Heat Pump Water Heaters

Evaluation of Field Installed Performance

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Improving the Built Environment Since 1972

JUNE 26, 2012

Contents

1 Executive Summary

Heat pump water heater (HPWH) technology is not new, but products designed for the residential market have achieved minimal market penetration in the past, primarily due to reliability issues and limited market infrastructure. Past products were produced by smaller, niche-market manufacturers. Prompted by increasing electricity prices, ENERGY STAR® qualification, and various incentives (state, federal, local, utility, etc.) that promote the installation of more efficient equipment, several manufacturers have recently introduced new HPWHs to the residential market. Furthermore, a new federal water heating standard will mandate energy factors around 2.0 for all new electric storage water heaters with capacities greater than 55 gallons in 2015. This regulation effectively requires installation of HPWHs in applications with large hot water demands and where electricity will be used to heat water.

This evaluation quantified the in-situ performance of three recently-released HPWH products (General Electric GeoSpring™, AO Smith Voltex®, and Stiebel Eltron Accelera®300) through the installation and monitoring of 14 units in Massachusetts and Rhode Island for over one year. Though not recommended as a general practice, sizing for the HPWH replacements in this study was based on the existing water heater tank size. Of the 14 units, ten were GE models (50 gallon units), two were Stiebel Eltron models (80 gallon units), and two were AO Smith models (one 60 gallon and one 80 gallon unit). The sites were chosen in the residential markets of the sponsoring electric utility companies, National Grid and NSTAR, and the sponsoring energy efficiency service program administrator, Cape Light Compact. Three of the homes had existing oil water heaters, one had a propane water heater, and the remaining were electric resistance water heaters (ERWHs).

Though a small sample set, the overall performance of these 14 HPWHs has been enlightening and shows great promise for this technology. In general, these HPWHs were more than twice as efficient as a traditional electric resistance tank water heater; though there are large variations in overall efficiency as performance is dependent on ambient temperature/relative humidity, mains temperature, hot water setpoint temperature, and water usage (consumption and concentration). Sizing and location of the HPWH in these test homes was not specified by SWA prior to monitoring; the HPWHs were installed based on preference of the homeowner and the size of the existing water heater. Three of the units did not meet the manufacturer's minimum volume recommendations, two of the units did not provide a proper air stream path from the heat pump exhaust air, and several of the HPWHs were undersized based on daily consumption averages for the household. Despite these issues, these new units performed with remarkable energy and cost savings over ERWHs.

Fortunately, these new units show much better reliability than previous HPWHs. To date, there has only been one instance in which a compressor for a HPWH unit had to be replaced. It is unclear as to the cause of this failure. No other major issues have been identified regarding durability and reliability of these units, but this is something that will need to be followed up as these systems age.

Input values for benefit cost calculations are shown in Table 1. Energy savings are shown as ranges, and the measures are divided into two categories: small and large water heater tanks. The measure lifetime was assumed to be 10 years, which is a conservative estimate based on NREL's National Residential Efficiency Measures Database values.

Table 1. Benefit-Cost Values

	Small Tank (50-60 gal)	Large Tank (80 gal)
Measure Life	10 years	10 years
Incremental Cost	$1,510	$2,610
Mean Annual kWh Saved over ERWH	1,687	2,670
Annual Energy Usage		
HPWH; Monitored (kWh)	734 – 4,035 [1,643][1]	1,200 – 2,040 [1,579][1]
ERWH; EF = 0.91 (kWh)	1,898 – 5,813 [3,330][1]	3,110 – 6,078 [4,249][1]
Gas, Oil, or Propane; EF = 0.56 (MMBTU)	1,289 – 3,105 [1,950][1]	1,880 – 3,226 [2,410][1]
Gas, Oil, or Propane; EF = 0.67 (MMBTU)	957 – 2,664 [1,577][1]	1,510 – 2,757 [1,987][1]
Mean Utility Bill Savings[4]		
over ERWH; EF = 0.91	$298	$472
over Gas; EF = 0.56	$40	$130
over Gas; EF = 0.67	$23	$58
over Oil; EF = 0.56	$178	$300
over Oil; EF = 0.67	$88	$198
over Propane; EF = 0.56	$454	$642
over Propane; EF = 0.67	$312	$480
Mean Winter Peak Demand Reduction over ERWH[2]	374.1 W	
Mean Summer Peak Demand Reduction over ERWH[3]	174.8 W	

[1] Minimum – Maximum [Mean]
[2] June-August, Weekdays, 1pm-5pm
[3] December-January, Weekdays, 5pm-7pm
[4] Utility rates for electricity, gas, oil, and propane are $0.1768/kWh, $1.6968/therm, $3.33/gal, and $3.50/gal, respectively.

These HPWHs installations were generally cost effective. Annual utility bill savings were calculated by comparing the monitored energy usage of each HPWH to the energy use of a modeled standard electric resistance water heater under the same system conditions. Simple paybacks for the sites ranged 3.2 years to 10.5 years with a mean of 5.7 years. Assuming a real discount rate of 3%, net present values of these systems ranged from $-284 to $3,480 with a mean of $1,117. Assuming a real discount rate, finance rate, and reinvestment rate of 3%, modified internal rates of return ranged from -0.65% to 12.0% with a mean of 6.4%. Thirteen of the fourteen sites had positive net present values.

Homeowners were generally satisfied with hot water delivery, efficiency, noise, and other characteristics. Ten out of the eleven survey respondents said that they would recommend a HPWH to a friend or family member. The one dissenting homeowner had issue with the noise of their HPWH as they had a home office in the room adjoining the basement mechanical room.

While HPWHs are a promising technology, installation and maintenance is slightly more complicated than a traditional electric resistance water heater. To address the needs of installers and homeowners to understand the needed maintenance and proper installation of HPWHs, SWA has worked with the sponsors of this evaluation to develop a “Selection and Quality Installation Guide” for HPWHs or use in the utility rebate programs and a tri-fold brochure to educate homeowners on HPWHs.

2 Introduction

Water heating is the third largest contributor to residential energy consumption in the United States, after space heating and space cooling. Residential water heating consumes 0.43 quadrillion BTUs in the Northeast, which is 17% of total residential end use energy (EIA 2005). The vast majority of water heaters in the Northeast are powered by natural gas (58.4 million households) and electricity (46.7 million households), but fuel oil (3.6 million households) and propane (4.2 million households) also have sizeable shares of the water heating market (EIA 2009). Fortunately, more efficient water heaters for both major water heating fuels are becoming more readily adopted in the marketplace. Heat pump water heaters (HPWHs) are a promising technology that can reduce water heater energy consumption by around 50% compared to traditional ERWHs. Heat pump water heaters produce such large energy savings by combining a vapor compression system, which extracts heat from the surrounding air at high efficiencies, with electric resistance element(s), which are able to help meet large hot water demands.

Prompted by increasing electricity prices, ENERGY STAR® qualification, and various incentives (state, federal, local, utility, etc.) that promote the installation of more efficient equipment, several manufacturers have recently introduced new HPWHs to the residential market. Furthermore, a new federal water heating standard will mandate energy factors around 2.0 for all new electric storage water heaters with capacities greater than 55 gallons in 2015 (Federal Register 2010). This regulation effectively requires installation of HPWHs in applications with large hot water demands and where electricity will be used to heat water.

This evaluation quantified the in-situ performance of three recently-released HPWH products (General Electric GeoSpring™, AO Smith Voltex®, and Stiebel Eltron Accelera®300) through the installation and monitoring of 14 units in Massachusetts and Rhode Island for over one year. Of the 14 units, ten were GE models (50 gallon units), two were Stiebel Eltron models (80 gallon units), and two were AO Smith models (one 60 gallon and one 80 gallon unit). The sites were chosen in the residential markets of the sponsoring electric utility companies, National Grid and NSTAR, and the sponsoring energy efficiency service program administrator, Cape Light Compact.

In addition to energy performance benefits over standard efficiency electric water heaters, this pilot study assessed installation considerations, cooling and dehumidification effects, and unit reliability. Special attention was given to the sensitivity of efficiency to setpoint temperature, incoming water temperature, inlet air temperature, and hot water demand. This project provides some of the first publically-available in-situ performance results on these new HPWHs.

2.1 How Heat Pump Water Heaters Work

A heat pump is a device – such as an air conditioner or a refrigerator – that moves heat from one place to another. While a refrigerator moves heat from the inside of the appliance into the kitchen, a HPWH moves heat from the basement or mechanical room into the hot water tank. Heat pump water heaters are primarily designed as replacements for traditional electric resistance water heaters and are able to achieve higher efficiencies through use of the vapor compression heat pump cycle. Auxiliary electric resistance elements are also installed for reliability and quicker hot water recovery. Most heat pumps operate as hybrid devices, meaning they use the heat pump whenever possible, but built-in controls switch to conventional resistance heating when there are large hot water needs. Figure 1 illustrates the components and operation of a modern HPWH.

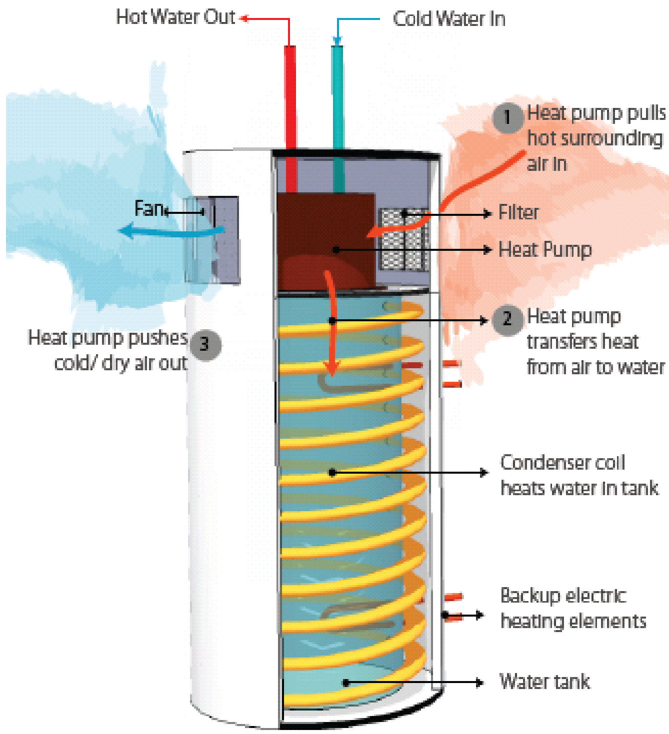

Figure 1. How heat pump water heaters work.

