Condensing Hybrid Water Heater Monitoring Field Evaluation

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National Renewable Energy Laboratory

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Technical Report
NREL/TP-5500-52234
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Executive Summary

Water heating is the second largest energy use in U.S. homes. A typical gas water heater has an efficiency of about 60%, although more efficient options are available. A hybrid condensing water heater with a high rated efficiency (thermal efficiency = 0.973, energy factor = 0.95) was installed in an occupied home in Sacramento, California, and monitored for one year to determine the actual *in situ* efficiency. This unit performed at an annual efficiency of 90.6% for this home and achieved its rated thermal efficiency during extended draws. The efficiency of this unit was largely independent of the mains water temperature, but varied significantly with the average daily draw volume. Due to the high hot water demand and temperate climate at this site, the measured *in situ* efficiency observed here is expected to be higher than what might be achieved by installations in other climates and in households with lower hot water demands.

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Nomenclature

c_p	specific heat of water
E_{elec}	electrical energy consumed
E_{gas}	gas energy consumed
$E(x)$	error associated with variable x
h	natural gas heating value
$\dot{m}$	mass flow rate of water
Q_{in}	thermal energy in
Q_{out}	thermal energy out
TF	therm factor
T_{in}	inlet water temperature
T_{out}	outlet water temperature
$\dot{V}$	flow rate of water through water heater
V_{gas}	volume of gas drawn by the water heater
$\dot{V}_{\mathrm{gas}}$	flow rate of gas to water heater
η	in-use efficiency
ρ	density of water

1 Introduction

The Sacramento Municipal Utility District (SMUD) Energy Efficient Remodel Demonstration program installs efficiency upgrades in homes to showcase their energy saving benefits. In partnership with the National Renewable Energy Laboratory (NREL), a package of efficiency upgrades was selected and installed at a home on Mascot Avenue in Sacramento, California (see Figure 1). This was an abandoned, 1950s vintage home that required extensive repairs, including a new roof, new heating, ventilation, and air-conditioning equipment, and wall repairs. The need for these repairs made it an ideal candidate for the efficiency upgrades, which included building envelope improvements, compact fluorescent lights, and a new water heater. Of these upgrades, the unique water heater installed in this home is of particular interest.

Field monitoring was performed to determine the in-use efficiency of the hybrid gas condensing water heater (Navien CR240-A) installed at the home. These results were then compared to the unit's rated efficiency. This unit is ENERGY STAR® qualified and has one of the highest rated efficiencies of the gas water heaters currently on the market. It consists of a tankless condensing water heater and a 0.5 gallon buffer tank (See Figures 2 and 3). A condensing water heater condenses the exhaust from the water heater to extract more heat that can be used to heat the water. The buffer tank eliminates the "cold water sandwich" issue common to tankless water heaters, but increases standby losses. The "cold water sandwich" commonly occurs between two closely spaced domestic hot water (DHW) draws (for example, two morning showers). After the first draw, hot water may still be in the pipes, but the tankless water heater will have turned itself off because no water is being drawn. The second event will start with hot water from the pipes, but will be followed by a slug of cold water right before the tankless water heater burner ignites and heats the water once the water heater fully fires.

NREL/PIX 19261

Figure 1. The Mascot home

The water heater was monitored for a full year (from March 2010 to March 2011), during which time the home was occupied by a single family. Based on the data collected, this hybrid condensing water heater demonstrated that it can reach its rated thermal efficiency of 97.3% during extended draws of 15 minutes or longer, but has an *in situ* efficiency of about 90.6%. This value is lower than the rated efficiency; the energy factor for this unit is 95%. This is still quite good for a gas water heater; typical gas storage water heater efficiencies are 50%–60%. Past field studies have shown this unit generally performs below its rated efficiency when installed in homes, in some cases far below its rated efficiency [1]. The likely cause of the discrepancy between rated and actual efficiency is the difference between the draw profiles used in the standardized U.S. Department of Energy (DOE) efficiency tests [2] and the actual in-home use draw profile.

