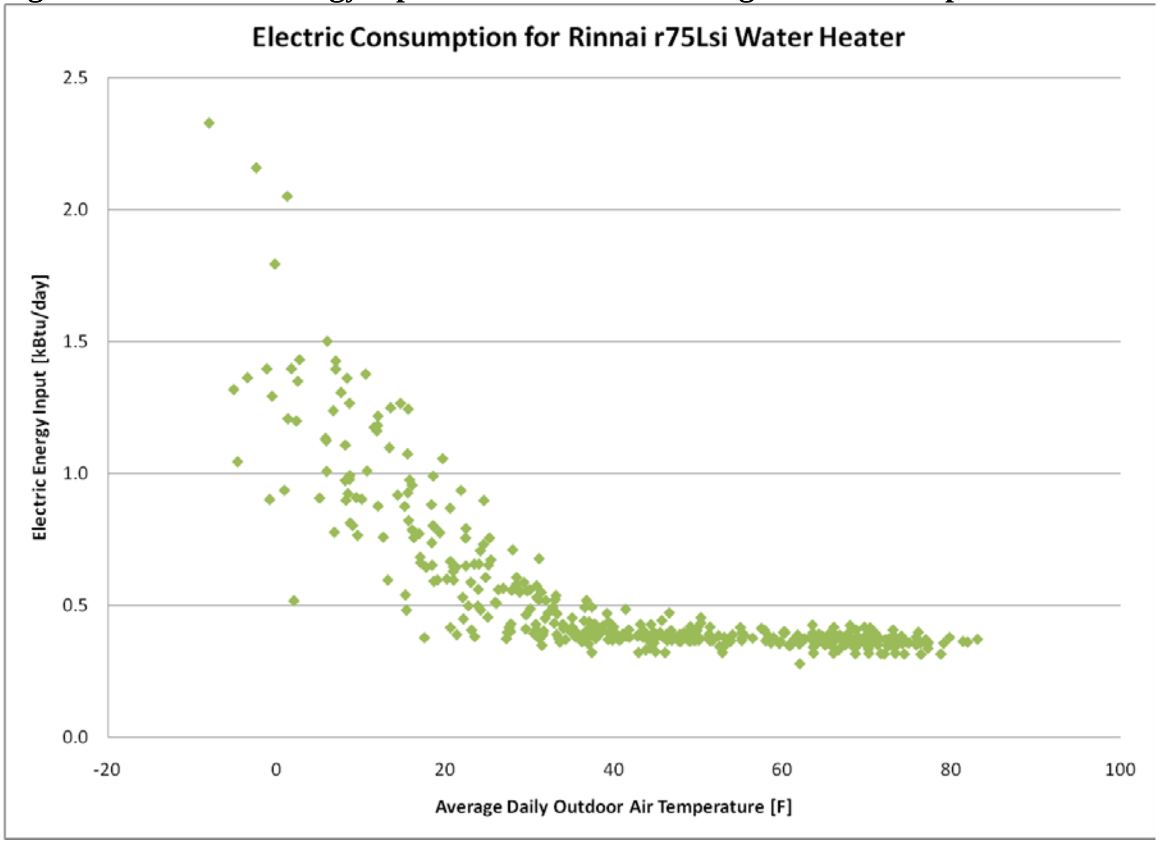
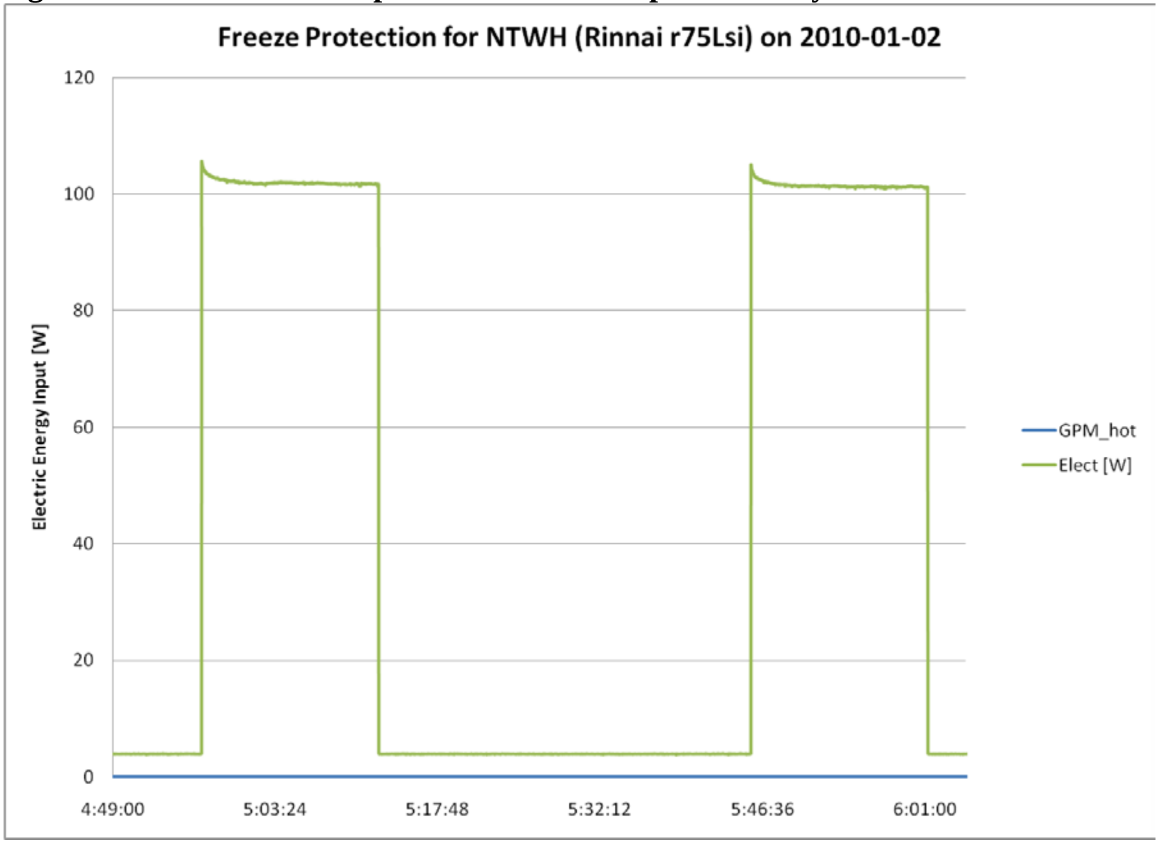


Figure 14. Electric consumption for two freeze protection cycles at Site 3



Some TWHs showed no substantial freeze protection operation, such as Site 8 shown in Figure 15. The relationship of freeze protection electrical consumption to outdoor temperature and the reference temperature below which the freeze protection was activated for each heater were used with outdoor temperature data from NOAA from 2009 to estimate annual energy consumption for freeze protection.

Table 19 shows the estimated freeze protection energy use for each heater, the adjusted total energy input including freeze protection energy use, and the adjusted percent energy savings. Three other heaters had some electrical usage that was probably a result of freeze protection, but consumption was not significant enough to include in this analysis, since in each case only one day showed increased electrical consumption due to freeze protection.

Figure 15. Electrical energy input to two water heaters at a site without freeze protection

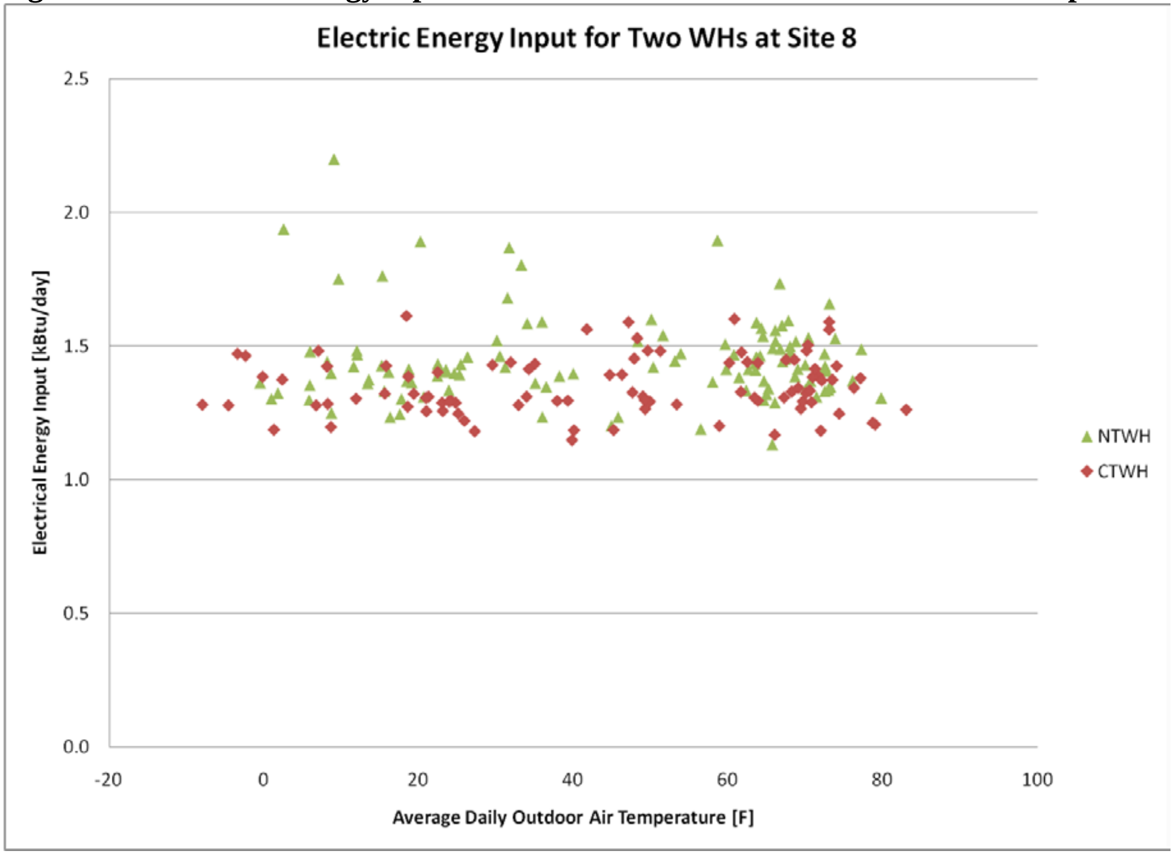


Table 19. Summary of electrical consumption due to freeze protection and total energy savings per site

Site	Freeze Protection, [kbtu/yr]		Energy Input, [kbtu/day]		Savings, %	
	NTWH	CTWH	NTWH	CTWH	StWH to NTWH	StWH to CTWH
1	0	0	13716	15388	31%	23%
2	N/A	580	N/A	13668	N/A	30%
3	86	N/A	11311	N/A	34%	N/A
4	0	0	6525	5697	51%	57%
5	50	N/A	4817	N/A	47%	N/A
6	0	0	16682	14602	24%	34%
7	0	0	9401	12223	36%	17%
8	0	0	13848	11696	31%	41%
9	0	N/A	4765	N/A	51%	N/A
10	0	0	8695	7985	41%	45%

Note:

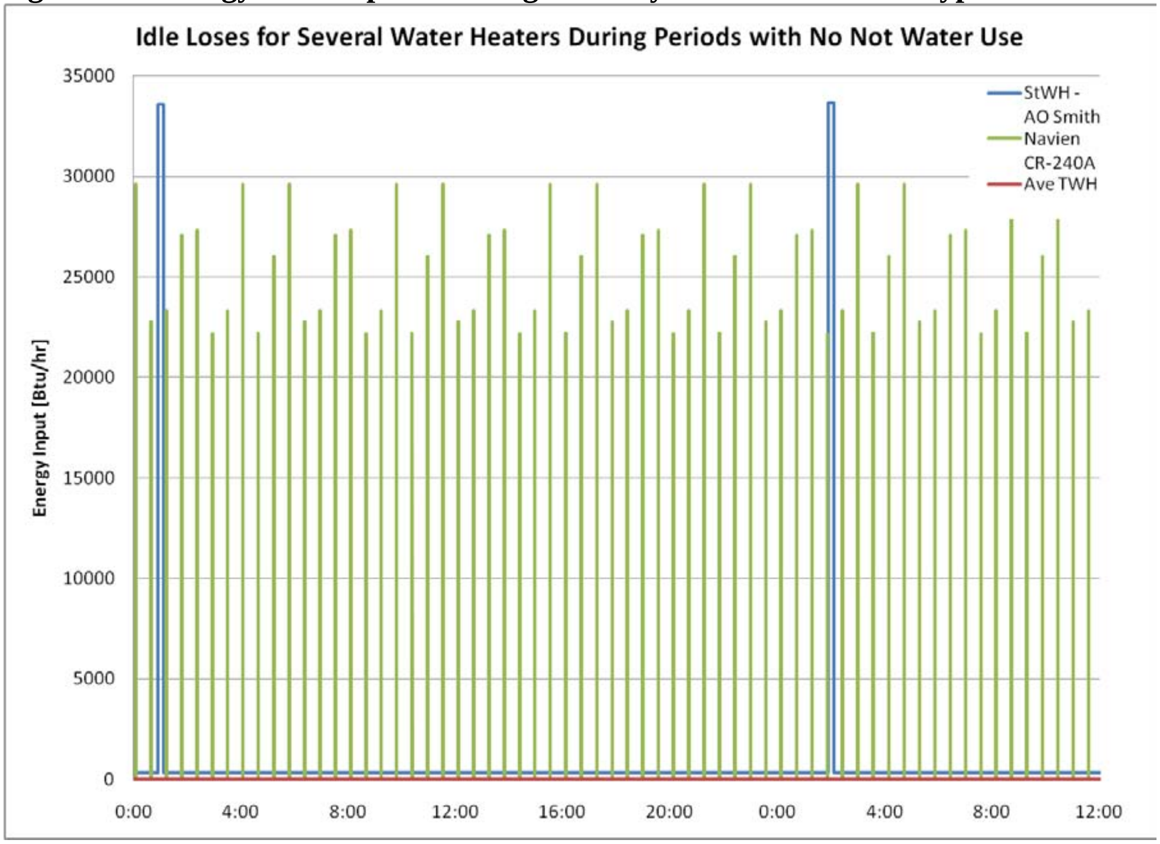
1. Site 1 and 7 had the Navien CR-240A with a small buffer tanks that reduces the water heaters efficiency.
2. Savings for Sites 3 and 7 were estimated from and ave. of StWH input-output models for the other eight sites.

When the savings and performance of the CTWHs were discussed above, the Navien CR-240A was excluded. This heater was handled separately because the 0.5 gallon buffer tank caused it to operate in a much different manner than other CTWHs. The buffer tank required gas input during standby to offset losses from the tank. Figure 16 shows the measured energy consumption during a 36 hour period with no draws for a StWH, a typical TWH, and the Navien CR-240A with the small buffer tank. The CR-240A water heater used only 33% less energy than the StWH to maintain the same temperature in a tank that was 99% smaller. The CR-240A also had standby losses almost 20 times greater than a typical TWH for a day with no draws. Table 20 shows the energy input and burner firing times for these three water heater groups. Since the performance of the Navien CR-240A was not like that of either the StWHs or the TWHs, it was analyzed separately.

Table 20. Stand-by energy consumption for water heaters

	Energy Input Rates			Time	
	No Draw Day	Fire Rate	Idle Rate	Between Fires	Burner On
	kBtu/day	Btu/hr	Btu/hr	hrs	min
StWH	16.6	33600	333	24.6	14
Avg TWH	0.6	NA, no firing	26	NA	NA
Nav 240A	11.1	25300	29	0.6	0.6

Figure 16. Energy consumption during stand-by for three different types of water heaters



Natural gas savings for NTWHs ranged from 44 to 79 therms per year, while electricity usage including freeze protection energy ranged from 31 to 170 kWh per year. TWHs had net energy savings ranging from 22% to 49% with an average savings of 36%. Natural gas savings for CTWHs (excluding the Navien CR-240A) ranged from 66 to 101 therms per year, while electricity usage ranged from 72 to 248 kWh per year. Excluding the Navien CR-240A, CTWHs had an average total energy savings of 39% with a range of 27% to 53%. The Navien CR-240A, saved 15% and 19% at the two sites where it was installed. Table 21 summarizes the energy input for each water heater and the savings for the TWHs at each site.

Table 21. Annual energy consumption for all water heaters and TWH savings

	Annual Energy Input[3], kBtu/yr			Saved	
	StWH	NTWH	CTWH	NTWH	CTWH
1[1]	19960	14201	16080	29%	19%
2	19656		14285		27%
3[2]	17577	11544		34%	
4	13195	6829	6239	48%	53%
5	9117	5023		45%	
6	22014	17327	15407	21%	30%
7[1,2]	15731	10545	13430	33%	15%
8	21752	14972	12758	31%	41%
9	9677	4976		49%	
10	14647	9154	8464	38%	42%

Note: 1. CTWHs at these sites were the Navien CR-240A
2. StWH numbers at these sites are estimated based on an average of the StWHs at other sites and the average hot water energy output for each of these sites.
3. These numbers include freeze protection where it was observed (sites 2,3 and 5)

The costs of electricity and natural gas must be considered in the economics of NTWHs and CTWHs. Electricity costs about three times are much as natural gas in the United States (about $12 per million Btu ($1.20/ therm) for natural gas (NG) and about $35 per MBtu ($0.12/kWh) for electricity (EIA 2010). Conventional StWHs do not require any electricity. Electricity consumption is necessary for TWHs but is only 2% to 6% of total site energy consumption. However, it accounts for about 5 to 18% of operating costs for TWHs. Table 22 shows the savings for each site from a cost perspective.

Table 22. Operating costs for water heaters and annual savings for TWHs

	Annual Operating Cost[2]				Annual Saving vs StWH		
	StWh	NTWH	CTWH	Nav 240A	NTWH	CTWH	Nav 240A
1	$ 240	$ 164		$ 185	$ 75		$ 55
2	$ 236		$ 157			$ 79	
3[1]		$ 135			$ 76		
4	$ 158	$ 78	$ 68		$ 80	$ 90	
5	$ 109	$ 57			$ 52		
6	$ 264	$ 200	$ 175		$ 64	$ 89	
7[1]		$ 113		$ 146	$ 76		$ 42
8	$ 261	$ 166	$ 140		$ 95	$ 121	
9	$ 116	$ 57			$ 59		
10	$ 176	$ 104	$ 96		$ 72	$ 80	

1. Savings for these sites were estimated from an average input output StWH model
2. For gas at $1.20/therm and electricity at $0.12/kWh.

Energy costs for the StWHs at different sites ranged from $109 to $264 per year. NTWHs had an energy cost range of $57 to $200 per year with an average cost savings of 40%. CTWHs without a tank had energy costs from $68 to $175 per year with an average cost savings of 43%. Costs for the Navien CR-240A heater, which had a small buffer tank, were $185 and $146 per year with savings of $ and $ an average cost savings of 23%.

Simple paybacks were calculated using total installed costs as discussed in the Background section of this report ($2500-$3350 for NTWHs and an additional $1000 for CTWH units) and $1000 installed cost for StWHs. The simple payback calculation showed that at current installed costs and energy prices 20 to 40 years would be necessary for a TWH to pay for itself, as shown in Table 23. The economics would be improved for TWHs on a life cycle basis if, as some TWH manufacturer's claim the lifetime of a TWH is significantly longer than the StWH. See Discussion of this paper for more information.

Table 23. Simple payback for TWHs

	Incremental Cost Range, $		Savings per year, $	Payback Range in years	
NTWH	1500	2500	72	21	35
CTWH	2500	3500	92	27	38
CR-240A	2500	3500	49	51	71

DOE Energy Factor versus In Situ Performance

Past work (Davis Energy Group 2007) suggested that the federal water heater rating metric, the Energy Factor, does not accurately capture the relative performance of StWHs and TWHs. While the EF was not intended to quantify actual performance, it *was* intended to be a meaningful comparison tool. The EF is often used by consumers to project operating costs, and should provide a reasonable representation of relative operating costs in typical homes. Two major factors limit the ability of the EF test to capture *in situ* performance. First, the draw profile used in the EF test is not representative of actual usage profiles. The EF takes six draws of over ten gallons each at one hour intervals, followed by a 19 hour standby period. The frequency distribution of draw volumes for these ten sites (See Hot Water Consumption and Use Section) shows that only 3% of draws were greater than ten gallons. Typically draws from these sites were also much shorter than the three and a half minute EF draws. Homes in this study had an average draw length of 54 seconds, with only 6% of draws greater than 3.5 minutes. There were an average of 32 draws per day with an average volume of 1.2 gallons. The differences between real world and test procedure draw patterns may not be consequential if the products being compared are very similar. However, when the technologies being compared are very different, as is the case with StWHs and TWHs, the differences in transient losses, standby loss rates and other factors can result in differences in real world performance that are not well captured by the EF.

The second factor, and perhaps bigger factor, that reduces the realism of the EF is the assumed hot water consumption usage of 64.3 gallons per day. All ten of the sites in this study averaged less than 64 gallons of hot water use per day, with a range of 20 to 62 gallons per day, a median usage of 37 gpd and an average of 41 gpd. For more information about hot water draw characteristics see Hot Water Consumption and Use section of the results on page 72. Conceptually, all water heaters approach their steady state efficiency as daily output approaches full load output (100% on-time). If different technologies approach this steady state efficiency at different rates, relative performance at low daily outputs will not be the same as that at high daily outputs. StWHs, because they have large standby losses, tend to have substantially lower efficiencies at lower outputs than do TWHs.

Across all sites and water heaters, the measured annual efficiency averaged 16% less than the DOE EF. The difference between EF and measured efficiency was not the same for all heaters. The StWH's efficiency averaged 23% less than its EF rating, with reductions ranging from 5 to 23 percentage points. Real-world NTWH efficiency averaged 10% less than EF, with a range of 7 to 14 percentage points. CTWHs without buffer tanks had efficiencies averaging 10% below their EF with a range of 5 to 12 percentage points. CTWHs with buffer tanks (Navien CR-240As) had annual real world efficiencies of 57% and 67% and EF ratings of 95%.

The differences in daily efficiencies are shown for one site in Figure 17. As hot water energy output increases the real world efficiencies approach the water heater energy factor. Using the linear input-output relationships it is straightforward to determine energy use and efficiency at various hot water outputs. Table 24 compares the performance of the water heaters at the actual daily average hot water energy output for each site, the project average HWEO, and the HWEO corresponding to the EF test. The CTWHs with buffer tanks are listed in their own category in Table 24. The off-cycle losses from the small buffer tank appear to be the cause of the reduced in-place efficiencies of these heaters. The energy consumption required by the Navien CR-240A in stand-by mode was calculated to account for about a 15 percentage point reduction in efficiency. Table 25 shows the average energy savings for each type of TWH compared to the standard StWH at three different HWEOs. Site average savings depended on the size of home where each water heater was installed. Savings at the project average HWEO were smaller than at the DOE HWEO but were a larger percentage savings.