The heat pumps in these hybrid water heaters can heat water at high efficiencies, but the heat pumps have heating capacities lower than those of traditional electric resistance elements. A typical 4.5-kW electric resistance element can reliably heat over 20 gallons of water per hour. The heat pump has a lower heating rate; General Electric, for example, publishes a rate of 8 gallons per hour at 68°F air temperature. This gap illustrates the benefit of a hybrid configuration – heat pumps are used when possible for highest efficiency, but resistance heat is used when there is high demand for hot water. Heaters with larger storage tanks generally revert to backup heating less often than lower-volume heaters.

Most HPWHs have several operating modes (manually adjustable by the users). The names of these modes differ by manufacturer, but most models include some combination of the operating modes listed below. More details of the operating modes of the units monitored in this study are given in Section 0.

- **Hybrid mode** is typically the default mode. Under this mode, the water heater uses both the electric resistance element(s) and the heat pump to meet demand, but prioritizes heat pump operation whenever possible to maximize efficiency.
- **Heat pump mode** uses only the heat pump. This improves efficiency, but dramatically reduces the recovery capacity of the water heater. If occupants use a large volume hot water in a short period of time, they may run out of hot water, as it will take longer to heat more water.
- **Electric resistance mode** works like a traditional ERWH. This mode can be used if there is a problem with the heat pump or when cooling effects from the heat pump are undesired .

2.2 Measuring Water Heater Performance

Domestic hot water appliances must be able to supply hot water as efficiently as possible while providing an adequate amount of water to the occupants. In order to quantify the performance of residential electric water heaters, the United States Department of Energy (DOE) has defined two performance metrics, energy factor (EF) and first hour rating (FHR).[1] Key specifications, including EF and FHR, for several HPWHs on the market today are shown in Table 2.

Table 2. Key Specifications of Some Integrated HPWHs Currently Available in the US Market.[2]

Model	Capacity (gal)	Energy Factor	First Hour Rating (gal)	Electric Resistance Elements (kW)
GE GeoSpring™	50	2.35	63.0	Upper: 4.5 Lower: 4.5
AO Smith Voltex®	60 / 80	2.33	68.0 / 84.0	Upper: 4.5 Lower: 2.0
Stiebel Eltron Accelera®300	80	2.51	78.6	Upper: 1.7 Lower: None
Rheem EcoSense	40 / 50	2.00	56.0 / 67.0	Upper: 2.0 Lower: 2.0
AirGenerate AirTap™ Integrated	50 / 66	2.39 / 2.40	60.0 / 75.0	Upper: 4.0

The energy factor represents the efficiency of the electric heating elements and tank losses under a consistent, 24-hour test procedure. In this procedure, 64.3 gallons of water are drawn from the tank in six equal draws spaced one hour apart. The temperature of the drawn water must be 135±5˚F and the ambient temperature is 67.5˚F. The energy factor is simply the ratio of energy output to energy input during the test procedure (Burch and Erickson 2004; Federal Register 1998).

The first hour rating represents the amount of hot water that can be supplied by a fully heated storage water heater during an hour of operation. First hour rating is measured using a standard test whereby water is withdrawn from the water heating storage tank until the outlet temperature drops 25°F below the initial water outlet temperature. Successive water draws occur after a specified heating device shuts off. Storage tank volume is often used as a proxy for water heating capacity, but first hour rating is the preferred metric.

3 Prior Research

While HPWHs are not new, past products designed for the residential market have achieved minimal market share. Commercialized HPWHs date back to the 1950s, when the Hotpoint Company (now a division of General Electric) began development on the first mass-market HPWH. Unfortunately, declining electricity rates reduced the appeal for the unit, and development of the unit was halted. During the mid-1970s, the emerging energy crises prompted greater interest in the technology, and by the mid-1980s, new HPWHs were available in the market (Calm 1984). Unfortunately, these new models failed to gain widespread adoption, primarily because past products were produced by smaller, niche-market manufacturers, encountered reliability issues, and/or operated with limited market infrastructure (Ashdown et al. 2004).

[1] Recovery efficiency (RE) is also used to quantify the efficiency of natural gas, fuel oil, and propane water heaters. Recovery efficiency is an approximate metric of the burn efficiency of the heating device. Since electric resistance elements have an efficiency of 1, RE is not tested or reported.
[2] Any omission of a manufacturer or product is unintentional, and no endorsement of any commercial product or manufacturer is implied.

Although HPWHs were first commercialized in the 1980s, they were typically add-ons to existing ERWHs, which required specialized knowledge for installation and often required both an HVAC contractor and a plumber to install the system. The development of drop-in, also referred to as integrated, HPWHs allowed for easy installation by a single trade (Tomlinson 2002). Steven Winter Associates, Inc. (SWA) has been researching the performance and control logic of HPWHs for the past decade, beginning with the an evaluation of ECR International's WatterSaver™ HPWHs for Connecticut Light & Power (CL&P) , a division of Northeast Utilities, SWA has continued to monitor the development of this technology ever since.

3.1 Previous Studies

Recent studies have investigated the efficiency of recent HPWH products. In the early 2000s, SWA conducted an evaluation of a new HPWH product, as discussed in Section 3.1.1. Laboratory testing of the most recent group of HPWH products has been conducted by EPRI and NREL, as discussed in Sections 3.1.2 and 3.1.3. EPRI is also conducting extensive field testing of HPWHs, but the data collected in this study is not readily available. Other studies have attempted to evaluate the cost effectiveness of HPWHs compared to other water heating technologies, but these studies do not directly address the in-field performance of HPWHs.

3.1.1 WatterSaver™ HPWH Evaluation

Late in 2002, SWA partnered with Connecticut Light & Power (CL&P) to install and evaluate the performance of the WatterSaver™ HPWH, an early drop-in replacement unit. Unlike most previous HPWH products, the WatterSaver™ was a stand-alone appliance – not a retrofit to existing ERWHs. This was the commercialized product version of a system developed at Oak Ridge National Laboratory (ORNL).

The CL&P-funded project consisted of finding twenty volunteers in CL&P's territory using traditional ERWHs, replacing the ERWHs with HPWHs, monitoring the performance for several months, and conducting surveys with home residents on the performance of the systems. SWA installed detailed monitoring systems to determine the efficiency of the HPWH systems (effective COP), the effectiveness of the systems (adequate temperature and quantity of hot water), and the dehumidifying potential of the systems. The average, effective coefficient of performance (COP) of the WatterSaver™ units was 1.67 (effective COP was calculated as thermal energy delivered to domestic water divided by total electric energy consumed).

Customer satisfaction was fairly high with many participants noting the dehumidification benefits. However, the study also identified some consistent drawbacks with the daily operation of the systems. Many customers complained about excessively hot water, and SWA's monitoring indeed showed water temperatures near the tops of the tanks often exceeding 150°F. These high temperatures were partly due to excessive tank stratification – water temperatures near the top could be 50°F higher than temperatures near the bottom – and in many systems the high-temperature safety switches shut down the water heaters completely (these were designed to shut down the system when temperatures reached 170°F). Ultimately, the WatterSaver™ was removed from the market because of identified problems with installed performance and a non-existent service infrastructure.

3.1.2 EPRI Laboratory Tests

Recently, the Electric Power Research Institute (EPRI) performed laboratory tests to investigate the performance of the recently released HPWHs by A.O. Smith, GE, and Rheem (Amarnath et al. 2010). These tests investigated the response of these models to modified versions of the DOE standard test procedure (Federal Register 1998). To determine EFs for a system installed with the factory defaults, the standard test was performed with each model at its default setpoint. An ERWH was tested as the control system. Furthermore, the standard test was performed on an A.O. Smith unit under varying inlet and outlet temperatures.

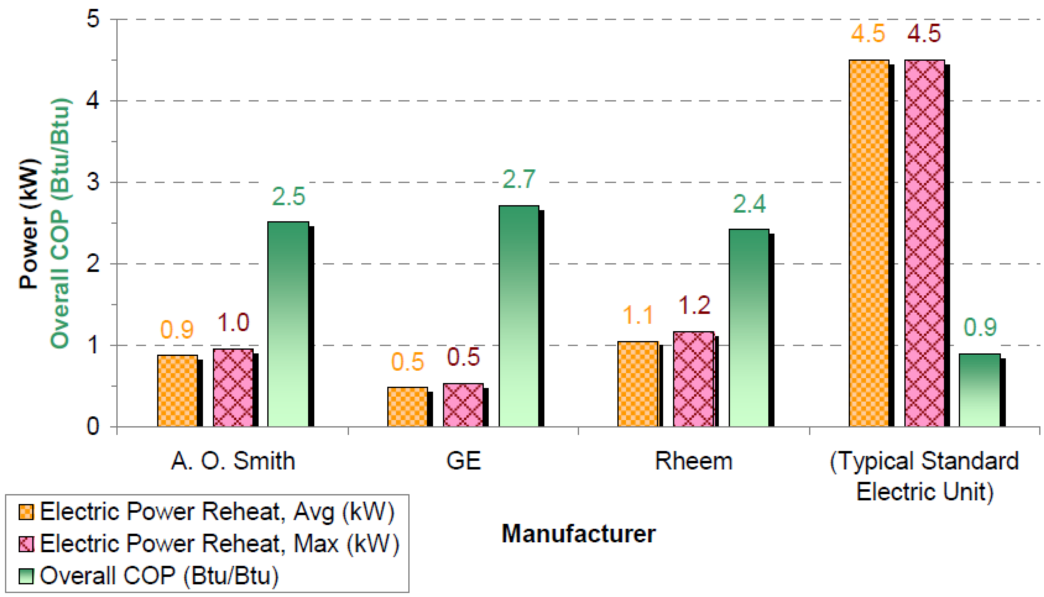

Figure 2. Draw test average and maximum power, and overall COP (Amarnath et al. 2010).