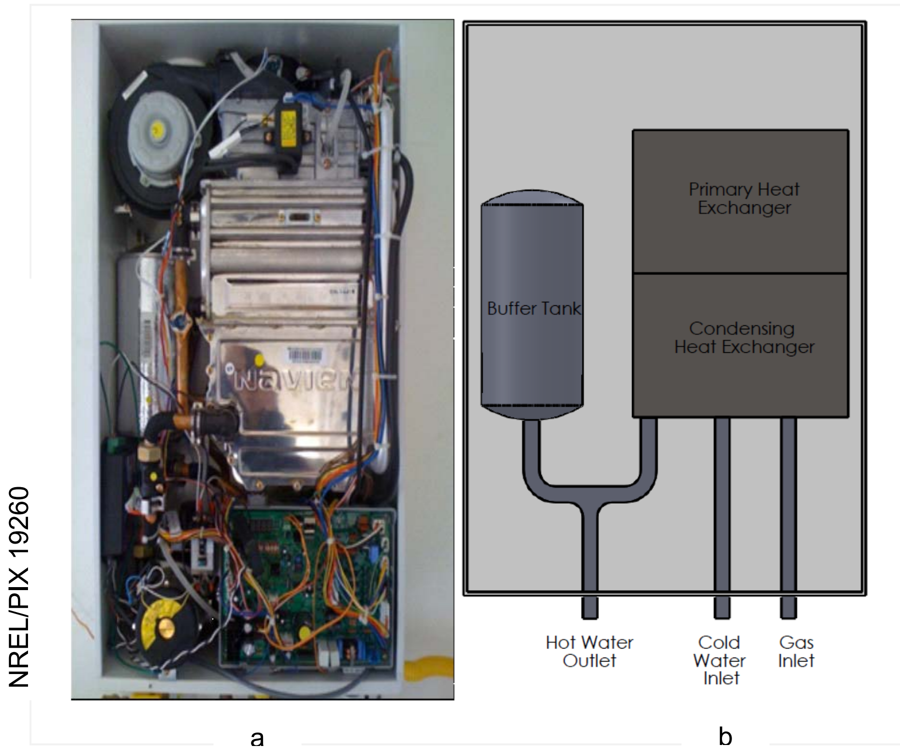

Figure 2. (a) The installed water heater and (b) a schematic of key components
Credit: Jeff Maguire/NREL

2 Procedure and Measurements

To determine the *in situ* efficiency of the water heater, the inlet and outlet temperatures for water, the flow rates for water and gas, and the electricity use were measured. Although the water heater is gas powered, electricity is required by the unit to operate the controls, ignition, venting fan, and freeze protection. A schematic of the measurement points is provided in Figure 3 and measurement equipment and accuracies are given in Table 1. Most measurements were of sufficient resolution to draw detailed conclusions, but the limited accuracy of the gas flow meter made it difficult to determine short term efficiencies that could be compared to the thermal efficiency. A more detailed discussion of this issue is provided in Section 3.2. Data were collected and recorded via a Campbell Scientific CR1000 data logger at 1 minute intervals, reported at 1 minute, 15 minute, 1 hour, and daily intervals, then transmitted back to the laboratory via a wireless modem. This unit was monitored for a full year to examine seasonal effects. This was an occupied home, so the draw profile reflects the actual DHW use of these particular occupants and may not be typical.

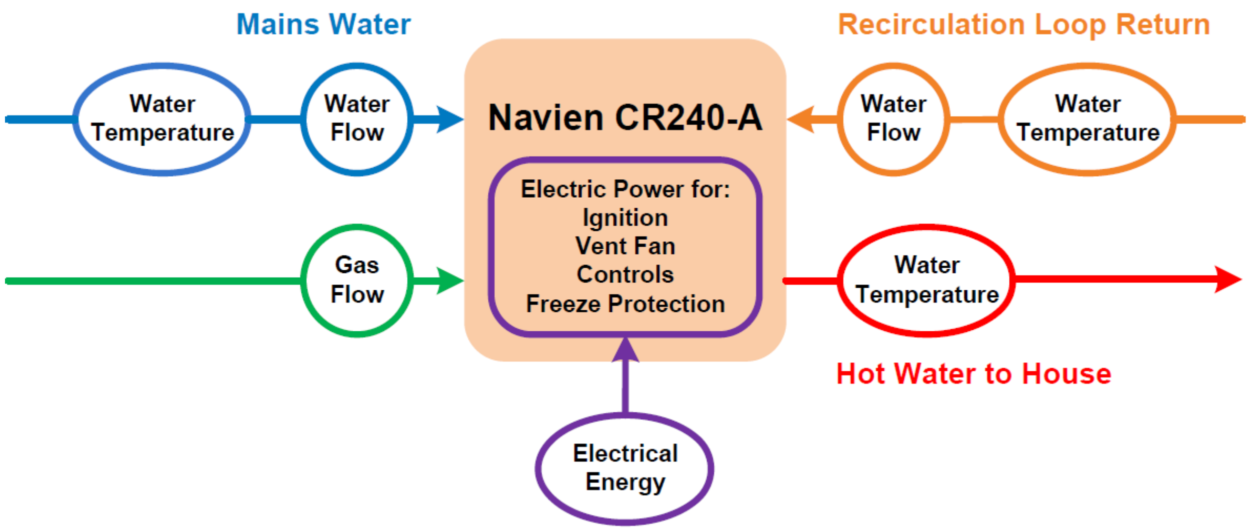

Figure 3. Measurement points for field monitoring

Table 1. Installed Measurement Equipment in the Mascot Home

Measurement	Equipment	Manufacturer	Accuracy
Temperature	Type T thermocouple	Omega	± 1.8°F (1°C) or 0.75%
Water flow	Hall effect flow meter	Omega	>10% cont. flow-max flow: ± 1.5%, <10% continuous flow: ± 2%
Gas flow	Diaphragm gas flow meter	Sensus	± 1 ft^3
Electric power	kWh transducer	Continental Control Systems	± 0.5%