Table 24. Comparison of *In Situ* and Energy Factor Efficiencies

		In Situ Efficiencies, fractional			Installed Energy Input, therms/yr		
WH Type	Ave EF	At Site Average HWEO[2]	At Project Ave HWEO[3]	At DOE HWEO[4]	At Site Average HWEO[2]	At Project Ave HWEO[3]	At DOE HWEO[4]
StWH	0.60	0.46	0.48	0.56	163	164	269
NTWH	0.83	0.74	0.74	0.76	102	106	197
CTWH[1]	0.92	0.82	0.81	0.85	110	97	177
Navien CR-240A	0.95	0.62	0.60	0.70	143	131	215

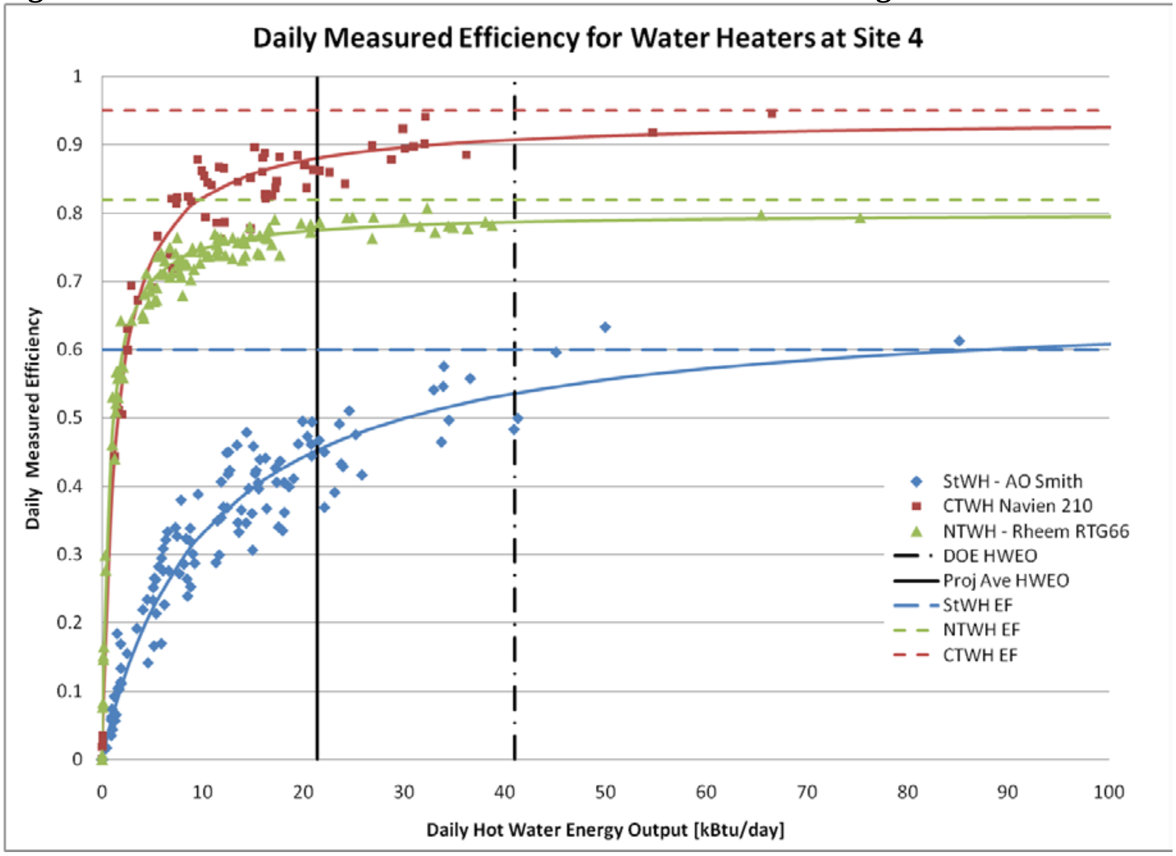
Note: 1. CTWHs do not include Navien CR-240A because of the buffer tank in this model
2. For site averages see Table 13
3. Project average HWEO is 21 kBtu/day
4. DOE EF test usage pattern results in an estimated HWEO of 41 kBtu/day

Table 25. Energy savings for TWHs

	Total energy savings compared to StWH, therms/yr			% savings compared to StWH		
	At Site Average HWEO[2]	At Project Ave HWEO[3]	At DOE HWEO[4]	At Site Average HWEO[2]	At Project Ave HWEO[3]	At DOE HWEO[4]
NTWH	60.3	58.9	71.8	37%	36%	27%
CTWH[1]	52.8	67.9	92.2	33%	41%	34%
Navien CR-240A	19.8	33.8	54.3	12%	21%	20%

Note: 1. CTWHs do not include Navien CR-240A because of the buffer tank in this model
2. For site averages see Table 13
3. Project average HWEO is 21 kBtu/day
4. DOE EF test usage pattern results in an estimated HWEO of 41 kBtu/day

Figure 17. Measured efficiencies for three water heaters at a single site



Water Heater Performance in the Test Laboratory

One water heater of each model was tested in the laboratory. A matrix of test draw patterns was performed on each water heater to develop a performance map that could be used to model energy use for any arbitrary draw pattern. A two point input/output laboratory test procedure was used to predict performance under any draw profile. A two point was selected because it was a small number of test to run in the lab and was were enough to characterize the linear relationship. The model was based on the observation that there was a linear relationship between energy input to the water heater and hot water energy output. The line for each water heater was established by a lab measured low use draw and a high use draw. The low use draw was Test 3 in the lab test matrix (Table 2), a one gallon draw at two gpm with 45 minutes of idle time for the TWHs. The high use draw was Test 32, a steady-state draw at 2.5 gpm. The results from each of these tests were the average of several run of the same draw pattern. The input energy and HWEO rates (Btu/hr), including the idle time after the draw, were plotted for tests conducted with each of these draw patterns. The fit line could then be used to determine the necessary input for any daily hot water usage profile.

The previously discussed non-linearities near zero are insignificant for daily averages but must be considered when individual flows are modeled. For this reason, the following approach is suggested for using the input/output relationship to predict performance under arbitrary draw patterns. During active draw periods, the linear relationship should be used to predict input required for specific hot water energy outputs. During extended idle periods (2 hours or longer) the actual measured standby energy should be used to estimate input required. For an active period Equation 1 is used to calculate the HWEO (in Btu/hr), where $V_{hot}$is the hot water volume in gallons, $C_1$is a constant calculated from the density and specific heat of water, T is the temperature, and times, t, are measured in hours. Note that Equation 1 assumes that the full temperature difference (T_{set} – T) is maintained throughout each draw. Equation 2 is used to predict the energy input required for each HWEO during an active period. Input and output energies are summed for all active periods and extended idle periods to compute the daily energy input required to meet that output corresponding to the daily profile.

Equation 1

$$HWEO = \frac{V_{hot}C_1(T_{set} - T_{main})}{(t_{draw} + t_{idle})}$$

Equation 2

$$Energy\ Input = Slope * HWEO + Intercept$$

This method was applied to the six-draw DOE Energy Factor draw pattern, a second, EF-like draw pattern modified to meet the project average HWEO, and a real draw profile for one week of actual days monitored from that water heater. The results were compared to the manufacturer’s ratings, an EF test run in our laboratory, the performance from the water heaters in the field (at DOE and project average output) and the actual performance for the week of profiles.

The two-point I-O model closely predicted the EF measured in our laboratory. The manufacturers’ EF ratings were higher than the EFs measured in the laboratory and the EFs computed from the two-point input/output (I/O) model for all water heaters. Table 26 shows the results from the Energy Factor comparison for all ten models of water heater installed in the study.

Table 26. Comparing label rating to those determined at Brookhaven National Laboratory

WH	EF Label	EF Lab	Two-Point I-O EF Model
Takagi Tk-3	0.84	0.79	0.81
Bosch 715	0.82	0.80	0.79
Rinnai r75			
Rheem 66			
Noritz 751			
Navien CR240A			
Navien CR210			
Noritz 841			
Bosch c800			
AO Smith GCV-40			

One week of field data was selected from each water heater at every site. Actual measured energy input and daily efficiencies were compared to those computed using the two-point lab I/O model. The I/O model was applied to both the computed and the actual measured hot water energy outputs. Computed daily HWEOs were about 10% to 25% higher than the actual measured HWEO for TWHs. The increase in the computed value is due to the assumption that all water is delivered at the desired set point temperature. For TWHs there is a significant delay time between the beginning of the draw and the time the outlet water temperature reaches the set point temperature. For StWHs the delay in temperature ramp up is shorter but draw temperatures are often below the set point temperature (more information about delay times and temperatures can be found in the Homeowner Evaluation Section). An increase in HWEO results in an increased efficiency because of the non-zero intercept of the linear relationship between energy input and HWEO. Table 27 compares the actual and modeled performance of the Takagi TK-3, NTWH, at site 1 for one week of actual measured data. During this week, on average, the lab I/O model with assumed HWEO over-predicted the energy input by 11% but over-predicted efficiency by only 2 percentage points. For the same time period the I/O model using measured HWEO over-predicted efficiency by 1 percentage point and under-predicted energy input by one percent, on average. Data for all ten water heaters is presented and summarized in Appendix V.

Table 27. Comparison of actual measured and lab modeled performance

	Actual Measured from Installed Units				Two-Point I/O Model and Computed HWEO			Two-Point I/O Model and Actual HWEO		
	HWEO [Btu]	Energy Input [Btu]	Daily Eff	Hot GPD	HWEO [Btu]	Energy Input [Btu]	Daily Eff	HWEO [Btu]	Energy Input [Btu]	Daily Eff
10/11/09	5752	8010	0.72	11.8	7036	9826	0.72	5752	8266	0.70
10/12/09	11907	15794	0.75	21.8	13065	17546	0.74	11907	16139	0.74
10/13/09	10633	14786	0.72	20.5	12272	16383	0.75	10633	14391	0.74
10/14/09	19176	25743	0.74	35.5	21253	27416	0.78	19176	24893	0.77
10/15/09	17834	24207	0.74	32.8	19633	25594	0.77	17834	23408	0.76
10/16/09	10634	14811	0.72	20.4	12226	16416	0.74	10634	14481	0.73
Total	75937	103351	0.73	143	85485	113180	0.76	75937	101577	0.75

Homeowner Evaluation and Qualitative Aspects of Water Heater Performance

All ten sites returned surveys for each water heater installed in their home. Residents rated StWHs higher than NTWHs or CTWHs on delay in delivery time and need to increase flow rate to get hot water at low flows (Table 28): 67% of households rated the wait time for hot water as favorable for StWHs and 44% of households rated the necessity to increase flow favorable, compared to 11% for both on the TWHs. Residents rated TWHs higher than StWHs on never running out of hot water, 83% favorable for TWHs compared to 33% for StWH. (Some percentages do not correspond to all ten homes, homes were only counted if they had that type of water heater installed. Only two respondents indicated that any aspect of performance would prevent them from purchasing any of the water heaters. One respondent would not buy a TWH because of the increased delay time. One respondent would not buy a StWH because it often ran out of hot water. See Appendix III for the survey instrument and responses from each resident.

Table 28. Responses to Resident Survey

	StWHs			TWHs		
Performance Attribute	Unfavor-able	No Effect	Favorable	Unfavor-able	No Effect	Favorable
Delay Time Until Hot Water Arrives	22%	11%	67%	72%	17%	11%
Need to Increase Flow to Get Hot Water	22%	22%	44%	44%	44%	11%
Consistent Temp for a Single Draw	11%	22%	67%	6%	0%	94%
Not Running Out of Hot Water	56%	11%	33%	6%	11%	83%
Consistent Temp for Multiple Simult. Draws	11%	44%	44%	17%	39%	44%
Decreased Flow Rate for Multi Simult. Draws	33%	56%	11%	28%	61%	11%

Several of the hot water performance characteristics examined in the homeowner survey can also be evaluated through measured data, including water temperature, the need to increase low flow rates, and delay time. Water temperatures were taken at the outlet of the water heater. Flow rates were recorded and can be compared between StWH and TWHs to determine if behavior was changed, and delay time can be determined from flow and temperature measurements.

There are several temperature concerns: the length of time it takes until the water gets hot, how consistent the temperature is once hot, and whether the water reaches its set point temperature. In order to eliminate distribution system issues, water temperature at the outlet temperature sensors was compared. These sensors were about six inches downstream of the water heater. Because not all water heaters had the same temperature set point, delay times are discussed in terms of how long it took the water heaters to first reach 95% of their set point temperature and how long it took them to get within 1°F of their steady-state. Temperatures were considered steady when the second by second variance was less than 0.5 °F. Table 29 shows the delay time of each water heater. It is important to remember that the distribution system delivery time must be added to this delay time. Clearly the StWH has a considerably shorter delay time than most of the TWHs. The benefit of the buffer tank on the Navien CR-

240A can also be seen in this table, as delay times are reduced to four seconds. For all water heaters, performance was the same or worse for low flow rates than for higher flow rates. There was a range of delay times for each water heater and what is presented is an average of the performance of each heater. Table 29 also shows the difference in performance among TWHs. One heater reaches 95% of its set point temperature in 20 seconds for low flow rate draws, while other heaters take over 50 seconds.