EPRI found COPs for the A.O. Smith, GE, and Rheem models to be 2.5, 2.7, and 2.4, respectively, when subjected to the standard test at default setpoint (Figure 2). The HPWHs were over twice as efficient as ERWHs, and peak loads were reduced to a quarter of ERWH peak loads. Tests over varying inlet and outlet water temperatures were performed on the A.O. Smith model. EPRI determined that COPs fell with both increasing inlet temperature (from 2.30 at 52°F to 2.12 at 67°F) and increasing outlet temperature (from 2.51 at 121°F to 2.22 at 135°F).

3.1.3 NREL Laboratory Testing

The National Renewable Energy Laboratory (NREL) performed laboratory testing of the five integrated HPWHs listed in Table 2. The five HPWHs were tested under five types of tests to isolate different aspects of the operation of the unit: (1) operating mode tests; (2) modified DOE tests; (3) draw profile tests; (4) heat pump COP tests; and (5) reduced air flow tests. The operating mode tests were performed to identify differences in performance between the available operating modes, which are described in Section 2.1. The modified DOE tests were performed under the standard setpoint of 135°F as well as under setpoints of 130°F and 140°F. The draw profile tests were performed under a constant flow draw profile and a more realistic draw profile. Heat pump performance was monitored under various dry bulb temperatures and relative humilities to create a performance map of the heat pump efficiency (see Figure 3). Air flow tests were performed to identify how reduced airflows affect performance (Sparn et al. 2011).

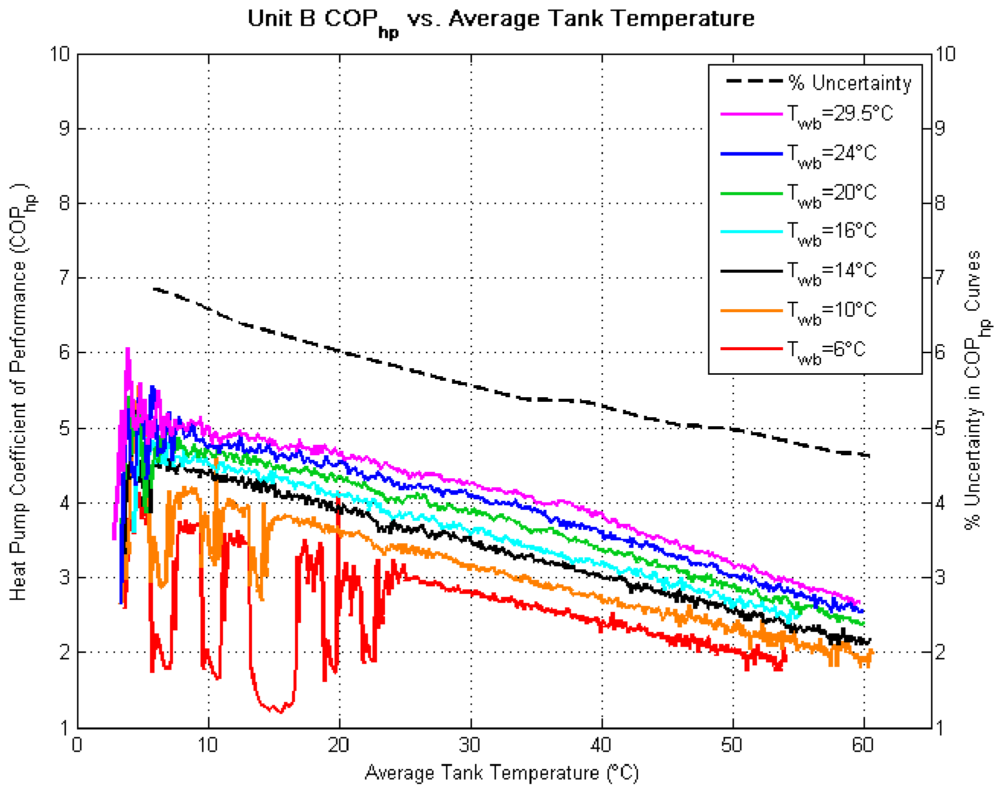

Figure 3. General Electric HPWH heat pump COP (Sparn et al. 2011).

3.1.4 Recent Cost-Benefit Studies

A 2009 Pacific Gas and Electric Company HPWH study (PGEC 2009) concluded that, in terms of source energy efficiency, a HPWH was more efficient (67%) than a standard natural gas (57%) or electric (29%) tank water heater when the HVAC interaction of the HPWH is ignored. If the HVAC interaction is included, then HPWHs are significantly more efficient (104%) than both standard systems in the cooling season and less efficient (44%) than natural gas tank water heaters in the heating season.

According to a 2010 life-cycle cost analysis paper (Franco et al. 2010) by Lawrence Berkeley National Laboratory (LBNL), HPWHs have the lowest life cycle cost for electric water heating technology in roughly half of all single-family residential homes (67% in the Northeast, 44% in the Midwest, 53% in the South, and 60% in the West). This study assumed that some houses would need venting for successful HPWH installation, and as a result, many older homes could not install HPWHs cost effectively. Furthermore, there was a greater cost benefit of HPWHs in new, single-family homes.

A 2012 NREL study (Hudon et al. 2012) modeled HPWH performance against gas and electric water heaters in six cities in the United States. Heat pump water heaters were found to save source energy compared to traditional electric water heaters regardless of climate and location of the unit (i.e. whether located in conditioned or unconditioned space). Savings over natural gas depended on climate and location of the unit.

4 Model Operation and Control Logic

All three manufacturers were contacted to obtain information about the operation of these units. Information from the manufacturers reveals that the control logic differs substantially between models.

The General Electric and AO Smith tanks have two electric resistance (upper and lower) elements in addition to the heat pump and operate in several modes, while the Stiebel Eltron unit has only one mode of operation and uses a small upper element to supplement the heat pump .

4.1 General Electric

The General Electric model has two 4,500 W electric resistance elements, one placed at the top and on placed at the bottom of the unit. The unit can operate under five operating modes, Hybrid, eHeat™, Standard Electric, High Demand Mode, and Vacation Mode.

Hybrid Mode is the default operating mode. Generally, this mode uses only the heat pump, but may use the electric resistance elements under the following conditions:

1. The ambient air temperature is outside the safe operating range (45°F – 120°F)
2. The water in the tank is significantly lower than the setpoint. The difference between the tank temperature and the setpoint depends on the circumstances, but is generally between 25°F and 30˚F. In this case, the upper element will operate.
3. The system senses that the water usage is too high, generally 25 to 30 gallons within a short time period. In this case, the lower element will operate.

eHeat™ Mode only uses the heat pump, unless the ambient temperature is outside the safe operating range. This mode is more efficient, but may fail to provide water at the setpoint.

Standard Electric Mode operates like a traditional electric resistance tank. The upper element will be used first to heat the top of the tank, and then the lower element will be used to heat the bottom of the tank.

High Demand Mode is similar to the Hybrid Mode, but with lower thresholds for criteria 2 and 3.

Vacation Mode is similar to eHeat™ Mode, but with a temperature setpoint of 50°F.

4.2 AO Smith

The AO Smith model has two electric resistance elements, a 4,500 W upper element and a 2,000W lower element. The AO Smith model has four operating modes, Hybrid Mode, Efficiency Mode, Electric Mode, and Vacation Mode.

Unlike the Hybrid Mode of the GE model, which uses a complicated algorithm to regulate the heat pump and electric resistance elements, the **Hybrid Mode** of the AO Smith model uses a simple temperature algorithm. If the average tank temperature (average of upper and lower thermostats) drops 9°F below the setpoint, the heat pump will be turned on to heat the water back to the setpoint. If however, the heat pump fails to heat the water sufficiently, and the average tank temperature drops more than 20°F below the setpoint, the upper element will replace the heat pump as the heating source. The lower element is not used in hybrid mode

Efficiency Mode does not use the electric resistance elements, unless the ambient temperature is outside safe operating range (45°F - 109°F) of the heat pump.

Electric Mode operates like a traditional electric resistance tank. The upper element will be used first to heat the top of the tank, and then the lower element will be used to heat the bottom of the tank.

Vacation Mode is identical to the efficiency mode with a setpoint of 60°F.

4.3 Stiebel Eltron

The Stiebel Eltron has one 1,690 W electric resistance element installed vertically at the top of the tank, and operates under a fixed operation mode. The heat pump is turned on when the temperature 16 inches from the top of the internal tank drops more than 4°F below the setpoint. If the heat pump cannot meet the demand, and the temperature at the top of the tank drops below 112°F, the upper element is used as a backup heat source. The upper element will only heat the top third of the water heater tank (approximately 27 gallons). The Stiebel Eltron unit is the only unit that allows simultaneous operation of the heat pump and booster resistance heater.

5 Experiment

5.1 Research Questions

This evaluation of heat pump water heaters provides valuable information for consumers and builders on efficient methods to provide electric water heating. In addition, this information could be used as validation by utilities and other program implementers throughout the United States attempting to develop incentive programs for this technology. While this study is primarily applicable to the colder Northeast climate, the results provided by this study can serve as a worst case performance for the country as a whole. Even though additional field evaluation is needed due to the small sample size of the evaluation, some clear answers were evident and similar results are being seen in other on-going field testing across the country.

This research effort provided answers to the following questions regarding the efficiency, reliability, and performance of each model:

- What are the critical criteria of the installation to assure that the installed efficiency of the heat pump water heater meets expectations? What specific installation conditions should be avoided?
- What information do homeowners need to understand whether this technology is right for them and, if they have one, what do they need to know to achieve and maintain efficient operation?
- What is the expected efficiency of a HPWH located in unfinished basements of cold climate homes?
- How do ambient temperature, temperature set point, inlet water temperature, and hot water demand affect the performance of each HPWH model?
- Does each model evaluated in this study effectively deliver hot water at the setpoint temperature?
- Are homeowners satisfied with hot water delivery, efficiency, noise, and other characteristics?

5.2 Technical Approach

Long term performance data was collected at 14 sites in Massachusetts and Rhode Island in the service districts of National Grid, NSTAR, and Cape Light Compact. Measurements were taken for a minimum of 12 months at all sites to establish the efficiency and performance of each unit. These measurements included water temperatures, flow rates, and electrical usage. Sensors were sampled at five second intervals and output at 15 minute intervals in the form of averages, minimums, and/or maximums over the time period. An additional data table captures the duration and volume of each hot water draw.