3 Average Efficiency Calculations

This water heater is rated at 97.3% thermal efficiency and 95% energy factor. Thermal efficiency provides a measure of the efficiency during continuous operation while energy factor provides an average overall efficiency based on a standardized daily draw profile. Although the rated thermal efficiency was observed during some events, on average the daily efficiency observed was lower than the rated energy factor. The efficiency can be calculated for any time interval using the equation:

$$\eta = \frac{Q_{out}}{Q_{in}} = \frac{\dot{m}c_p(T_{out} - T_{in})}{E_{elec} + E_{gas}} \tag{1}$$

In Equation 1, the energy out is calculated from the flow rate of water through the water heater ($\dot{m}$), the temperature difference between the inlet and outlet water ($T_{out} - T_{in}$), and the water's specific heat (c_p). The energy out (Q_{out}) is calculated internally by the data logger and is reported at every time interval. The electric energy term includes the energy used by the controls, ignition, venting fan and freeze protection from an electric heater. The energy from gas is calculated according to Equation 2 using the volume of gas used and the therm factor (an average gas heating value defined as the number of therms per 100 ft^3 of gas) as reported by the local utility, Pacific Gas and Electric (PG&E).

$$E_{gas} = \frac{V_{gas}}{100}(TF) \tag{2}$$

For this home, PG&E gave a therm factor of 1.01616 therms/100 ft^3. Monthly measured energy consumption, DHW use, and efficiencies are given in Table 2.

Table 2. Monthly Average Energy Use and Efficiency

Month	DHW Draw Volume (gal)	Daily Draw Volume (gal/day)	DHW Electricity Use (kWh)	DHW Gas Use (therm)	Electricity Use (% of total energy use)	DHW Energy Out (therm)	Efficiency
March	3424	110.5	7.35	16.3	1.54%	15.4	92.6%
April	2712	90.4	6.80	12.5	1.85%	11.6	90.6%
Map	2285	73.7	6.81	9.8	2.38%	8.8	88.2%
June	2297	76.6	6.50	8.8	2.51%	8.2	90.6%
July	2883	93.0	6.80	9.4	2.47%	8.8	91.5%
August	2191	70.7	6.55	8.4	2.67%	7.6	88.7%
September	2325	77.5	6.49	8.9	2.50%	8.2	89.8%
October	2908	93.8	6.96	11.8	2.01%	10.9	90.4%
November	2761	92.0	7.24	12.9	1.91%	11.8	89.5%
December	3411	110.0	7.59	17.2	1.50%	15.9	90.6%
January	3902	125.9	8.04	20.7	1.33%	19.2	91.8%
February	2868	102.4	6.94	15.1	1.57%	13.9	90.5%
Total (average)	**33967**	**(93.1)**	**84.05**	**151.9**	**(1.89%)**	**140.2**	**(90.6%)**

3.1 Discussion of Factors Impacting Overall Efficiency

The freeze protection system for this water heater turns on a backup electric heater whenever it detects an ambient air temperature close to freezing. Typically, the freeze protection threshold temperature is set above 32°F, as any freezing in the water heater would lead to catastrophic failure. Freeze protection was seen to turn on at temperatures as high as 45°F for this unit. This threshold was crossed in very few instances (see Figure 4). Overall, the energy used for freeze protection accounted for 5.5% of the total energy used during standby (when no water was being drawn) over the year. The energy consumed during any hour for freeze protection varied depending on how long the freeze protection was on in that hour. The baseline energy consumption of 8 Wh comes from the controls.