Table 29. Average delay time until water heater produces hot water

		95% of Tset		w/in 1°F of Steady - State	
		low flow	high flow	low flow	high flow
CTWH	Navien CR-240A	4	4	45	35
	Nortiz N-0841-DVMC	22	12	32	16
	NAVIEN CR-210	32	22	270	61
	Bosch GWH-c800 ES	52	18	80	30
NTWH	Rheem RTG 66 DV	23	18	75	37
	Takagi TK-3	20	12	90	45
	Noritz N-0751-DVMC	30	14	42	30
	Rinnai R75Lsi	31	19	58	33
	Bosch GWH - c800 ES	57	20	80	40
StWH	AO Smith GCV-40[1]	5	5	11	9

1. Many StWH draws never reached 95% of their temperature setting. Values listed are delay time until reaching 95% of steady-state temperature.
2. Low flow draws are around 1 gpm and high flow draws are about 2.5 gpm

All ten water heater models in the study were kept the water temperature consistent once hot. This agrees with the survey results (Table 28) in most cases. At sites where consistency was reported as unfavorable for StWHs, running out of hot water may have been an issue.

TWHs were much more capable that StWHs of producing outlet water at the set point temperature. Due to the differences in delay time across products, outlet temperatures examined at two different times, 15 and 60 seconds into a draw. Fifteen seconds into a draw is during the ramp up of the TWHs and sixty seconds into the draw is after most of the TWHs have come up to their steady-state temperature. The frequency distributions of temperatures fifteen seconds into hot water draws are basically the same for TWHs and StWHs: 47% of StWH draws and 44% of TWH draws are within 10°F of the set point temperature (Figure 19). At sixty seconds, storage heaters are the same as at 15 seconds (46% within 10°F of setpoint) but TWHs have reached steady-state so 79% of draws are within 10°F of setpoint (Figure 20). At sixty seconds the TWHs have gone through their start up phase and have leveled off at the desired temperature, most of the time. StWHs reach the steady-state temperature within the first few seconds of the draw, and temperature only changes if the burner comes on due to extended use. The outlet temperature of a StWH depends on where in the temperature dead band the tank temperature is. As the time since the last burner fire increases the tank temperature drops. Figure 18 illustrates the relationship between time since burner fire and steady-state outlet temperature at one site. At this site with a set point temperature of 120°F, the outlet temperature would be 120°F on average just after a tank fire, but at 23 hours, at the end of the longest period without a burner ignition, the outlet temperature would be 100°F.

Figure 18. Effect of the tank temperature dead band (time since last fire) on the outlet temperature so the StWH at Site 1

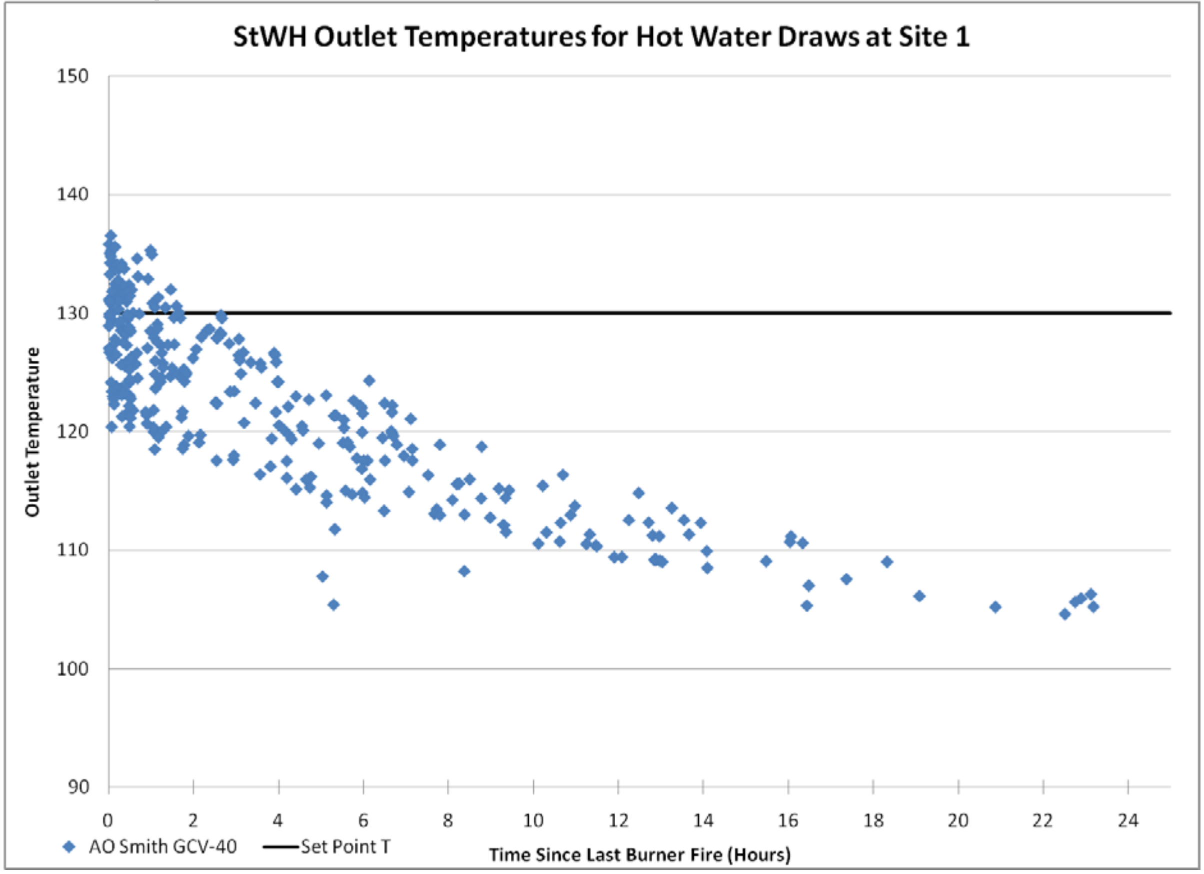


Figure 19. Percentage of draws by outlet temperature bins during TWH temperature ramp up

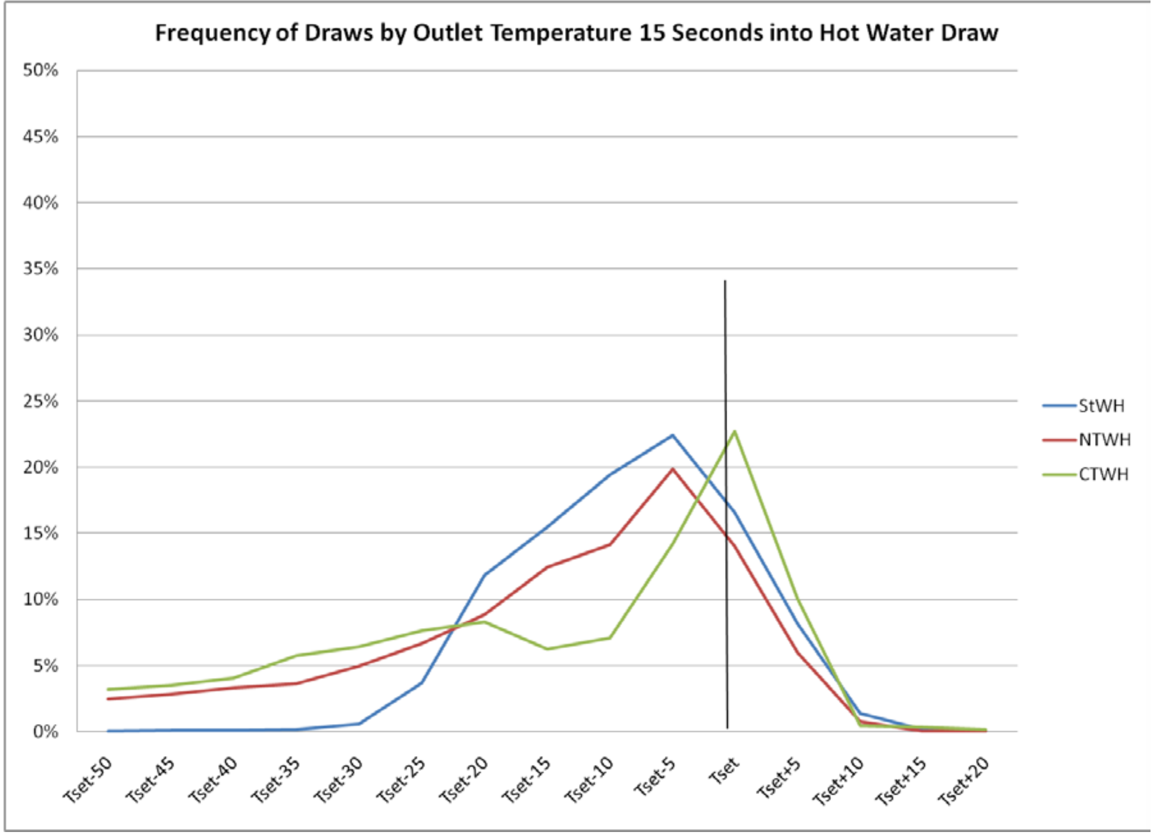
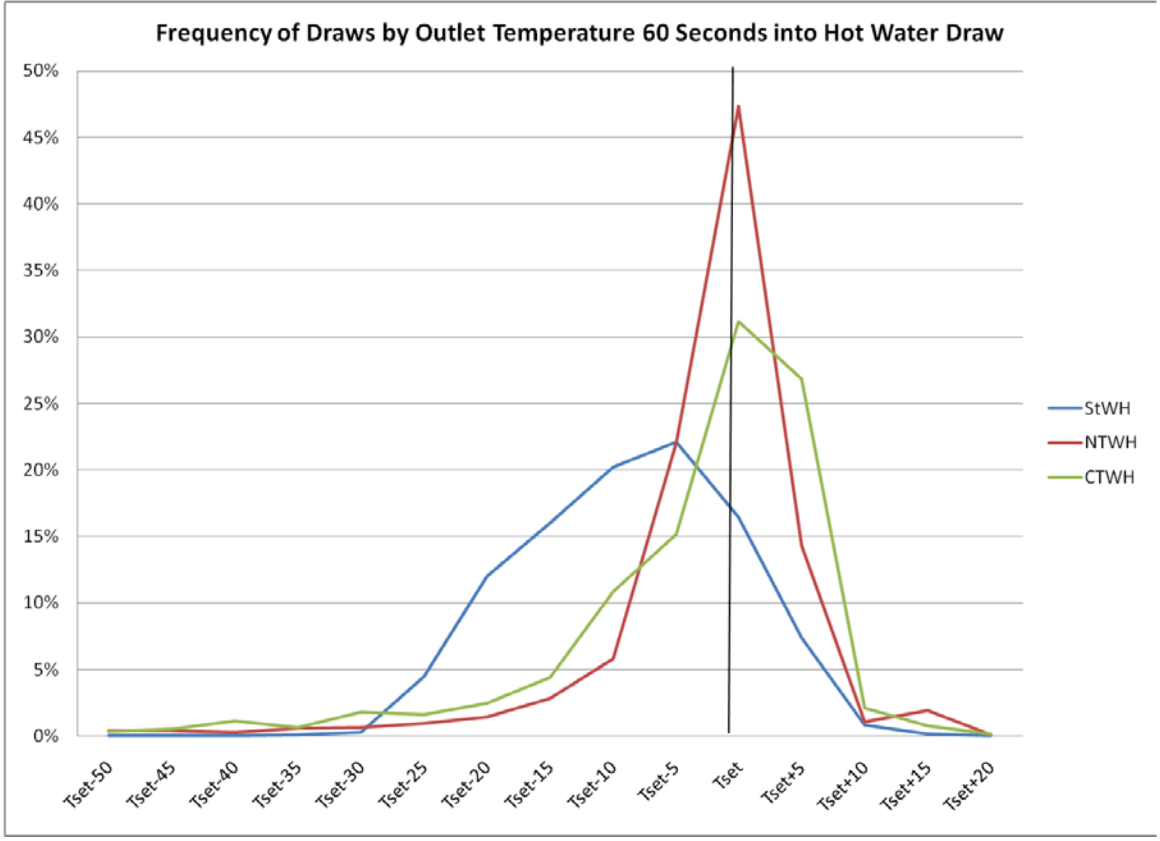
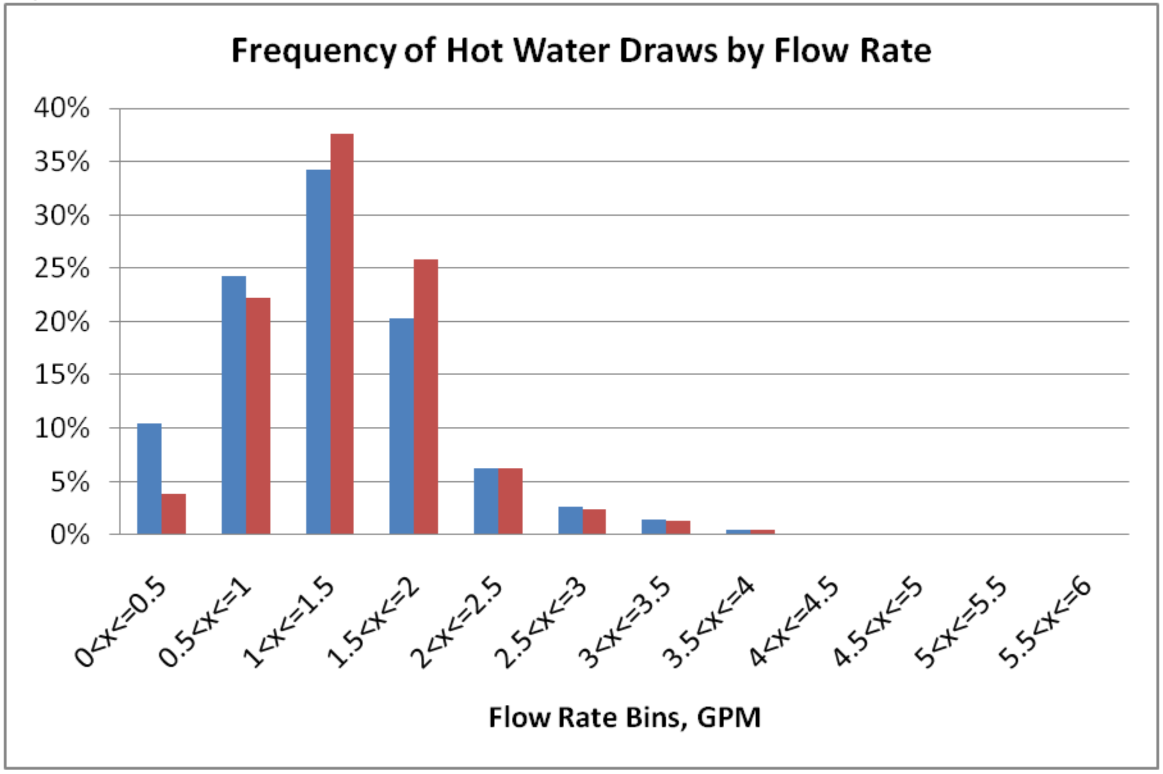