5.3 Measurements

At each of the sites, the following HPWH parameters were measured every 5 seconds:

- Inlet Water Temperature [°F]
- Outlet Water Temperature [°F]
- Inlet Air Temperature [°F]
- Inlet Air Relative Humidity [%]
- Hot Water Flow [gals]
- Compressor Energy Consumption [Wh]
- Heating Element Energy Consumption [Wh]
- Entire System Energy Consumption [Wh], not including condensate pump.

Based upon the measured parameters, the following data were calculated for each 15 minute logging period:

- Average Water Inlet Temperature [°F]
- Average Water Outlet Temperature [°F]
- Minimum Water Inlet Temperature [°F]
- Maximum Water Outlet Temperature [°F]
- Average Inlet Air Temperature [°F]
- Average Inlet Air Relative Humidity [%]
- Total Domestic Hot Water Usage [gals]
- Domestic Hot Water Energy [Btu]
- Total Compressor Only Energy Consumption [Wh]
- Total Upper Heating Element Energy Consumption [Wh]
- Total Lower Heating Element Energy Consumption [Wh]
- Total System Energy Consumption [Wh], not including condensate pump
- Total Heat Pump Energy [Wh]
- Total Standby Energy Consumption [Wh]
- Start and End of Each Hot Water Draw [time stamp]

In addition to daily sums, averages, min, and/or max of the 15-min data, the coefficient of performance was calculated on a daily basis. Since the energy factor is defined under the specific test conditions outlined in Section 2.2, for a unit that operates under real-world conditions or conditions different than the standard test, the coefficient of performance (COP) was the term used here to describe the efficiency of the unit under the measured conditions. Like EF, COP is the unit-less ratio of energy output to energy input during its operation.

5.4 Equipment

A datalogger and various sensors (see Table 3) were required to measure the system variables proposed above in Section 5.3. A Campbell-Scientific CR-1000 datalogger was used at each site to take measurements every five seconds and output data every fifteen minutes. A wireless modem was used for the remote downloading of data for evaluation throughout the monitoring period. The datalogger, modem, and other support equipment were installed in a fiberglass enclosure.

Figure 4. Example of a HPWH monitoring system installation.

Thermistors were used for all temperature measurements. HPWH cold water inlet and hot water outlet water temperature were measured using an Omega tubular immersion sensor with a 4-1/2" probe length and NPT threads. These were installed directly in the water flow by the HPWH installer. For domestic hot water flow Omega FTB4607 low flow (0.22 – 20 GPM), turbine-type flow meters were used. A SeaMetrics SPX-100 low flow (0.5 – 40 GPM), turbine-type flow meter was used at Site 13 as an alternate measuring device. All flow meters was installed by the HPWH installer and located on the cold water inlet side.

Air temperature and relative humidity in the space surrounding the HPWH were measured by a Humirel HTM2500 Temperature and Relative Humidity Probe located to minimize heat transfer from radiation, surrounding equipment, etc. All electrical energy consumption measurements used a Continental Control Systems WattNode and right-sized current transformers. The transducer was a true-RMS, AC, watt-hour transducer with pulse-output.

Table 3. Necessary Equipment

Measurement	Equipment Needed
Record and output measurements	Campbell-Scientific CR-1000 datalogger in a GE NEMA 4X fiberglass enclosure.
Inlet and outlet water temperatures	Omega tubular immersion sensor
Inlet and lower tank temperature	Omega fast response, exposed element sensors
Inlet air temperature and relative humidity	Humirel HTM2500 temperature and relative humidity probe
Inlet water flow	Omega low flow, turbine-type flow meter and/or SeaMetrics SPX-100
Compressor energy, heating element energy, and system energy	Continental Control Systems WattNode

5.5 Analysis

Data collected on site were compiled in separate Excel spreadsheets for each site. Spreadsheet summary tables include the following information: (1) Participant ID, (2) # of Days Monitored, (3) Water Usage, (4) Inlet Temperature, (5) Outlet Temperature, (6) Low Element Energy, (7) High Element Energy, (8) Heat Pump Compressor Energy, (9) HPWH Total Energy Usage, (10) Ambient Air Temperature, (11) Ambient Air Relative Humidity, (12) HPWH COP, and (13) % of Electric Consumption from Electric Resistance (this was the % of total electric kWh that was used by resistance, not the thermal energy fraction provided by electric resistance).

The Coefficient of Performance (COP) has been defined differently in numerous studies (AIL Research 2001, AIL Research 2002, ORNL 2002, Zogg 2002). For this evaluation the standard definition of COP, which is the net heat delivered to the hot water system divided by the total electrical energy consumed over a period of time, is being presented.

$$COP = \frac{useful\ heating\ energy}{net\ energy\ input} = \frac{Q_{DHW}}{W_{DHW} \times 3.413\ \ Btu/Wh}$$

where:

COP	= coefficient of performance (dimensionless)
Q_{DHW}	= useful heat energy (Btu)
W_{DHW}	= energy consumed by the HPWH (Wh)

The water heating energy (Q_{DHW}) was calculated by the datalogger every five seconds using measured data. These energy values were summed and logged at 15 minute intervals.

$$Q_{DHW} = (\Delta T_{T_{Out}-T_{In}} \times \dot{V} \times C_p \times \rho)$$

where:

$\Delta T_{T_{Out}-T_{In}}$	= T_{Out} minus T_{In} (°F)
$\dot{V}$	= hot water volumetric flow rate (ft^3/hr)
C_p	= specific heat of water (Btu/lbm ·°F)
ρ	= density of water (lbm/ft^3)

6 Installation Issues

As noted in the introduction, these hybrid heat pump water heaters are new to the mainstream market. As a result, installation is not as straight forward as a traditional electric resistance water heater. Heat pumps require special attention to air flow around the unit and condensate collection. Furthermore, to improve the efficiency of the units, AO Smith and Stiebel Eltron manufacture models substantially larger than typical resistance tanks. Installers may not be familiar with these units or heat pump models in general, and it may be difficult to install these units in existing homes. During installation we noted specific challenges faced by the installer at the various sites.

6.1 Clearances and Weight

The AO Smith 80 gallon and Stiebel Eltron units are much larger than traditional electric resistance tanks. As a result, the weight and height of the units may not allow for installation in existing spaces. The Stiebel Eltron Accelera 300 80-gallon HPWH is a large unit. Its diameter is 25.98" and maximum height is 74.92", not including the additional 16" of clear space above the unit that is required for maintenance and servicing. The total required installation height is 7'-7", and the wet weight is 950 lb. The 7'-7" required installation height is fast approaching the traditional 8' ceiling height.

Figure 5. Clearance can be an issue with larger HPWHs.

The 80-gallon A.O. Smith HPWH is similarly large. Although the unit was located in a roomy basement, had plenty of clearance, it could not be placed on blocks. Adding four inches to its 81.5" height would have raised it to within a few inches of some overhead PVC plumbing (Figure 6). However, smart installation potentially would have allowed the unit to be moved a small amount to prevent the potential plumbing interference while providing extra space for the use of blocks.

The extra weight of the Stiebel Eltron and AO Smith units may pose additional problems. One of the two Stiebel Eltron sites, a small, two-family home required that the floor be reinforced to handle the nearly ½-ton unit weight before it could be installed. The unobstructed area above this unit appeared to be in line with factory requirements (not verified) but physically accessing it was a bit challenging due to miscellaneous plumbing and wiring runs on the perimeter of the clear space.

In addition to the extra required clearances for these large units, HPWHs require extra clearances around the unit to allow proper air circulation to the heat pump. The A.O. Smith Installation Manual states that: "For optimal efficiency and serviceability, the following clearances should be maintained: 3 feet on the air inlet side, 5 feet on the air outlet side, 6 inches in the back, and 2 feet in the front." The 60-gallon site fell a bit short on the outlet air clearance recommendation, coming in at an estimated 2.5' to 3' (Figure 6). The output air was directed towards a concrete basement wall (Figure 7).

Figure 6. This HPWH was installed with proper clearances for ambient air circulation.

Extra clearances for service may also be required. The GE installation manual recommends a 7” air space clearance with a 5.5” minimum clearance between any object and both front and rear covers in order to be able to remove the covers if service is required. Also, a 14” minimum clearance is required in order to remove the filter for cleaning. This filter clearance requirement forces hot and cold water pluming as well as electrical connections to be routed so as not to prevent filter removal. Although these may provide issues in some situations, all sites tested in this report complied with the extra clearance requirements for servicing.

Figure 7. This HPWH was improperly installed resulting in the outlet air being directed into a wall.

6.2 Mixing Valves and Heat-Traps

The Stiebel Eltron unit is not equipped with homeowner-adjustable controls and comes with the hot water temperature factory set at 140°F. This high setpoint temperature means that a mixing valve must be installed to reduce the risk of scalding. The installer at one site did not include a mixing valve as part of the original installation, and a return visit was required to install a mixing valve. Stiebel Eltron's installation manual does show a mixing valve as part of the system installation and notes that it is an installer supplied item.

Figure 8. Example of a mixing valve installed downstream of the HPWH.

Both GE and A.O. Smith installation manuals address heat traps as part of the plumbing on the hot water outlet and both show pictures of this. However, only the GE installation manual addresses a heat trap for the cold water inlet side. Of the 14 sites visited, approximately half had heat traps plumbed into the hot water outlet and five had heat traps plumbed into the cold water inlet. A fair amount of thermosiphoning, especially on the cold water inlet plumbing, was noticed on all units without heat traps.

Figure 9. (left) HPWH without heat traps, (right) HPWH with heat traps.

6.3 Drain Pans

Drain pans are used to capture overflow due to condensate pump failure, piping failure, and condensate line obstructions, etc. Both A.O. Smith and Stiebel Eltron call for the use of drain pans in their installation manuals, while GE states that drain pan use must conform to local codes. Given the low cost, all HPWHs should have a drain pan installed. Concrete blocks are often used to raise the bottom of the unit above the lip of the drain pan or at the very least to get it off of the floor to prevent the bottom of the unit from resting in water should a leak occur (Figure 10). This prevents rusting of the bottom.