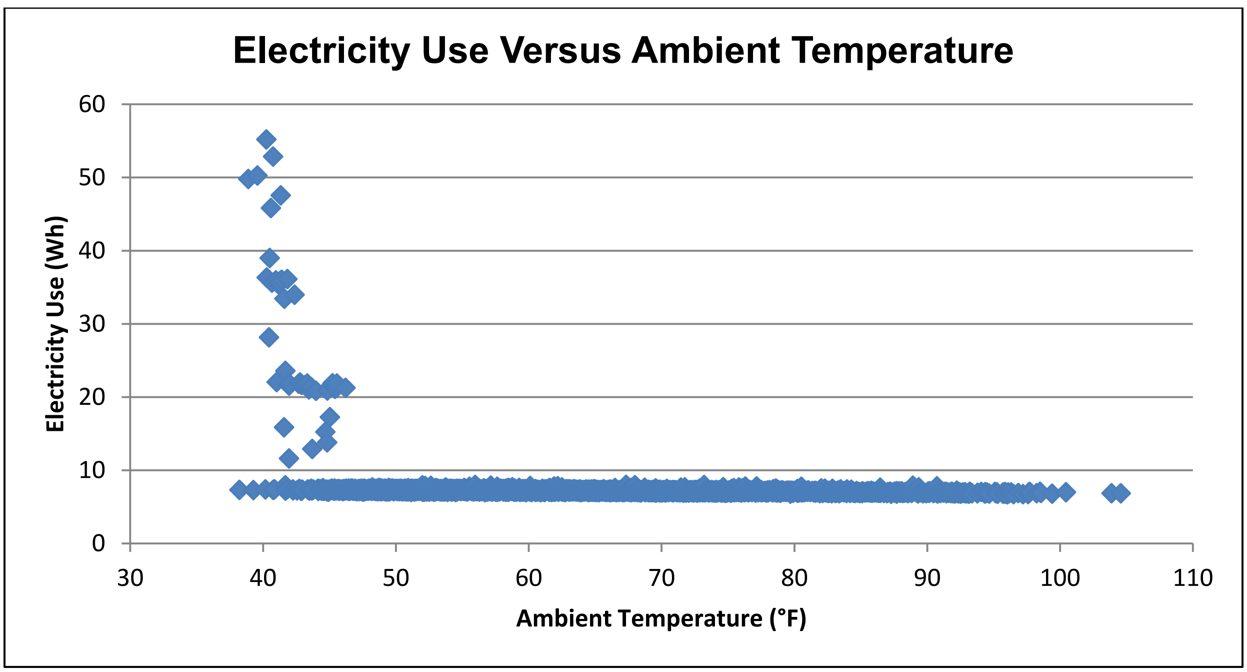

Figure 4. Electrical energy used per hour during standby as a function of average ambient temperature

Another factor that could reduce efficiency during colder months is the buffer tank. Past work has suggested that this tank is poorly insulated and could significantly affect the efficiency of the water heater, especially when it is located in unconditioned space [1]. During the year that the water heater was monitored, only one event was observed where the water heater had to fire to replace standby losses. Since such an event would be difficult to detect with the resolution of the gas flow meter, it is likely to have occurred more than once over the full year. Overall, the DHW use was a much larger factor in the overall efficiency than ambient temperature. This is likely due to the temperate climate of Sacramento; past work where a significant impact was seen involved field monitoring of this water heater in a garage in Minnesota [1].

One factor could *increase* the efficiency of the system during the winter. Condensing water heaters are more efficient when the inlet water temperature is lower because the cold temperature increases the amount of water vapor that can condense in the unit (or, if full condensation has occurred, further reduces the temperature of the remaining flue gas and condensate). Based on previous case studies that showed very low efficiencies in cold climates, it is expected that this unit should be less efficient overall in cold conditions. The current dataset suggests that the efficiency of this water heater is not a strong function of inlet water temperature (see Figure 5).