Figure 20. Percentage of draws by outlet temperature bins after TWH steady-state (60 seconds)



The final performance characteristic evaluated was the necessity to increase flow rates due to the minimum flow rates of TWHs. TWHs have a minimum flow required to turn on the burner. This flow rate is typically 0.5 gallon per minute. Eight of the ten sites in the study had both a StWH and at least one TWH. All eight of these sites showed a reduction in flows under one GPM when using the TWH compared to the StWH. At three sites the reduction was minimal (~1%) , with one site showing a significant reduction in draws under 0.5 gpm but an increase in draws between 0.5 and 1 gpm. The remaining five sites showed a significant reduction including site 9, where draws under one gpm were reduced by 65% for TWHs. Figure 21 shows the average frequency of draws by flow rate bin for all sites and illustrates the behavioral change caused by the minimum flow rate requirement of the TWHs. The reduction in frequency of draws can be attributed to either a increase in the flow rate for low flow draws for the TWH or users stopped trying to use low flow hot water draws.

Figure 21. Reduction of low flow draws for TWHs



Hot Water Consumption and Use

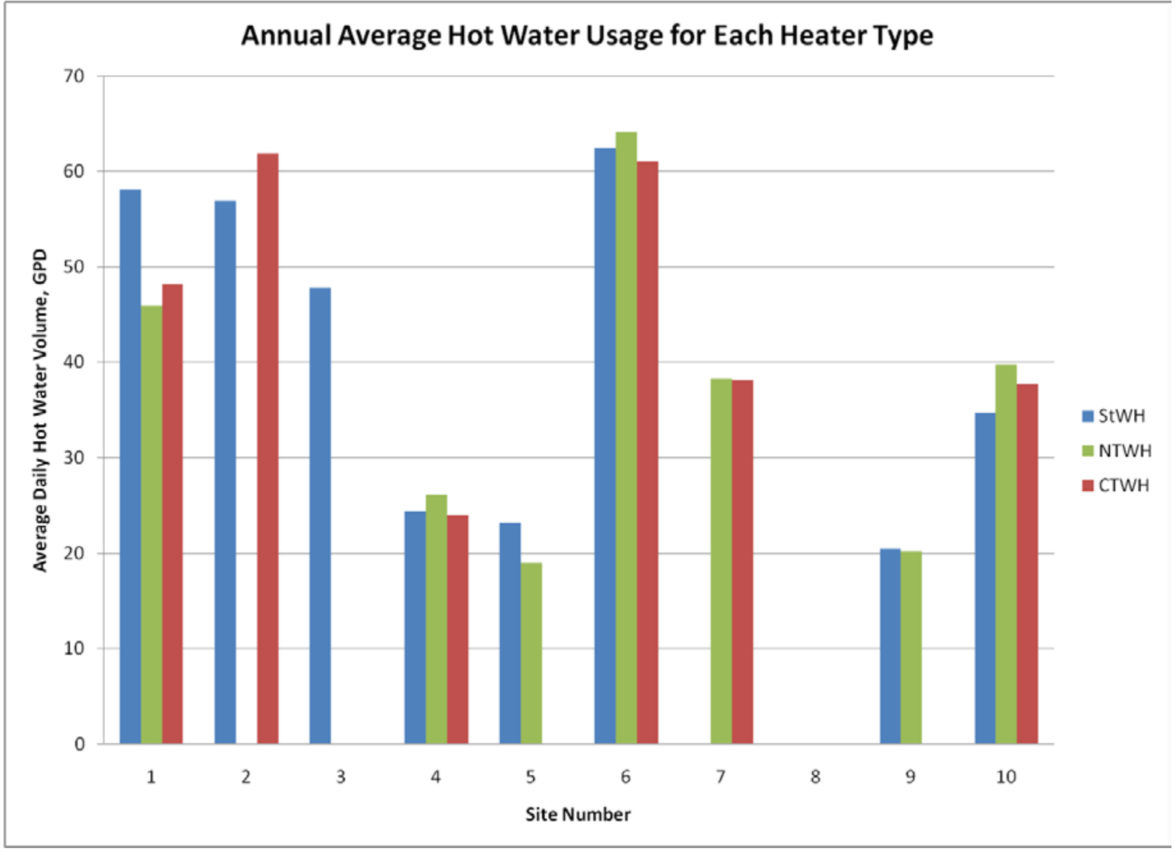
The same seasonality analysis applied to hot water energy output was applied to daily hot water consumption. The results were very similar. Sites 1 and 9 had only very small seasonal variance and were not analyzed. Site 8 had a resident move out in November of 2009 causing an abrupt change in water usage. Of the remaining sites a statistically significant difference between water heaters was only detected at one site (site 4). Six of the seven sites analyzed showed no statistical significant difference in hot water consumption by water heater type used. To further illustrate this point the seasonal GPD regressions for each heater were used with each site’s measured main temperatures to determine the average annual hot water consumption per day. Figure 22 and Table 30 show that the difference between water heaters was small at most sites and are not consistent in direction from site to site. At sites 1and 5 the StWH used more hot water than the TWHs. At sites 2 and 10 the TWHs used more hot water that the StWHs. At sites

4, 6 and 9 it was unclear which type of water heater used more hot water. The differences at all sites were much smaller than the daily variance in water consumption (standard deviations ranged from 12 to 35 gpd).

Table 30. Average daily hot water consumption by water heater type

	Annual Average GPD		
Site	StWH	NTWH	CTWH
1	58	46	48
2	57		62
3	48		
4	24	26	24
5	23	19	
6	62	64	61
7		38	38
8	Occupancy Change Prohibited Analysis		
9	20	20	
10	35	40	38

Figure 22. Average daily hot water consumption by water heater type

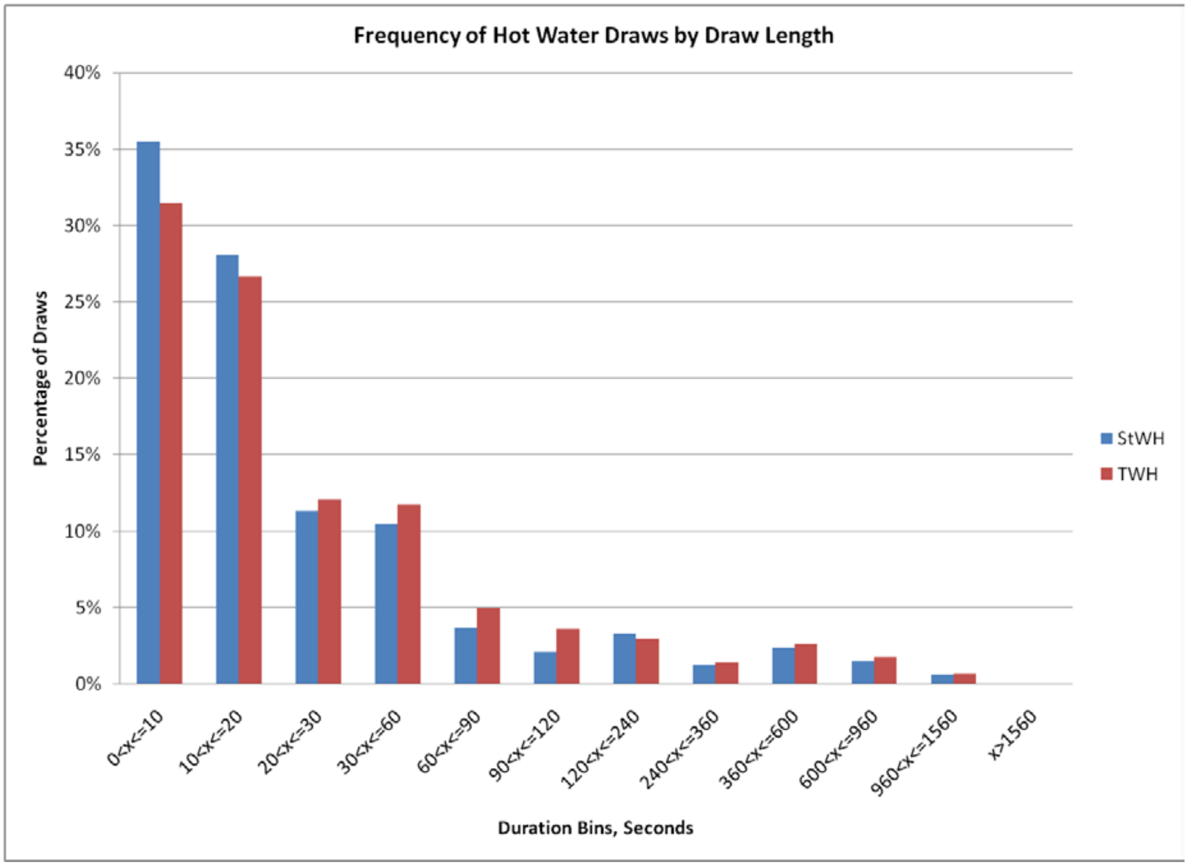


Note: Missing bars are sites where only one or two water heaters were installed.