Because HPWHs are relatively new on to the mainstream market, the installers may not be aware of the need for drain pans. We observed the installation of these units at our test sites to look at the typical installer practice. Both Stiebel Eltron HPWHs were placed on concrete blocks, 4” thick at one site, approximately 2” thick at the second site. Despite the installation of concrete blocks, both of these units lacked a drain pan. The 80-gallon A.O. Smith unit was installed in a drain pan but was not placed on blocks, likely because of its height, while the 60-gallon unit was both on blocks and in a drain pan. Of the ten GE units, three were both on blocks and in drain pans, two were in drain pans but not on blocks, two were on blocks but not in drain pans and three were sitting directly on the floor without blocks or drain pans.

Figure 10. Drain pans need to be installed as a precautionary measure.

One pan-only site had experienced a major condensate draining issue, the result of an improperly pitched condensate line which failed to drain (Figure 10). The drain pan was full and the bottom 2.5” of the HPWH was sitting in water. Until we noticed the issue, the homeowner was unaware of the problem. Once called, the installer quickly corrected the problem. Also, this site had no condensate pump.

All 14 HPWHs observed were located on the lowest level of the home, meaning that damage to lower levels due to catastrophic leakage was not a concern.

6.4 Condensate Pumps

Eleven of the 14 sites used condensate pumps. Of those, one was cleverly installed in the drain pan along with the HPWH, which was also on blocks.

Figure 11. Example of a condensate pump located in the drain pan.

6.5 Locations

A HPWH's efficiency is affected by the temperature of its inlet air. Cooler air reduces efficiency, warmer air increases efficiency. Some units were located in cool to cold unconditioned basements. All 14 HPWHs replaced older, less efficient water heaters, and given the existing plumbing and wiring, the HPWHs were placed in the original water heater's location which was sometimes suboptimal. Eight units were installed in basements, had good airflow, and saw reasonable ambient temperatures. Five units were installed such that the cool, dehumidified outlet air could potentially be confined to a small space by closing a door. One unit was located in a Massachusetts basement that, during its first winter, consistently saw inlet air temperatures of between 77°F - 81°F due to standby losses for a old boiler located next to the HWPH.

Three HPWHs were located in areas adjacent to finished living space. It is possible that these units could negatively impact the home's heating load due to the cool outlet air. Of these three HPWHs, one was located in a small mechanical room adjacent to a finished, basement bedroom. The occupant keeps the mechanical room's door closed during the heating season. This arrangement has the potential to simultaneously increase the home's heating load while reducing the efficiency of the HPWH. Another home had been built with a 4" diameter PVS pipe running from near the top of an interior wall in a room with a vaulted ceiling, directly down to the mechanical room. The occupants had redirected the pipe's exit to be as close as practical to the HPWH's inlet air grill. They were investigating the installation of an inline fan to help provide a constant warm air source for the HPWH which, they hoped, would increase the HPWH's efficiency. If the HPWH's efficiency does increase it will be interesting to see if that increase is a large enough gain to offset the cost of running the fan.

6.6 Filter Maintenance

If the HPWH has an air filter, the filter must be regularly cleaned to ensure that the unit runs at peak efficiency. In Figure 12, a HPWH with a dirty air filter is shown. Only a couple of the filters were found to be dirty during the removal of the monitoring equipment. On some units, the air filter is removed from the top of the unit, and therefore extra clearance must be provided to ensure that the unit's filter can be properly cleaned.

Figure 12. By rubbing a finger against this filter, the amount of dirt accumulation is evident.

6.7 Noise

Installing a HPWH in or near finished living space requires that noise be considered. The difference between tolerable and objectionable noise levels is subjective, but none of the 14 units installed appeared to be particularly noisy. Even though, a couple homeowners noticed the noise of the heat pump when in their basements, it was only an issue for one of the homeowners who had a home office in the room adjoining the basement mechanical room.

7 Results

Each site was monitored for over a year, and summary statistics for each site are shown in Table 5. Average COPs over the entire monitoring period were lower than the rated energy factor for all three models. The AO Smith and Stiebel Eltron models were only slightly lower than the rated energy factor, while the General Electric model showed a more pronounced difference between measured COP and rated energy factor. These results are influenced heavily on storage volumes and the ability to meet high demand over short periods with only heat pump recovery. While the AO Smith and Stiebel Eltron units used the heat pump to provide the vast majority of the load (approximately 95% of the total energy was consumed by the heat pump), the electric resistance elements in the GE units consumed almost one-third of the measured energy (excluding Site 5, where low ambient temperatures forced the unit into backup mode).

Table 4. Summary Statics of Performance by Model.

HPWH model	Capacity (gal)	Rated Energy Factor**	First Hour Rating (GPH)	Avg. COP	COP Range	% Electric Resistance
General Electric	50	2.35	63.0	1.82*/ 1.61	1.0-2.1	32.74%*/ 44.01%
AO Smith	60/80	2.33	68.0/84.0	2.12	2.1-2.1	5.60%
Stiebel Eltron	80	2.51	78.6	2.32	2.0-2.6	5.46%

*** Average COP calculation for the GE Units does not include Site 5 (cold air = high electric resistance usage)**
**** COP and EF are similar, except the EF is the ratio of heat output to energy input as measured *during a specific 24-hour test procedure*.**

While the two AO Smith units had remarkably similar COPs, the COPs of the Stiebel Eltron and General Electric units varied significantly between sites. The difference between the COPs of the Stiebel Eltron sites is largely attributable to the large difference between the average daily hot water draw at the two sites. The residents at Site 2 used an average of 73 gallons per day with a COP of 2.6, while the residents at Site 10 used an average of 41 gallons per day with a COP of 2.1. Larger hot water draw volumes will dilute the impact of tank thermal losses and elevate the COP of the unit. As a result, Site 2 has a COP slightly higher than the rated energy factor (which is measured at 64.3 gallons), and Site 10 has a COP lower than the COP at Site 2 and the energy factor. The differences between the measured COPs at the sites with General Electric units were significantly larger than those of the other units. With a smaller tank and a lower capacity heat pump, the GE model requires more electric resistance element heating to meet the required demand of the unit.

Table 5. Summary Table of Performance by Site.

Site	Sponsor	HPWH Model	Adults + Children	Water Heater Setpoint Temp (°F)	Days Moni-tored	Avg. Daily Hot Water Usage (gal)	Avg. Cold Water Temp. (°F)	Avg. Hot Water Temp. (°F)	% of Electric Consumption from Electric Resistance**	Avg. Air Temp. (°F)*	Avg. RH (%)*	Avg. Wet Bulb (°F)*	Total COP
1	National Grid - MA	AO Smith-80	2 + 1	120	454.0	44	54	119	0%	59	47%	49	2.1
2	National Grid - MA	Stiebel Eltron	5 + 0	140	437.8	73	57	136	8%	71	45%	58	2.6
3	National Grid - MA	GE	2 + 1	125	468.9	60	53	121	48%	64	38%	51	1.8
4	National Grid - MA	AO Smith-60	3 + 0	120	445.1	45	53	119	11%	63	56%	54	2.1
5	National Grid - RI	GE	2 + 0	129	459.5	64	52	127	78%	53	62%	46	1.0
6	National Grid - RI	GE	2 + 0	122	475.0	35	53	118	5%	62	55%	53	2.1
7	National Grid - RI	GE	2 + 0	125	450.0	23	58	123	11%	66	49%	55	1.8
8	National Grid - RI	GE	2 + 1	125	429.6	33	55	122	15%	66	44%	54	2.1
9	National Grid - RI	GE	2 + 2	120	468.4	41	55	122	22%	62	48%	52	2.0
10	National Grid - RI	Stiebel Eltron	2 + 0	140	423.8	41	57	138	2%	68	55%	58	2.0
11	NSTAR	GE	2 + 3	140	459.0	72	58	136	58%	76	34%	58	1.5
12	NSTAR	GE	2 + 1	130	491.6	42	56	128	29%	71	46%	58	1.9
13	Cape Light Compact	GE	2 + 0	130	387.7	32	59	126	15%	70	57%	60	1.4
14	Cape Light Compact	GE	2 + 0	120	433.2	32	53	119	15%	62	52%	52	1.9

***Average of Daily Averages**

***Electric resistance percentage = % of total electric kWh that was used by resistance NOT thermal energy fraction provided by electric resistance! Unfortunately, we cannot find the thermal energy fraction because we cannot accurately account for standby losses.**

8 Analysis

Analysis of the data collected during the year of monitoring uncovered the key variables the affect heat pump water heater performance and the differences between the operations of the different units. Across all models, ambient temperature, the volume of hot water draws, and the pattern of the hot water draws were the most important variables that affect water heater performance. Between units, however, these variables can have a different impact, particularly with regards to hot water usage and electric resistance element operation.

8.1 Water Usage

As discussed in the previous section, the smaller capacity GE units used the electric resistance elements to provide a much larger percentage of the needed energy than other models. As a result, the GE unit operated as a more fully hybrid water heater than the AO Smith and Stiebel Eltron models. Figure 13 shows seven days of operation at Site 9. These days are representative of typical operation across the sites. During day one and days three through six, the water draws from the tank were distributed throughout the day and therefore relatively small. As a result, the heat pump was able to provide the total amount of hot water drawn during the day. During day two and seven, the water draws were more concentrated and larger, and therefore the electric resistance elements were needed to provide additional hot water.