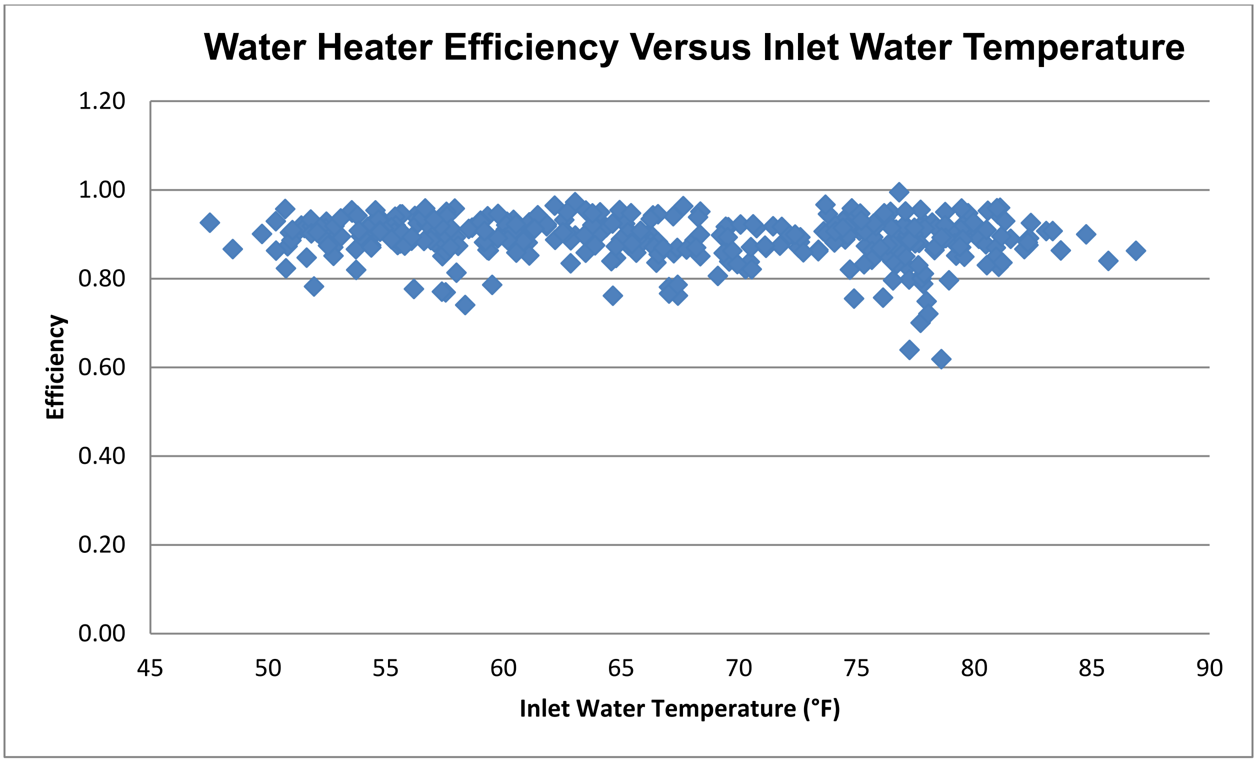

Figure 5. Effect of inlet water temperature on water heater efficiency

Efficiency is only weakly influenced by inlet water temperature, but it is strongly influenced by the volume of water drawn from the water heater (see Figure 6). However, there is still a wide spread in the data because of fluctuations in ambient temperature and daily draw profiles. This home is a particularly high DHW user (an "average" home is 64.3 gallons/day [2], and this home averages 93.1 gallons/day), so the *in situ* efficiency of this unit may be higher than what would be seen in other homes with more typical use.

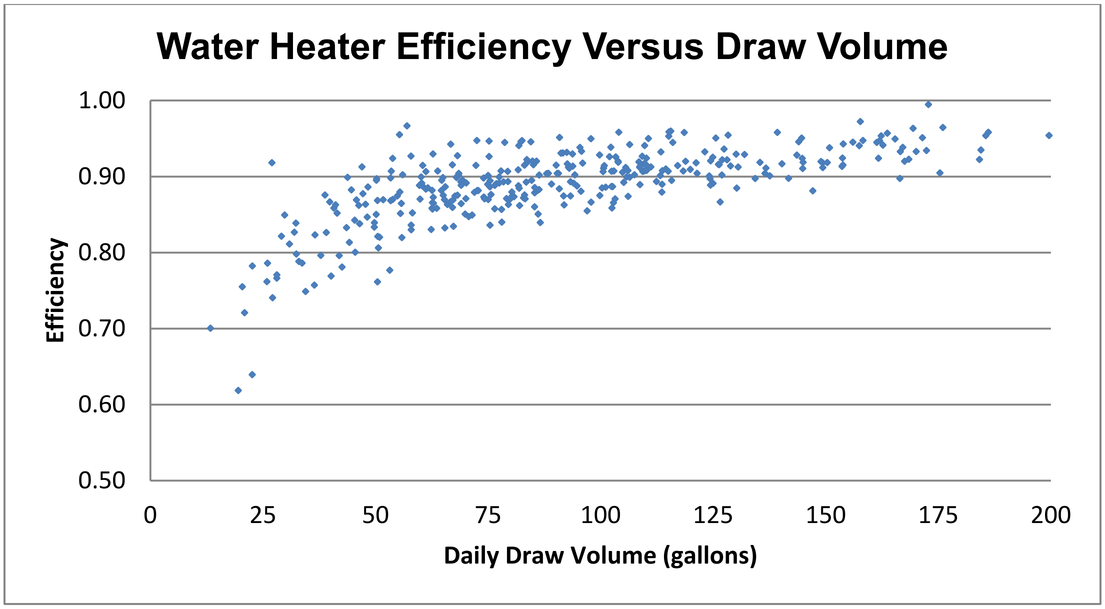

Figure 6. Efficiency versus daily draw volume. As use increases, the water heater's efficiency increases.

The discrepancy between the water heater's rated efficiency and its measured *in situ* efficiency is most likely due to significant differences between the draw profiles used in the rating tests and actual draw profiles used by the homeowners, although other factors such as fluctuations in mains temperature and ambient temperatures also have some effect. Thermal efficiency is determined with a continuous use test, which means that the efficiency decrease from heating the heat exchanger are unaccounted for. For the energy factor test, six draws of equal volume over the course of six hours are used as an estimate of a home's water use. The energy factor test also includes an 18 hour period when no water is drawn so standby losses can be determined. In actual use, there are many short draws over the course of a day (see Figure 7). These short draws require the heat exchanger to heat up and cool down with each draw, reducing the system efficiency. The energy factor test draws a set amount of water (64.3 gallons) that is intended to represent typical use, although use can vary widely from one home to another based on the number of occupants and their behavior.