Hot water usage patterns were analyzed at all ten sites. In addition to the flow rate information presented previously, usage patterns for draw duration, draw volume and idle time between draws were also analyzed. For this analysis a hot water pulses were only considered draws if flow was detected on the hot water flow meter for at least three consecutive seconds.

Draws were typically short, with about 73% of draws lasting thirty seconds or less. The frequency of short draws varied from site to site, with a minimum of 62% of draws and a maximum of 82% of draws being 30 seconds or less. Figure 23 shows the frequencies averaged for all ten sites. This figure also illustrates that the StWHs had a higher percentage of small draws than the TWHs, which was the case to varying degrees at all sites.

Figure 23. Duration distribution for hot water draws



Most draws were not only short but had small total volume as well. Seventy percent of hot water draws had total hot water volumes of a half gallon or less (Figure 24). Only 4% of draws were between 2.5 and 5 gallons. Five percent of draws are above 5 gallons per draw. These consist mostly of shower draws. Figure 25 looked at the same data but as a percentage of total volume instead of total draws. This figure shows that draws over 5 gallons were small in number but made up 51% of the total volume of draws.

Figure 24. Frequency distribution binned by draw volume

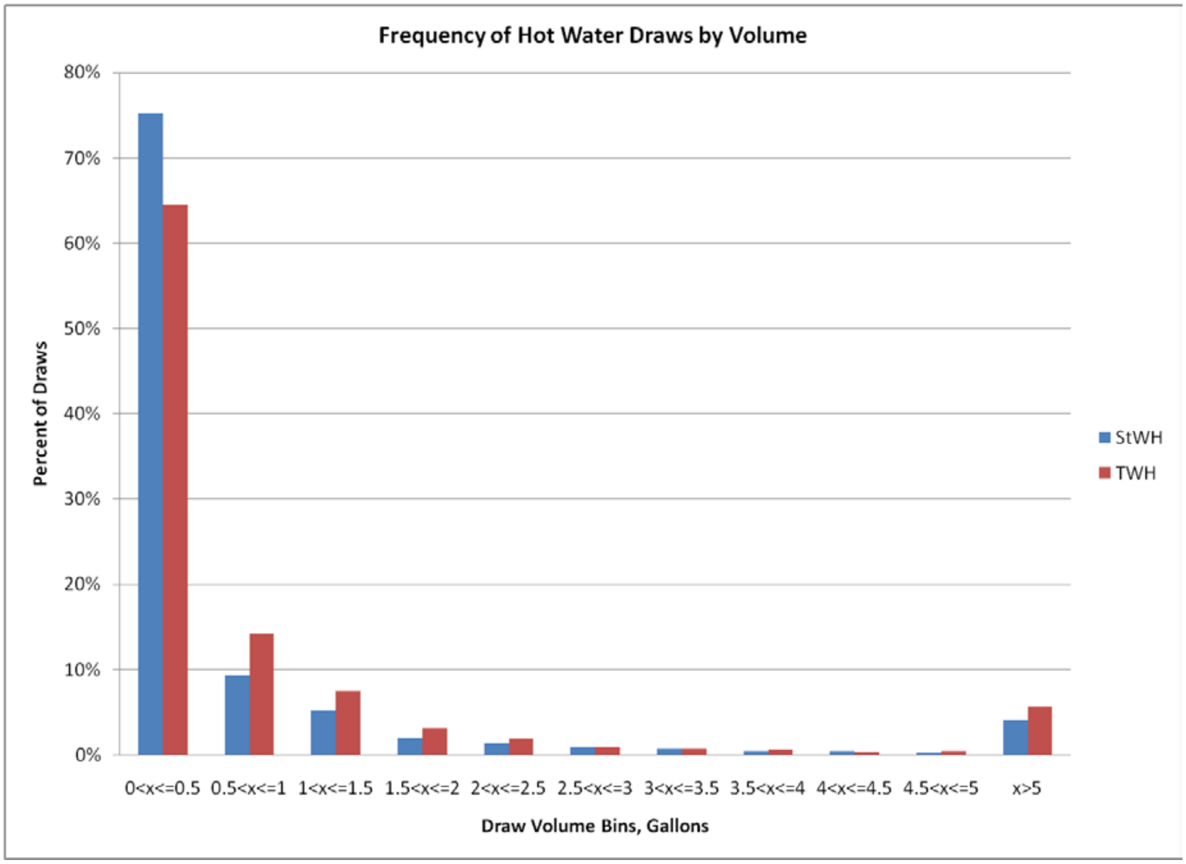
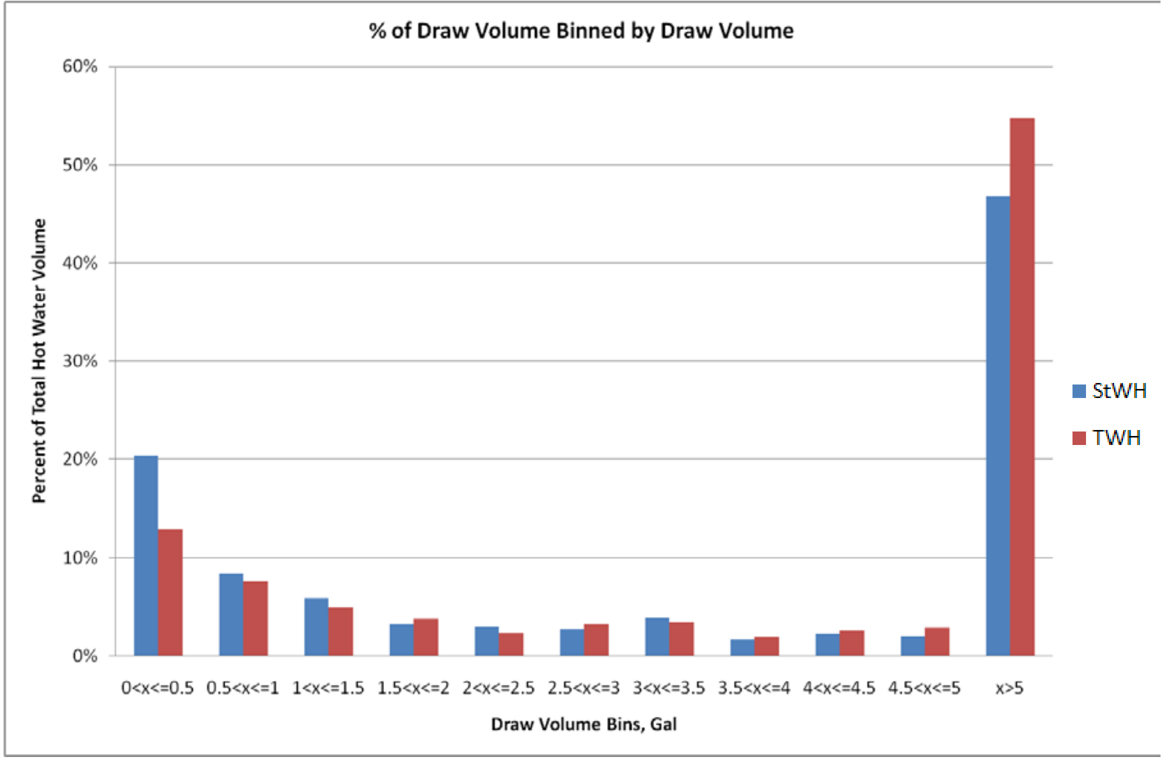
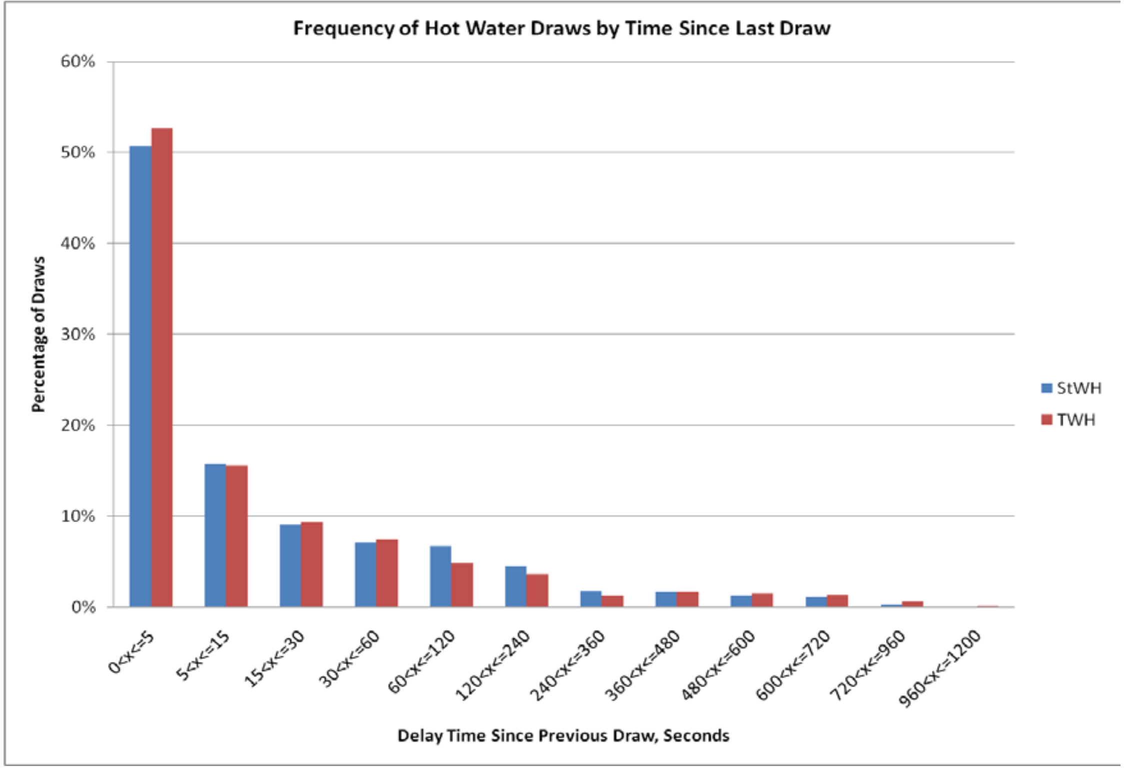


Figure 25. Draw volume as a percentage of total daily volume



The delay between draws is especially important for TWHs. When there are long idle times between draws the water heater must reheat the small volume of water and the metal inside the unit for each draw. If draws are closely spaced some of the heat will remain in the heater from the previous draw reducing wasted heat. Fifty-two percent of draws were 5 seconds or less apart and 84% were one minute or less apart. The close spacing of draws mean that few draws must start with a completely room temperature TWH.