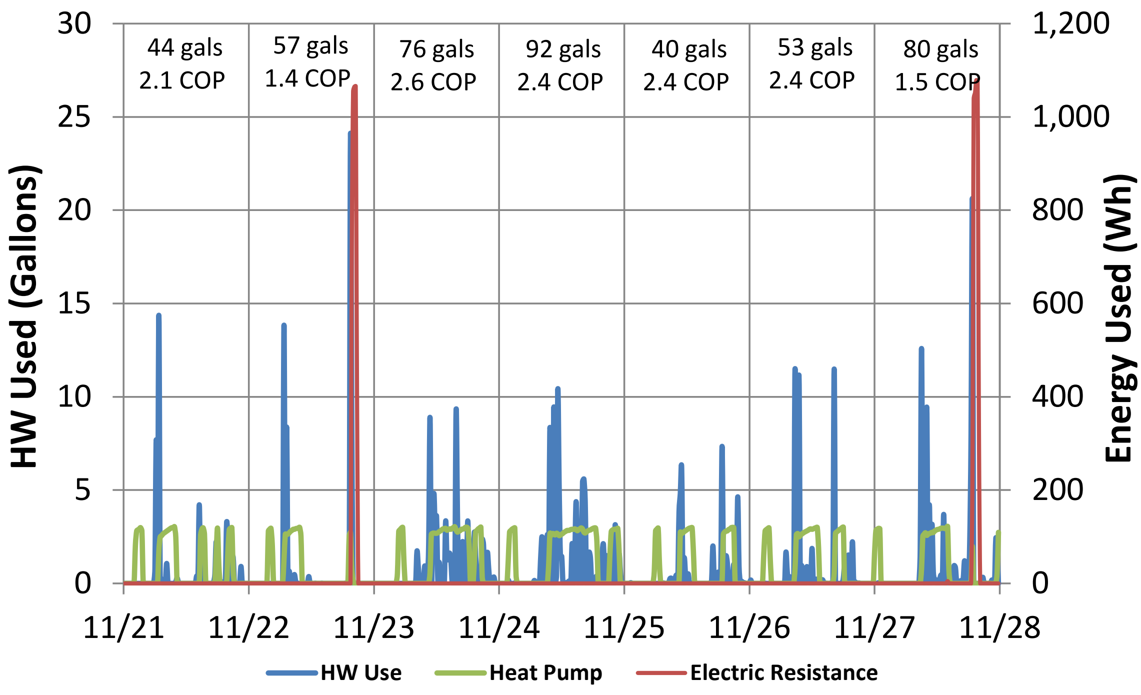

Figure 13. Ideal operation of the GE HPWH in hybrid mode.

While Figure 13 shows how large and concentrated draws can reduce the efficiency of the unit, low water usage can also reduce the efficiency of the unit, as shown in Figure 14. In this figure, although the heat pump was used to meet the entire hot water demand, the low daily draw volumes reduced the efficiency of the unit. In this case, the standby thermal losses from the tank accounted for a larger percentage of the total energy demand from the tank, reducing the efficiency of the unit.

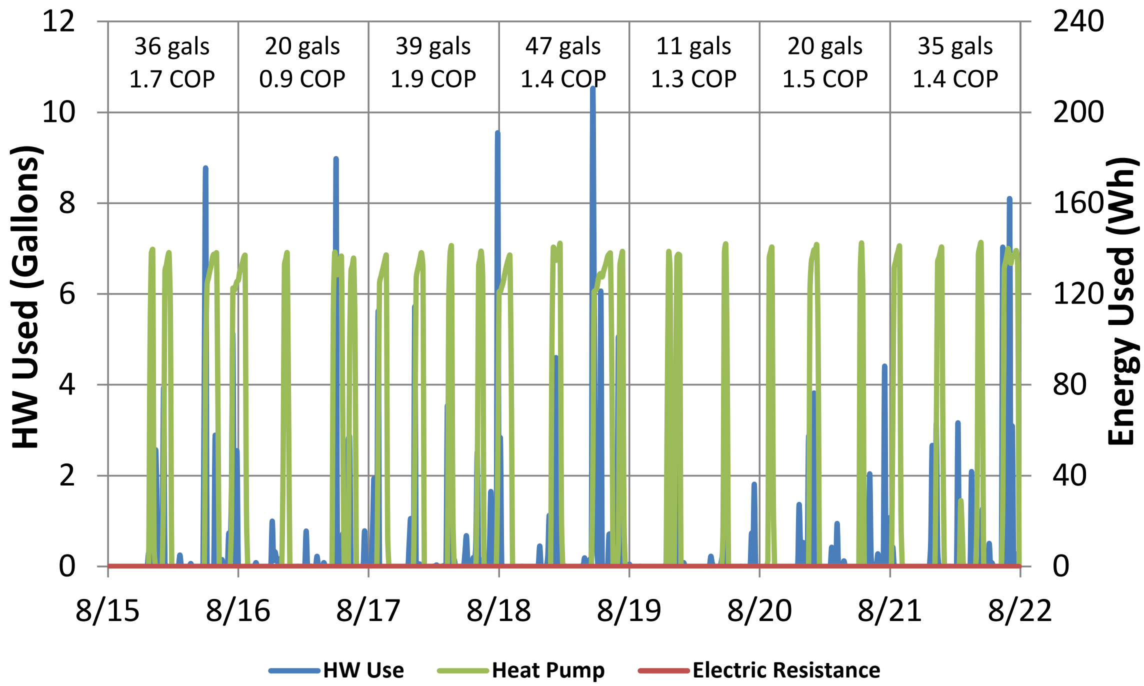

Figure 14. Low water use can reduce the overall benefit of a HPWH when assessing cost benefit.

8.2 Air Temperature

While Figure 13 describes the typical operation of the GE unit, other factors can affect how the unit behaves between sites. At Site 5, the HPWH was installed in a cold basement with ambient air temperatures dropping below 50°F from December through April, as shown in Figure 15. These temperatures are close to the cut-off temperature of the heat pump in the GE unit, and as a result, the HPWH at Site 5 operated like a traditional electric resistance water heater, as shown in Figure 16.

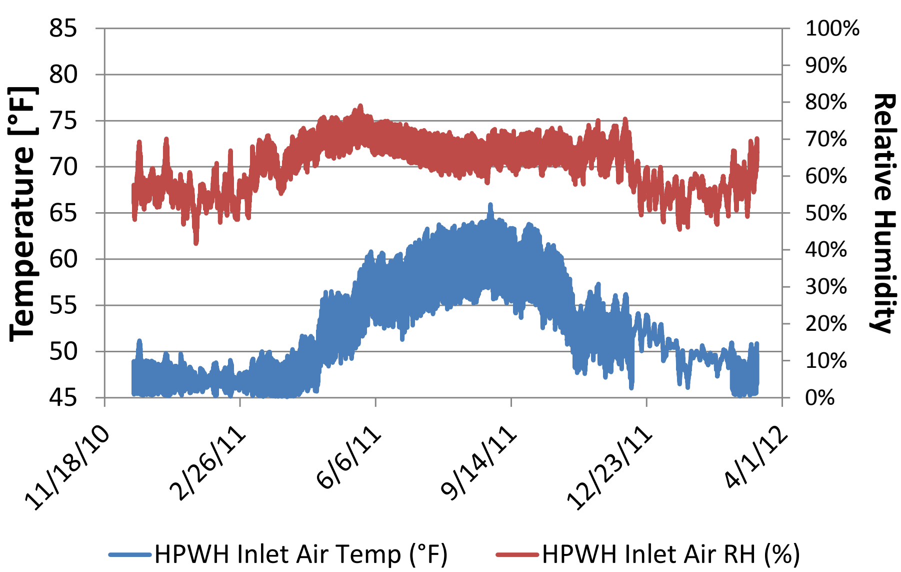

Figure 15. The ambient air temperatures at Site 5.

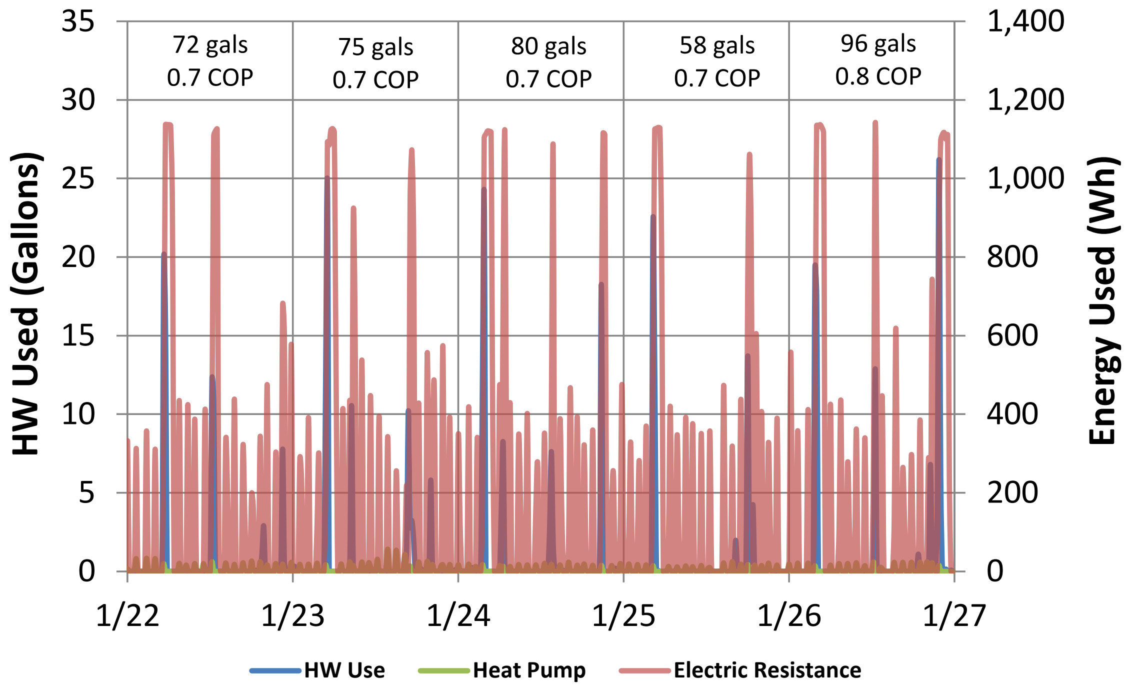

Figure 16. Due to the Site 5 basement being too cold, this GE HPWH switched primarily to electric resistance mode during the winter months.

At the other end of the spectrum, Site 11 experienced higher COPs during the winter months because the HPWH was placed in a boiler room (Figure 18) with ambient temperatures between 75 and 80°F (Figure 17). At the beginning of January, the unit was able to supply hot water in large quantities with COPs greater than the rated EF of 2.35, as shown in Figure 19. There were two days over this week of data in which high water use concentrations results in electric resistance operation to meet demand.