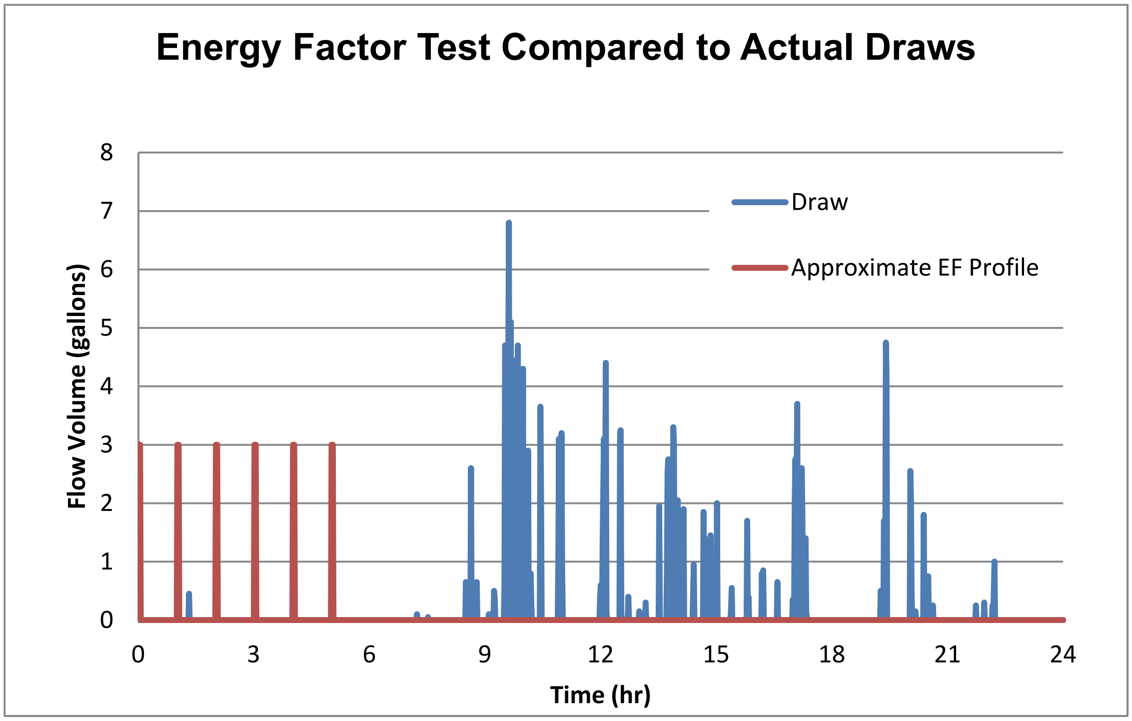

Figure 7. Draw profile for one day compared to the energy factor test draw profile

3.2 Short-Term Efficiency Measurements

To determine the water heater's efficiency during actual use, the one minute interval data was analyzed during periods when the water heater was in use. However, the limited resolution of the gas flow meter made detailed analysis of the short term performance of the water heater difficult. The gas flow meter is accurate only to the nearest cubic foot, and the water heater draws gas at less than 1 cfm when it is in use. This meant that the reading for any one minute period would either be 1 or 0 ft^3. This created such a large error that doing detailed analysis of the short term performance for most draws was not possible. Fortunately, some longer draws could be analyzed to look at the performance of the water heater under constant use. The one minute data was used to identify periods where there was a continuous 15 minute draw, and those periods were analyzed to determine the water heater's efficiency during use. During these periods, the electrical energy use was very small compared to the gas energy use, typically affecting the efficiency by less than 0.1%, and was therefore ignored. The equations used to calculate the uncertainty in energy in, energy out, and efficiency are given in Equations 3–5. The error propagation calculations were done with Engineering Equation Solver. A sample efficiency calculation is given in Table 3. In Equations 3-5, h is the natural gas heating value, V_{gas} is the gas flow rate, V is the water flow rate, T_{in} is the inlet water temperature, and T_{out} is the outlet water temperature.

$$E(Q_{in}) = \left(\frac{h}{3412}\right) E\left(V_{gas}\right) \tag{3}$$

$$E(Q_{out}) = \left(\frac{\rho c_p}{3600000}\right) E(V_{gas})[V(T_{out} - T_{in})]\sqrt{\left(\frac{E(V)}{V}\right)^2 + \frac{E(T_{out})^2 + E(T_{in})^2}{(T_{out} - T_{in})^2}} \quad (4)$$

$$E(\eta) = \left(\frac{Q_{out}}{Q_{in}}\right)\sqrt{\left(\frac{E(Q_{out})}{Q_{out}}\right)^2 + \left(\frac{E(Q_{in})}{Q_{in}}\right)^2} \quad (5)$$

Table 3. Uncertainty Analysis of Each Measurement Instrument During One Extended Draw