Figure 26. Frequency distribution of hot water draws by idle time between draws

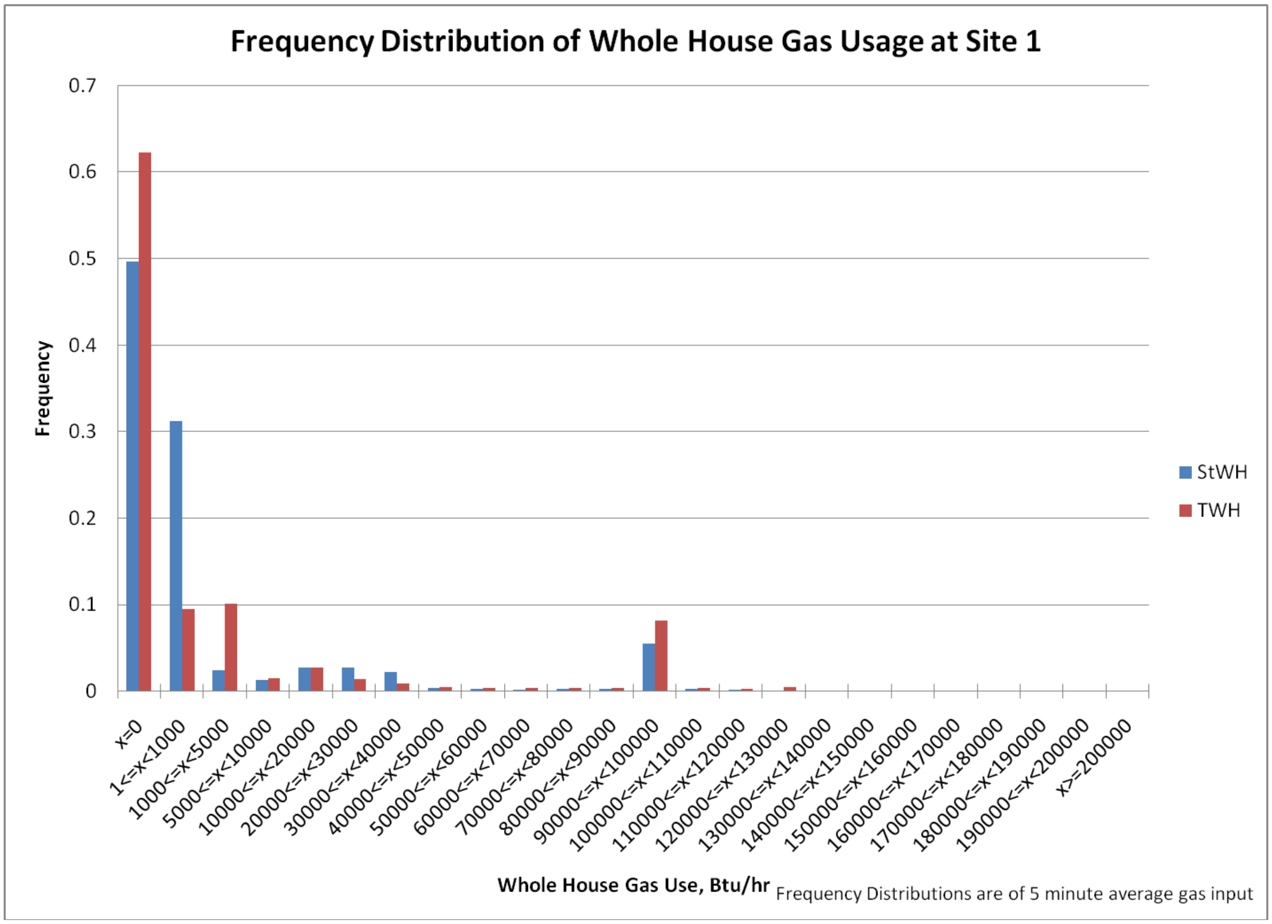


The hot water draw pattern analysis showed that TWH draws are typically longer and have a higher volume and flowrate than StWH draws. However, the total daily volume was not significantly greater. This was because on average the TWH was used less times per day. An average of 28 draws per day was found for homes on the StWH and only 22.5 hot water draws per day were used with the TWH.

Effect of TWHs on Whole House Gas Demand

TWHs have much larger gas input ratings than StWHs (180-199 kBtu/h vs. 40 kBtu/hr). Some gas utilities have expressed concern that a drastic increase in the water heater gas demand for a neighborhood will affect the gas distribution network. Whole house 5 minute average gas demand was analyzed for each site. Whole house gas demand during times where the TWHs were active was compared to demand when StWHs were active. Figure 27 shows the frequency distribution of whole house 5-minute natural gas demand for Site 1. There was only a small fraction of the time (10% for either water heater type) where 5-minute demand was above 40,000 Btu/hr. The home’s furnace was largely responsible for the greater frequency of demand around 100,000 Btu/hr (this home's furnace input rate). The jump was greater for periods when the TWHs were active, due to their higher input rates. For this site, there was no five minute interval where whole house gas demand was above 140,000 Btu/hr.

Figure 27. Frequency distribution of 5 minute average whole house gas demand for one site.



Average daily whole house gas load profiles were also constructed for each season at each house.. The winter load profile for the entire home by water heater type is shown for Site 1 in Figure 28. Site 1 had significant night and daytime space heating setbacks and a regular water use schedule. This resulted in strong peaks in the morning, when the house warms up and people take showers, and again in the afternoon when the house warms and water is used. The morning peak at Site 1 was mostly due to space heating. This site had a single stage 100,000 Btu/hr input gas furnace. The morning peak was about the same magnitude and width regardless of the type of water heater in use. Figure 29 shows the average summer load profile, which does not include any space heating. The StWH showed the highest peak while the NTWH showed almost no increased morning gas consumption. The CTWH at this site was the Navien CR-240A with the small buffer tank, and showed behavior intermediate between the StWH and NTWH. Figure 30 plots the winter whole house load profile for Site 6. This site shows a similar usage pattern to Site 1. Site 6 has a two stage gas furnace with natural gas input rates of 66,000 and 45,000 Btu/hr, which accounts for the reduction in the morning peak from Site 1 to Site 6. At both sites the morning peaks are similar in duration and magnitude regardless of which water heater is being used.