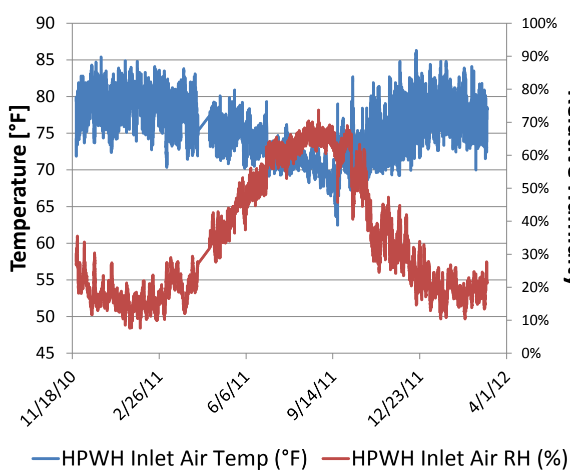

Figure 17. Ambient temperature at Site 11.

Figure 18. This HPWH benefited from the waste heat of the boiler used for space heating.

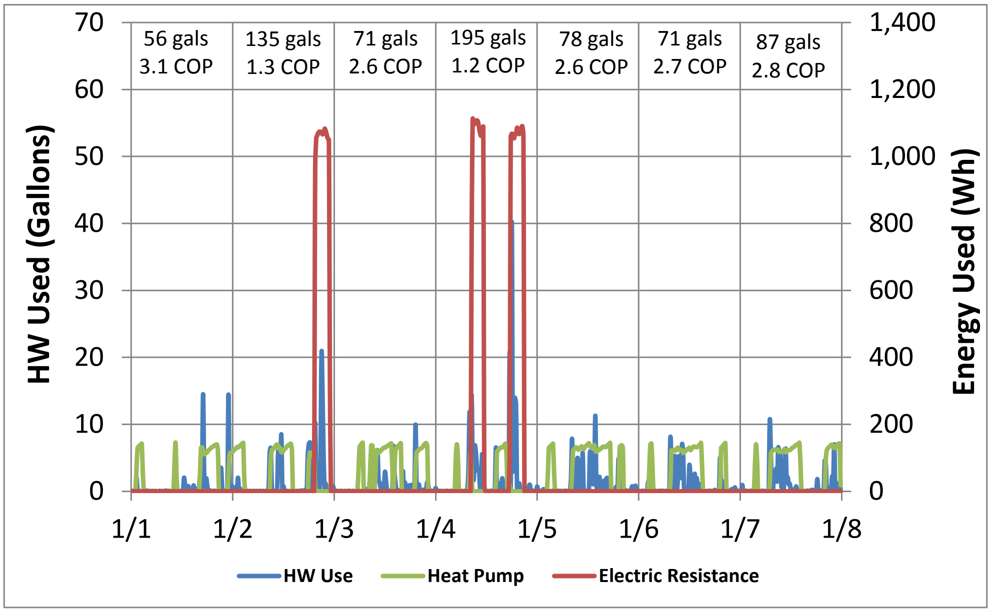

Figure 19. Typical winter performance of the GE HPWH in the Site 11 warm mechanical room.

8.3 Stiebel Eltron

Graphing of several days of high water use at a site with a Stiebel Eltron HPWH revealed that this unit is able to meet very large hot water demands at surprisingly high COPs, as shown in Figure 20. While the electric resistance element was needed to supply additional heating, the unit performed with COPs higher than 2.6 for the four days of large hot water usage. The Stiebel Eltron unit is distinguished from the other two models by its ability to simultaneously use the electric resistance and heat pump heating elements to provide heating. Furthermore, the water heater was able to deliver water temperatures in excess of 115°F during all four days of large hot water demand, as shown in Figure 21.

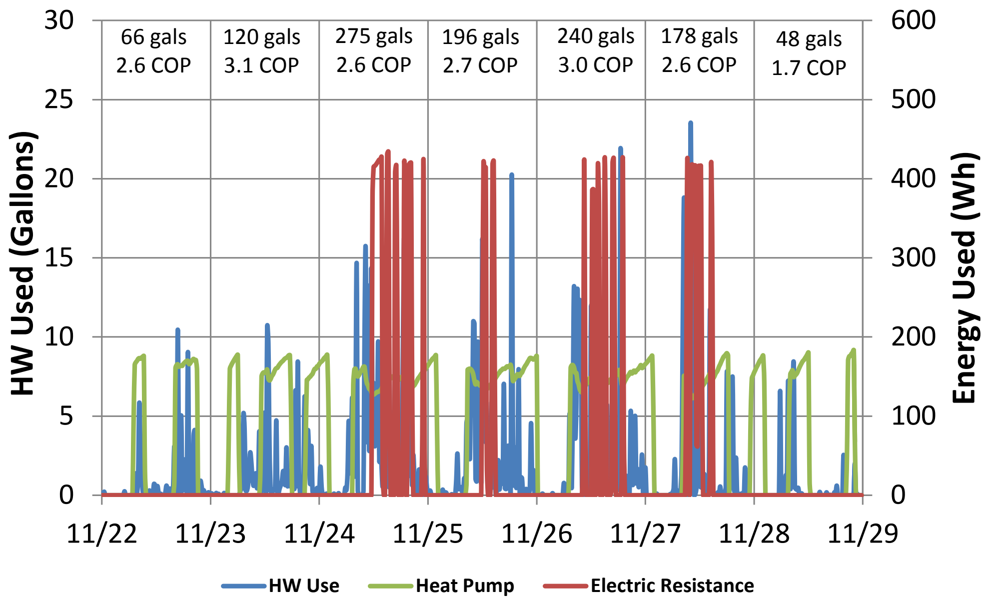

Figure 20. The Stiebel Eltron HPWH at Site 10 was able to achieve high COPs due to the simultaneous operation of the heat pump and electric resistance heater.

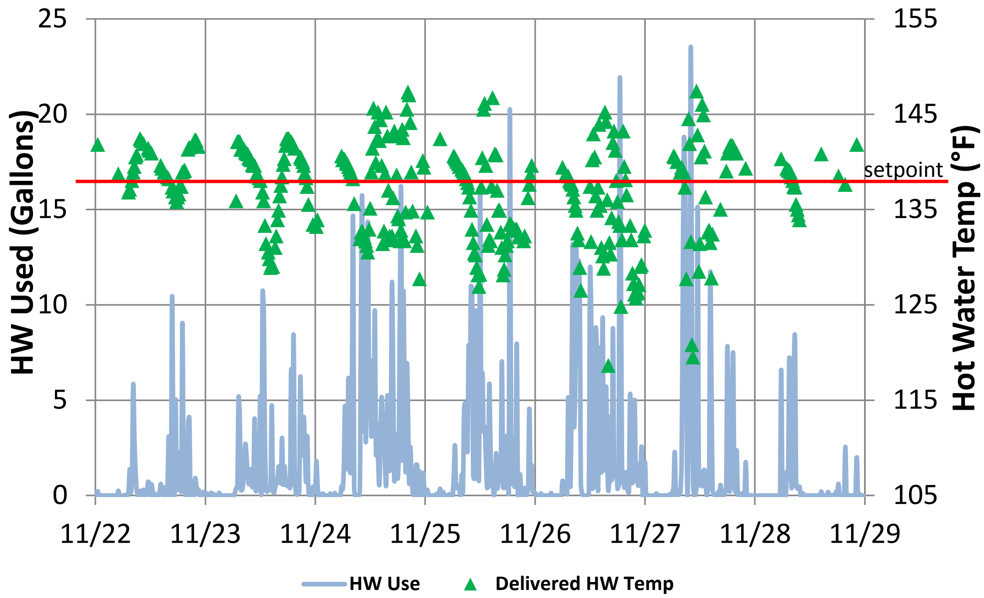

Figure 21. Even with this extreme water usage (period over Thanksgiving), the Stiebel Eltron HPWH at Site 10 was able to supply a hot water temperature of no less than 118°F.

8.4 AO Smith

As previously mentioned, the two AO Smith water heaters performed similarly and were exposed to similar operational variables, such as ambient temperature, ambient RH, setpoint temperature, and average daily hot water usage. Interestingly, the 80 gallon unit operated with no instances of electric resistance operation during the entire monitoring period. Provided in Figure 22 is sample data over one week that shows the typical operation of this particular unit.

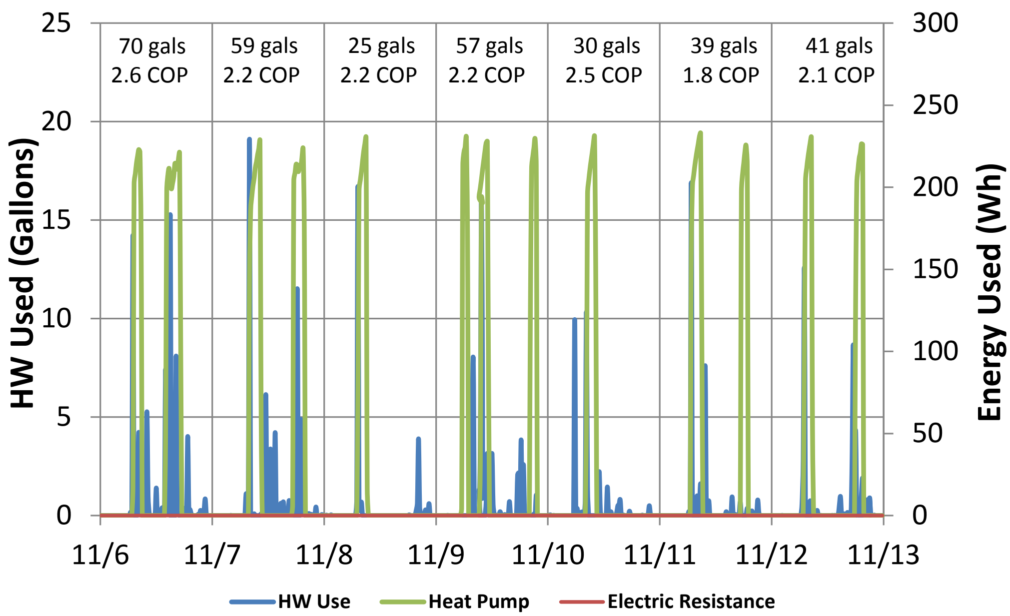

Figure 22. The AO Smith HPWH at Site 1 was able to provide all domestic water heating with heat pump mode only.