Variable ± Uncertainty	Partial Derivative	% Uncertainty
η = 0.9464 ± 0.0968	–	–
T_{in} = 14.74 ± 1 (°C)	$\partial\eta/\partial T_{in}$ = –0.02826	8.52%
T_{out} = 48.42 ± 1 (°C)	$\partial\eta/\partial T_{out}$ = 0.02794	8.33%
V = 79.61.42 ± 1.592 (l)	$\partial\eta/\partial V$ = 0.01189	3.82%
V_{gas} = 11 ± 1 (ft^3)	$\partial\eta/\partial V_{gas}$ = –0.08621	79.32%

From the start of testing in March through June of 2010, 57 continuous draw events lasted for 15 minutes or longer. A more accurate efficiency measurement could be calculated during continuous use, although the accuracy of each event was still not particularly high. The uncertainty was as large as ±20% for the efficiency of each event, largely because of the error in gas flow measurement. By averaging these events together, an *in situ* efficiency of 99.0±1.7% was found. This is consistent with the rated thermal efficiency of 97.3%, because the thermal efficiency is within the error bounds.

To more accurately determine the efficiency of the water heater while it is in use, a more accurate gas flow meter with an accuracy of at least ±0.1 ft^3 would be required to keep the uncertainty in gas flow measurement on the same order of magnitude as the other measurements. A potential replacement for the currently installed gas flow meter is the AC-250 diaphragm gas flow meter available from IMAC Systems, Inc. [3]. This gas flow meter can be fitted with a pulse output attachment to achieve an accuracy of ± 0.025 ft^3, which would be sufficient for future studies on tankless gas water heaters. However, it is significantly more expensive than the gas flow meter that was used in this study.

4 Economic Analysis

To determine how cost-effective this unit is, a comparison was made to a simulated standard gas storage water heater at the same house. The draw profile, ambient temperature, and inlet water temperature recorded during field monitoring were all used as inputs to the model to ensure the comparison would be as direct as possible. The gas water heater modeled is a 50 gallon unit with an energy factor of 0.59, a typical efficiency for this style of water heater. The model is based on a specific unit made by a major water heater manufacturer. Model parameters were derived from standard rating test results [4]. The modeling was done using the TRNSYS simulation program. Modeling results and operating costs for both units are shown in Table 3.

Table 4. Annual Operating Costs for the Monitored Water Heater and a Modeled Typical Gas Water Heater

Month	Hybrid Condensing Water Heater Total Energy Use (therm)	Gas Storage Water Heater Gas Use (therm)	Hybrid Condensing Water Heater Operating Cost ($)	Gas Storage Water Heater Operating Cost ($)
January	16.6	31.23	$20.16	$37.07
February	12.7	23.68	$16.07	$29.06
March	10.0	25.64	$12.79	$31.56
April	9.0	20.08	$12.98	$28.07
May	9.6	16.47	$15.23	$25.38
June	8.6	14.32	$14.34	$23.16
July	9.1	16.60	$16.49	$29.36
August	12.0	13.83	$19.44	$21.84
September	13.1	14.71	$18.33	$19.97
October	17.5	19.47	$22.25	$24.27
November	21.0	20.09	$21.76	$20.23
December	15.3	27.43	$15.79	$27.29
Annual total	**154.7**	**243.6**	**$205.64**	**$317.27**

Annual operating costs were calculated based on monthly gas and electricity prices from SMUD and PG&E for 2008 [5][6]. The cost of installing a gas storage water heater was estimated based on the NREL National Residential Efficiency Measures Database as $780 [7]. The condensing hybrid water heater installed in this house had an installed cost of $4924. However, this home underwent extensive repairs and it is unknown how much of this cost is associated with repairs to this home, which makes it difficult to determine the installed cost in more typical retrofit situations. To determine the cost effectiveness of this unit, the simple payback of the hybrid water heater was calculated. For these calculations, both units were assumed to have zero maintenance cost, although the hybrid water heater may need regular maintenance [1]. If no incentives (tax credits, rebates, etc.) are considered, the simple payback is about 37 years, far longer than the expected lifetime. A typical water heater has a life of about 13 years. Most tankless water heater manufacturers advertise a 20 year lifetime, but these units have not been on the market long enough to validate that claim. There is especially large uncertainty in the lifetime of the hybrid unit because it will depend on the lifetime of the buffer tank as well. An incentive of about $1910 (39% of the installed cost) would give this unit a 20 year simple payback; an incentive of about $2690 (55% of the installed cost) would give it a 13 year simple payback. Current federal incentives for this unit are $300 [8], so significant state and local incentives would be necessary to make this unit cost effective in this case. Using this water heater would save 91.8 therms of gas (about 9000 ft^3 for this site) relative to the 0.59 energy factor storage tank while using 85 kWh of electricity annually.