Figure 28. Whole house gas load profile for average winter day at Site 1

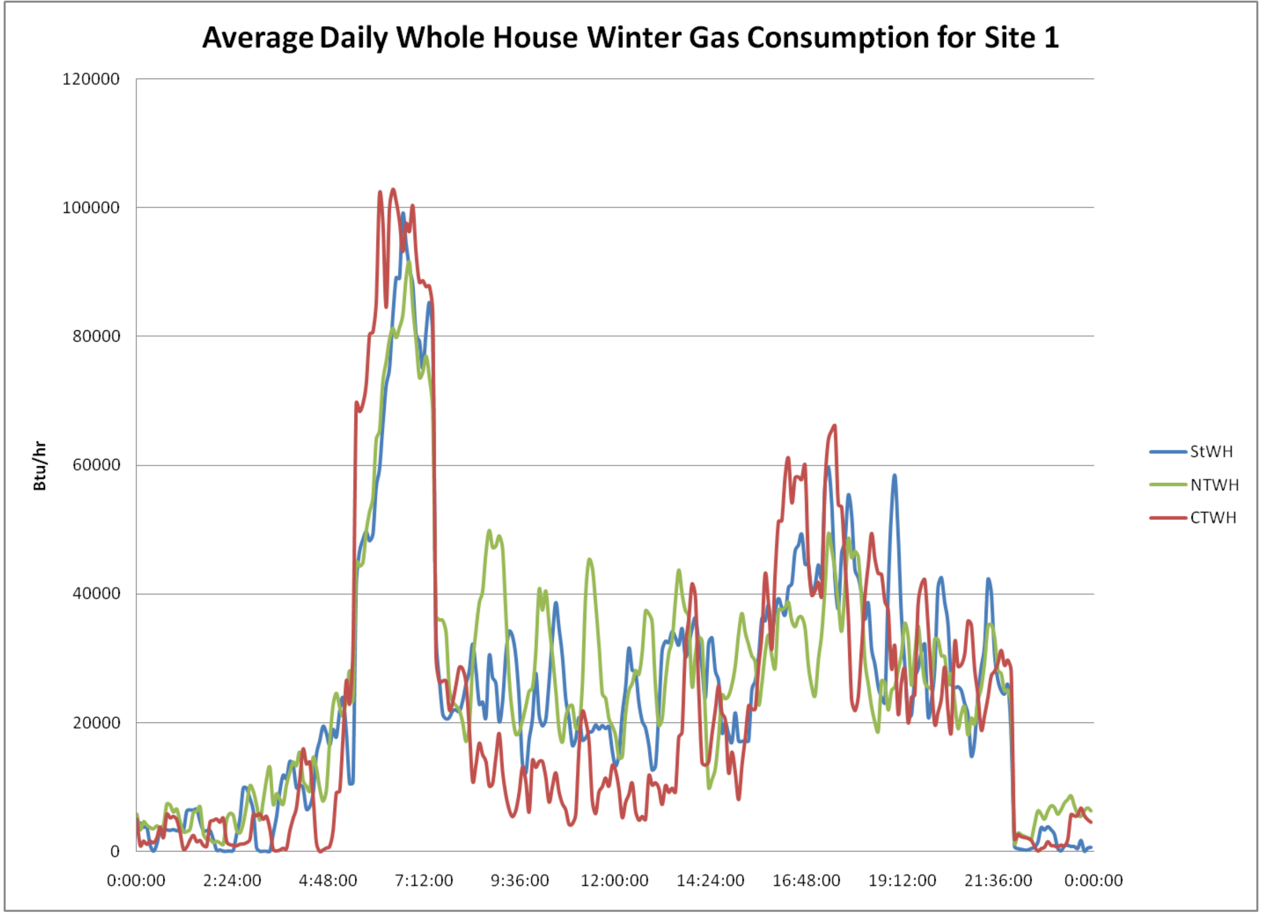


Figure 29. Whole house gas load profile for average summer day for Site 1

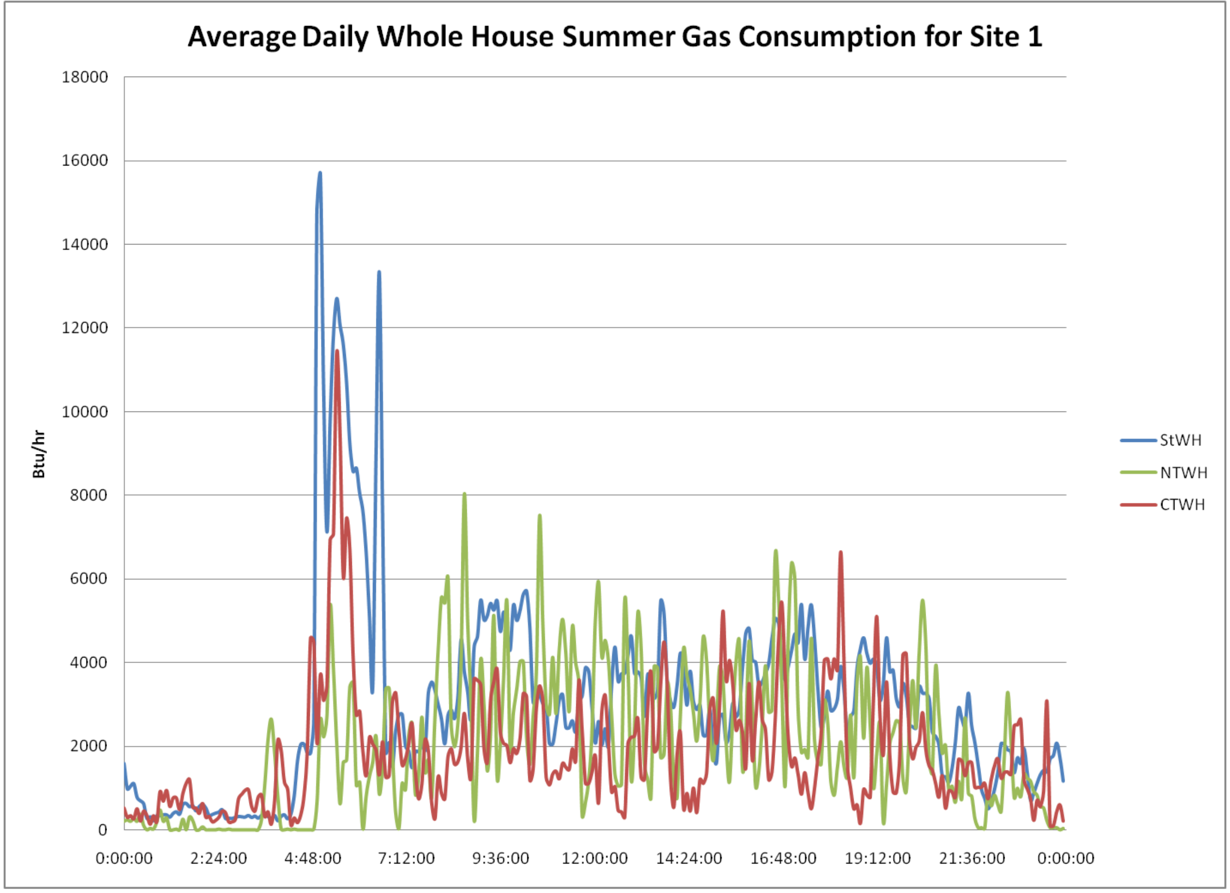
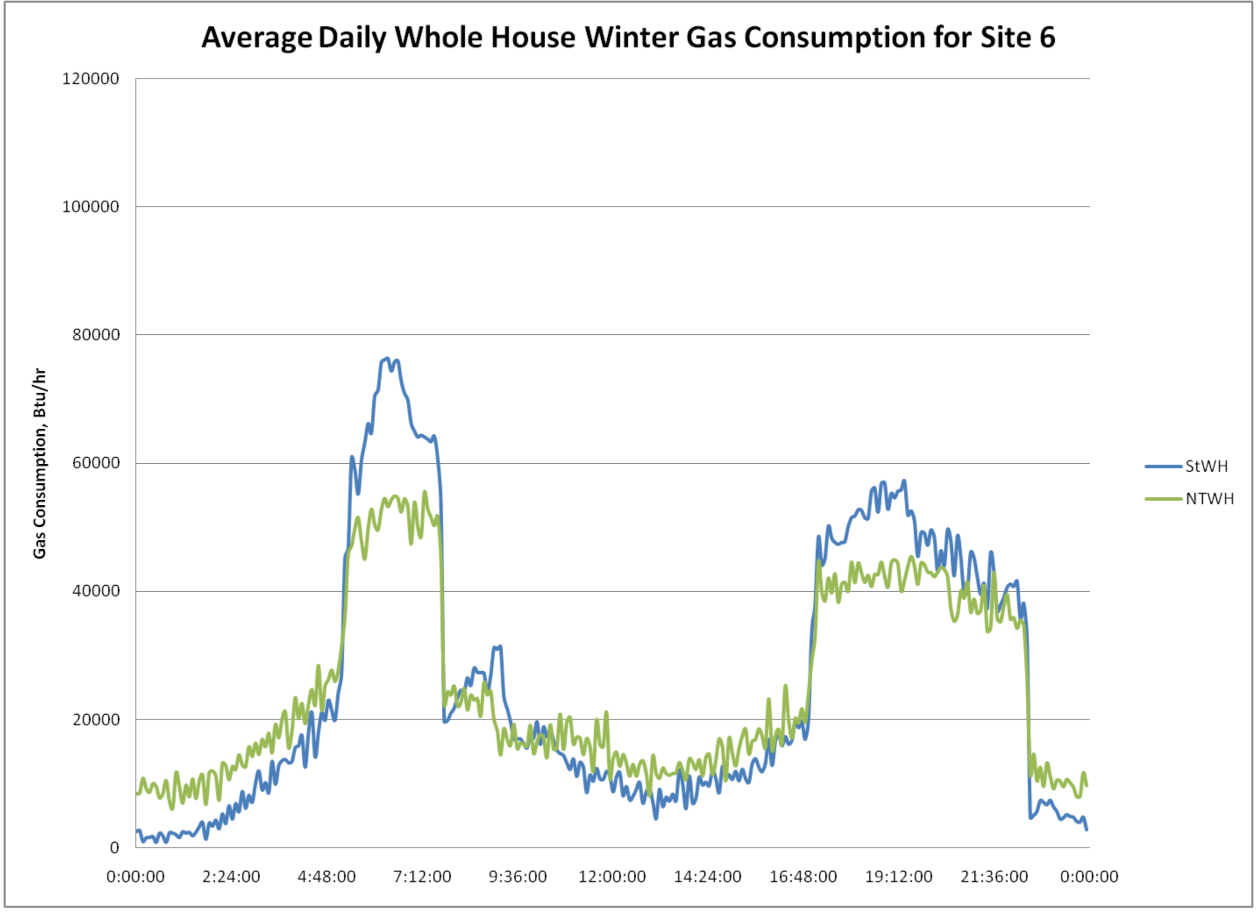


Figure 30. Whole house gas load profile for average winter day for Site 6



DISCUSSION

TWHs in this study had simple paybacks of 21 to 71 years. These paybacks are too long for TWHs to make sense from an economic standpoint with current energy costs.

Current federal rebates for energy-efficient products make the paybacks for TWHs much better. Water heaters that meet the federal energy-efficiency requirements can have 30% of their total cost rebated up to $1500. Applied to the previously discussed payback analysis this rebate would reduce homeowners’ incremental costs for TWHs to $750-$2200. Reducing incremental costs improve paybacks to a much more manageable 10 to 23 years.

Assuming these federal rebates continue, a utility program with additional rebates could make TWHs economically feasible as an energy-efficiency technology. For instance, if a 0.82 EF NTWH can be installed for $2500, the federal rebate brings that cost down to $1750, which is about a $750 incremental cost over a typical StWH. In this project the 0.82 EF NTWHs saved about $72/year and about 75 therms/year. An additional $200 utility rebate would bring the payback for this heater down to 7.5 years and a $500 rebate would bring the payback down to 3.5 years. However, this would be a very high rebate rate per therm saved and may not be viable. With the gross payback period generally exceeding the expected TWH life, TWHs would not pass the societal test required for CIP programs.

The simple paybacks of tankless water heaters may be better than indicated in the analyses conducted here if the TWH manufacturers' claim that the TWH has twice the lifetime of StWHs is valid. StWHs are generally considered to have a lifetime of 10 to 12 years, and manufacturers claim a lifetime of 20 years for TWHs. There has not been enough information collected to verify this lifetime. If this claim is true the incremental cost is reduced by about $1000, reducing simple paybacks to 7 to 27 years.

These findings leave the search for economic, high efficiency water heating alternatives unresolved, though many alternatives remain to be examined. One alternative, for example, is the use of TWHs for both domestic hot water and space heating, since the economics would likely improve if one appliance could be used for both functions. Another alternative is the use of storage water heaters with higher efficiencies. Residential StWHs with electronic ignition or with power venting/power combustion can have higher efficiencies: for instance, 40 gallon models on the market today have EFs ranging from 0.58 to 0.70. Residential condensing StWHs are not available but commercial models are available and have efficiencies exceeding 90%. These more efficient StWH options also have higher costs. StWHs can also be used as combination heating/water heating appliances. Other options include use of boilers for both heating and water heating, solar water heating, heat pump water heaters, point-of-use heaters for small draws, and more. These options, while worthy of further investigation, are outside the scope of this study.

The findings from this study strongly suggest that the DOE Energy Factor needs to be modified. This report shows that it does not accurately predict installed performance or provide a non-biased metric for comparison between technologies. Comparing measured daily efficiencies versus rated EFs showed that EF over-predicted efficiency by 14 percentage points (23%) for StWHs compared to 9 percentage points (10%)for TWHs. The American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) is currently working to update their residential water heater test standard (118.2). A proposed U.S. Senate bill would

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force DOE to revaluate the rating procedure for both commercial and residential water heaters. Two methods are under consideration to improve the EF test, (1) updating the draw profile to be more representative of how hot water is actually used or (2) switching to a modeling approach where two-point lab tests are used to generate an input-output line and performance is modeled from this line and a standard load profile. Data and knowledge gathered from both the field and lab portions of this project have been and will continue to be used to support efforts to improve the water heater rating methodology.

CONCLUSIONS

Tankless water heaters can be successfully installed and operated in Northern Midwest climates. TWHs can be used in residential applications with only moderate changes in qualitative aspects of water heating performance, with some attributes rated better and some worse than for StWHs. TWHs save a considerable amount of energy over natural draft StWHs. TWHs saved an average of 37% of site energy consumed for water heating at ten sites in the Minneapolis/St Paul area, which was about 6000 kBtu per home per year. TWHs provided this energy savings with no significant change in hot water consumption. Even with these positives of tankless water heaters the low cost of natural gas and the high installed cost of TWHs limits their feasibility. Without considerable rebates the simple paybacks for these heaters were 20 to 40 years, making widespread installations seem unlikely.

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Appendix I – Table of available TWHs

Appendix II – Table of Incentive Programs

		TANKLESS INCENTIVES										
		Have One		Source of Info			Incentive Details			How	#	
Utility Name, Territory, Web Site	**Incentive Netwk**	**Yes**	**No**	**E-Sour**	**Web**	**Verbal**	**Amount**	**Min EF**	**Other**	**Long**	**Reb?**	**Other**
Alliant Energy												
parts of IA, MN, WI	Focus on Energy	x		x			$100	0.80				
www.alliantenergy.com												
Aquilla												
CO, IA, KS, NE, MO		x		x		x	$100	none		2003	5	Only in Iowa
www.aquila.com												
Avista												ODOE for OR
parts of OR, WA, ID		x		x	x		$200	0.80				.80 EF in OR
www.avistautilities.com							$200	0.82				.82 EF in WA, ID
Bay State / Northern Utilities (NiSource)												
Parts of MA, ME, NH	GasNetworks	x		x	x	x	$300	0.82	IID	2004?	200	
www.baystategas.com; northernutilities.com												
Berkshire Gas Company												
Western MA	GasNetworks	x		x	x	x	$300	0.82	IID	2005?		
www.berkshiregas.com												
Cascade Natural Gas												ODOE for OR
Parts of OR, WA	Energy Trust OR	x			x		$200	0.80				.80 EF in OR
www.cngc.com							$200	0.81				.81 EF in WA
Enbridge Gas Distribution												Commercial
Parts of Ontario, Canada		x		x	x	x	$300	Pre-Approved Mfgrs				Cust. Only
https://portal-plumprod.cgc.enbridge.com												
Gainesville Regional Utilities												
Gainesville, FL and surrounds		x		x	x		$350	none				For fuel switch
www.gru.com												or add'l gas unit
Gaz Metro												Goes to Installer
VT, USA; Quebec, Canada		x				x	$450	none				Commercial
www.gazmetro.com						x	Pilot Pgm	Pre-Approved Mfgrs				Residential
Madison Gas & Electric												
South-central & Western WI	Focus on Energy	x		x			$100	0.80				
www.mge.com												
MN Energy Resources												
Parts of MN		x				x	$250	0.84		2007	8	
www.minnesotaenergyresources.com												
NationalGrid / Keyspan Energy Delivery *												
Parts of NY, MA, NH, RI	GasNetworks	x		x	x	x	$300	0.82	IID	2006	900	
www.nationalgridus.com/rigas												
New England Gas Company												
Parts of MA	GasNetworks	x		x	x		$300	0.82	IID			
www.negasco.com												
Northwest Natural Gas												Oregon also
OR, Southwest WA	Energy Trust OR	x		x			$200	0.80				eligible for ODOE
www.nwnatural.com/index.asp												tax credits
NSTAR Gas												
Parts of MA	GasNetworks	x		x	x	x	$300	0.82	IID	2005?	900	
www.nstaronline.com/residential												
Palo Alto City Utilities												
City of Palo Alto, CA and surrounds		x		x	x		$300	0.80	IID			
www.city.palo-alto.ca.us												
Pacific Gas & Electric												
Northern and Central CA		x		x		x	$200	0.80	IID			New Const. Only
www.pge.com/myhome												
Pacific Power												Oregon also
Elect for parts of OR, WA, CA	Energy Trust OR	x		x			$200	0.80				eligible for ODOE
www.pacificpower.net/Homepage												tax credits
Portland General Electric												Oregon also
Elect for most of SW Portland, OR	Energy Trust OR	x		x			$200	0.80				eligible for ODOE
www.portlandgeneral.com												tax credits
Questar												
Parts of UT, WY		x		x			$300	0.80				
www.questargas.com												
Southern California Gas (Sempra)												Pilot Program
Central and Southern CA		x		x	x	x	$200	0.80				Mfgrs give rebate
www.socalgas.com												
Unitil Corp.												
Parts of MA; Elect parts of NH	GasNetworks	x		x	x	x	$300	0.82	IID			
www.unitil.com												
WE Energies												
Parts of WI; Elect parts of WI and UP of MI	Focus on Energy	x		x			$100	0.80				
www.we-energies.com												
Wisconsin Public Service												
NE & Central WI, parts of UP of MI	Focus on Energy	x		x			$100	0.80				
www.wisconsinpublicservice.com												
Xcel Energy												
CO, MI, MN, NM, ND, SD, TX, WI	Focus on Energy	x		x	x		$100	0.80				
www.xcelenergy.com												

III – Survey Information

IV – Additional Figures and Plots

V – Daily Measured vs Lab I/O performance