The actual water heating energy use for this home was larger than the predicted energy use. BEopt modeling had suggested that the annual energy use for this water heater would be 119.7 therms per year; the actual use was 147.7 therms per year, 23% larger than the predicted value (see Figure 8). This additional energy use can largely be attributed to differences in the estimated and actual amounts of DHWused per day. The original assumed amount was only 54.5 gallons/day, significantly less than the actual average 93.1 gallons/day drawn by this household. The actual energy consumption was not accurately captured, but the magnitude of the savings was captured fairly well. BEopt predicted a 39% energy savings, while the savings when comparing the actual monitored energy use to the energy use predicted by the TRNSYS storage tank model is 36%.

Based on this economic analysis, this unit is not a cost-effective replacement for a standard gas water heater. However, one issue not captured by this modeling is that the standard gas storage water heater will not always be able to keep up with demand, especially in high use cases such as the one studied here. Thus, the occupants would likely either use less hot water or raise the set point temperature of the water heater. Either behavior would alter the amount of energy used by the gas storage water heater, although it probably would not be enough to significantly change the cost effectiveness of the hybrid water heater considered here.

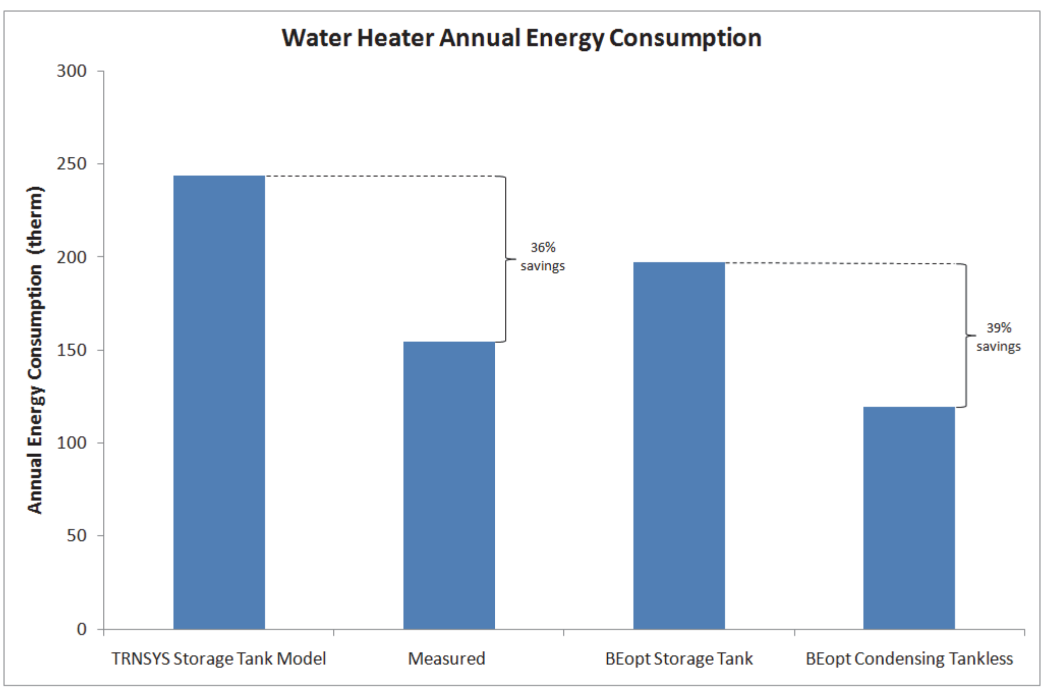

Figure 8. Annual energy consumption using measured data and the BEopt models

5 Conclusions

- Actual *in situ* efficiency for this water heater is about 5% lower than the rated efficiency (energy factor). The *in situ* efficiency was significantly influenced by the daily DHW draw profiles. Differences between the actual draw profile and that used in the energy factor test procedure is the primary reason for this difference between the *in situ* efficiency and the rated efficiency. Under conditions similar to those used for the thermal efficiency test, this unit does achieve its rated efficiency.

- The occupants of this home used larger than typical DHW volumes. The actual *in situ* efficiency will vary depending on DHW use patterns, and is likely to decrease for many homes with lower DHW demands because of standby losses and more energy being wasted in heating and cooling the heat exchanger when compared to the delivered energy in the heat exchanger.

- Ambient air temperature and mains water temperature had little impact on the measured efficiency of this water heater. However, mains and ambient temperatures have the potential to have a large impact under extreme conditions, as demonstrated by the efficiency of this unit when compared to that monitored in Minnesota [1]: This unit's *in situ* efficiency was about 90%, compared with 57%–67% for units tested in Minnesota.

- For future studies of tankless and hybrid gas water heaters, a more accurate gas flow meter should be installed so efficiency during short draws can be determined. Such gas flow meters are more expensive than the unit that was used in this study.

- Finally, this water heater is not currently a cost-effective solution compared to a typical gas storage water heater, because of its high installed cost.

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