9 Cost and Energy Savings

When comparing energy use of water heaters using different fuels, EF or COP can be misleading because energy use is only measured at the home and does not include the cost of extraction, conversion, or transmission of the energy. Therefore, water heaters using different fuels should be compared using a different metric. While energy usage is usually measured in site energy, which is the energy used at the home and is typically measured at a utility meter in units of kWh (electricity), therms (natural gas), or gallons (fuel oil or propane), a better metric is cost to deliver each unit of water heating energy ($/delivered MMBTU).

Traditional ERWHs are an inefficient and expensive form of water heating. As shown in Table 6 , electric resistance water heating has the highest cost per MMBTU of delivered water thermal energy. HPWHs, on the other hand, have operating costs similar to natural gas storage water heaters. HPWHs are an excellent choice for homeowners who currently use an electric resistance, fuel oil, or propane water heater and do not have access to natural gas. Replacement of natural gas water heaters with HPWHs is not recommended in heating dominated climates because HPWHs will increase the load on the space heating system without a similar benefit to the space cooling system.

Table 6. Comparison of Water Heaters by Fuel Type.

Water Heater Type	Storage Tank	Fuel Cost	EF	$/Delivered MMBTU
Electric Resistance	Tank	$0.1768/kWh	0.90	$57.57
Heat Pump	Tank	$0.1768/kWh	2.00	$25.91
Fuel Oil	Tank	$3.33/gal	0.59	$40.70
Natural Gas	Tank	$1.6968/therm	0.59	$28.76
Natural Gas	Tankless	$1.6968/therm	0.82	$20.69
Condensing Natural Gas	Tankless	$1.6968/therm	0.94	$18.05
Propane	Tank	$3.50/gal	0.59	$64.48

Table 6 compares water heater costs and efficiencies based on rated values, not the monitored field data. Table 7 presents the cost savings for the HPWHs installed at the fourteen sites compared to modeled usage of electric resistance, fuel oil, natural gas, and propane water heaters using EPRI's WATSMPL 2.0 software or a simulation model based on TRNSYS. Daily mains temperature, setpoint temperature, water usage, and ambient temperatures were used in this model. Fuel costs were identical to those listed in Table 6. Red numbers in the table show negative cost savings over the comparison water heater.

Table 7. Utility Bill Savings for HPWHs over Various Fuel Types by Site.

Site	Electric Resistance (EF = 0.91)	Natural Gas (EF = 0.56, RE = 0.78)	Natural Gas (EF = 0.67, RE = 0.82)	Fuel Oil (EF = 0.56, RE = 0.78)	Fuel Oil (EF = 0.67, RE = 0.82)	Propane (EF = 0.56, RE = 0.78)	Propane (EF = 0.67, RE = 0.82)
1	$338	$107	$44	$239	$150	$506	$365
2	$714	$187	$107	$414	$301	$872	$693
3	$413	$51	$16	$221	$126	$563	$412
4	$351	$96	$36	$229	$144	$496	$362
5	$144	$238	$320	$40	$156	$358	$173
6	$305	$114	$54	$230	$144	$463	$327
7	$206	$89	$33	$180	$100	$363	$236
8	$290	$102	$43	$215	$131	$442	$309
9	$300	$71	$12	$192	$109	$437	$305
10	$365	$96	$23	$246	$142	$547	$383
11	$471	$30	$105	$189	$83	$630	$461
12	$339	$79	$17	$212	$126	$482	$345
13	$211	$28	$32	$140	$55	$365	$230
14	$252	$82	$25	$188	$107	$402	$273
Mean	**$336**	**$60**	**$6**	**$204**	**$112**	**$495**	**$348**

In nearly all cases with the exception of Site 5 (which operated more frequently in electric resistance more), a HPWH was a better option than other typical tank water heater types. In terms of operational cost of just the water heater, a HPWH is the preferable technology unless natural gas is available and either a tankless water heater (standard or condensing) or a high-efficiency condensing tank water heater (typically are rated at 95%+ thermal efficiency) is installed.

While HPWHs show cost savings over nearly all of the fuel types presented in Table 7, it needs to be noted that these calculations do not include the impact of the HPWH on the space conditioning systems. Since these units were installed in heating dominated climates, the HPWH negatively impacts the heating system load. As a result, the HPWHs may be less cost effective than the tank natural gas units. Other fuels will likely be more expensive to operate than the HPWH even when accounting for space conditioning interactions.

Since HPWHs are more expensive than traditional electric resistance water heaters, the cost effectiveness of these installations must include the greater incremental cost of HPWHs in the cost benefit calculations. Installed costs were estimated based on the customer costs through this evaluation report, as shown in Table 8. The installed costs are similar to those listed in the National Renewable Energy Laboratory's National Residential Efficiency Measures Database (NREMD), which are $2,100 and $3,300, respectively, for the small (50/60 gal) and large (80 gal) HPWHs. The prices of similarly sized electric resistance water heaters are $590 and $690, respectively, according to the NREMD

Table 8. Installed HPWH Cost Estimates from Study

	Small Tank (50-60 gal)	Large Tank (80 gal)
Unit	$1,399	$2,403
Extra Labor	$69	$69
Condensate Pump	$154	$154
Electric and Plumbing Permit	$100	$100
Breaker	-	$54
Tempering Valve	-	$142
Labor	$200-$400	$400-$600
Total	**$1,922-$2,122**	**$3,318-$3,518**

The cost effectiveness of replacing ERWHs with HPWHs was evaluated using three metrics: simple payback period (SPB), net present value (NPV), and modified internal rate of return (MIRR). This analysis assumed a 10 year lifetime for both water heaters and that the existing ERWH was at the end of its lifetime. The simple payback is simply the ratio of the annual utility bill savings to the total incremental installation cost.

Table 9. Cost Effectiveness of Replacing ERWHs with HPWHs.

Site	Annual Utility Bills Savings	Incremental HPWH Cost	Simple Payback (yrs)	Net Present Value	Modified Internal Rate of Return
1	$338	$2,610	7.7	$270	2.45%
2	$714	$2,610	3.7	$3,480	10.42%
3	$413	$1,510	3.7	$2,014	10.42%
4	$351	$1,510	4.3	$1,484	8.64%
5	$144	$1,510	10.5	$284	-0.65%
6	$305	$1,510	5.0	$1,093	7.13%
7	$206	$1,510	7.3	$245	2.98%
8	$290	$1,510	5.2	$963	6.58%
9	$300	$1,510	5.0	$1,051	6.95%
10	$365	$2,610	7.2	$501	3.25%
11	$471	$1,510	3.2	$2,505	11.87%
12	$339	$1,510	4.5	$1,383	8.26%
13	$211	$1,510	7.2	$290	3.24%
14	$252	$1,510	6.0	$639	5.09%
Max	**$714**	**$2,610**	**10.5**	**$3,480**	**11.87%**
Mean	**$336**	**$1,746**	**5.7**	**$1,117**	**6.19%**
Min	**$144**	**$1,510**	**3.2**	**$284**	**-0.65%**

The modified internal rate of return (MIRR) is an annualized rate of return calculation that takes into account the time value of money. For this analysis, the real discount rate was assumed to be 3%, and the finance and reinvestment rates for the cash flow were assumed to be equal to the real discount rate. The

SPB and MIRR at each site are shown in Table 9. All sites except Site 5 had a net present value greater than zero. It should be noted that cost-effectiveness in the Massachusetts efficiency program is done through the Total Resource Cost Test. The Technical Reference Manual will include those fuel types and sizes that are cost-effective for inclusion in the program and may vary slightly from the information presented here.

10 Peak Demand Reduction

In addition to yearly total energy savings, HPWHs also have the potential to considerably reduce peak electricity demand in the residential market. A site-by-site comparison of measured HPWH electricity consumption and modeled electric resistance water heater electricity consumption on an hourly basis is shown in Figure 23. In these graphs the mean electric usage (y-axis) of the sites by hour of the day (x-axis) is shown for both the monitored HPWH (in red) and the modeled electric resistance tank (in blue).

As expected, most water heating energy occurs during the morning and evening hours of the day. The largest load reduction attributable to the HPWH occurs during this period, suggesting that HPWHs are an effective method of peak load shaving. While HPWHs could possibly provide load shifting opportunities because the heating rate of the heat pump is lower, these graphs do not reveal a large load shift occurred at these sites.

While Figure 23 shows the site-by-site load reduction attributable to replacing ERWHs with HPWHs, a more robust method was used to investigate the effect of HPWH replacements on the seasonal load profiles of residential water heating energy use. Since electric peaks typically occur during the summer months, the effect of HPWHs on the summer peak power is important to analyze. To measure this impact, the data was split by season to create a mean water heating profile for each season of the year.

Hourly measured HPWH water heating loads and modeled ERWH loads for all sites were split by season and averaged to create a mean water heating profile for each season of the year. While more sites would be useful to reduce the impact of the uniqueness of each home's water patterns, this method created enough cases for each season to create a large number of observation points. This method essentially assumes that the water usage patterns and distribution of the water heater models installed in this study will be similar to the overall water usage patterns and model distribution of the region. As a result, this method is limited in its ability to accurately predict the impact of HPWHs on the load profile of the region. Furthermore, the impacts of space conditioning loads are ignored, which could have an impact on space cooling load profiles as well.

Figure 24 shows the mean hourly water heater consumption for ERWHs and HPWHs based on season. As in the site-by-site analysis, the largest magnitude reduction in water heater energy occurred during the morning and evening hours of the day. However, during all seasons, the period between 6am and 8pm experiences the similar percentage reductions in water heating energy use. During the summer months, when peak electricity consumption in the New England ISO occurs around 2pm,[3] HPWHs will reduce residential water heating energy consumption by nearly 70% during that period. However, since the peak loads are not coincident, the reduction in the total load during the peak period will be smaller than the evening and morning period. During the winter months, however, the peak load of the total system will be

[3] http://www.ferc.gov/market-oversight/mkt-electric/new-england/isone-archives.asp

coincident with the peak load of the water heating energy, and HPWHs will reduce total electricity demand to a greater extent

The winter peak period for the sponsors occurs during weekdays December through January between 5pm and 7pm. The summer peak period occurs during weekdays June through August between 1pm and 5pm. The mean demand savings of these HPWHs over ERWHs was 374.12 W and 174.75 W, respectively for the winter and summer peak periods.

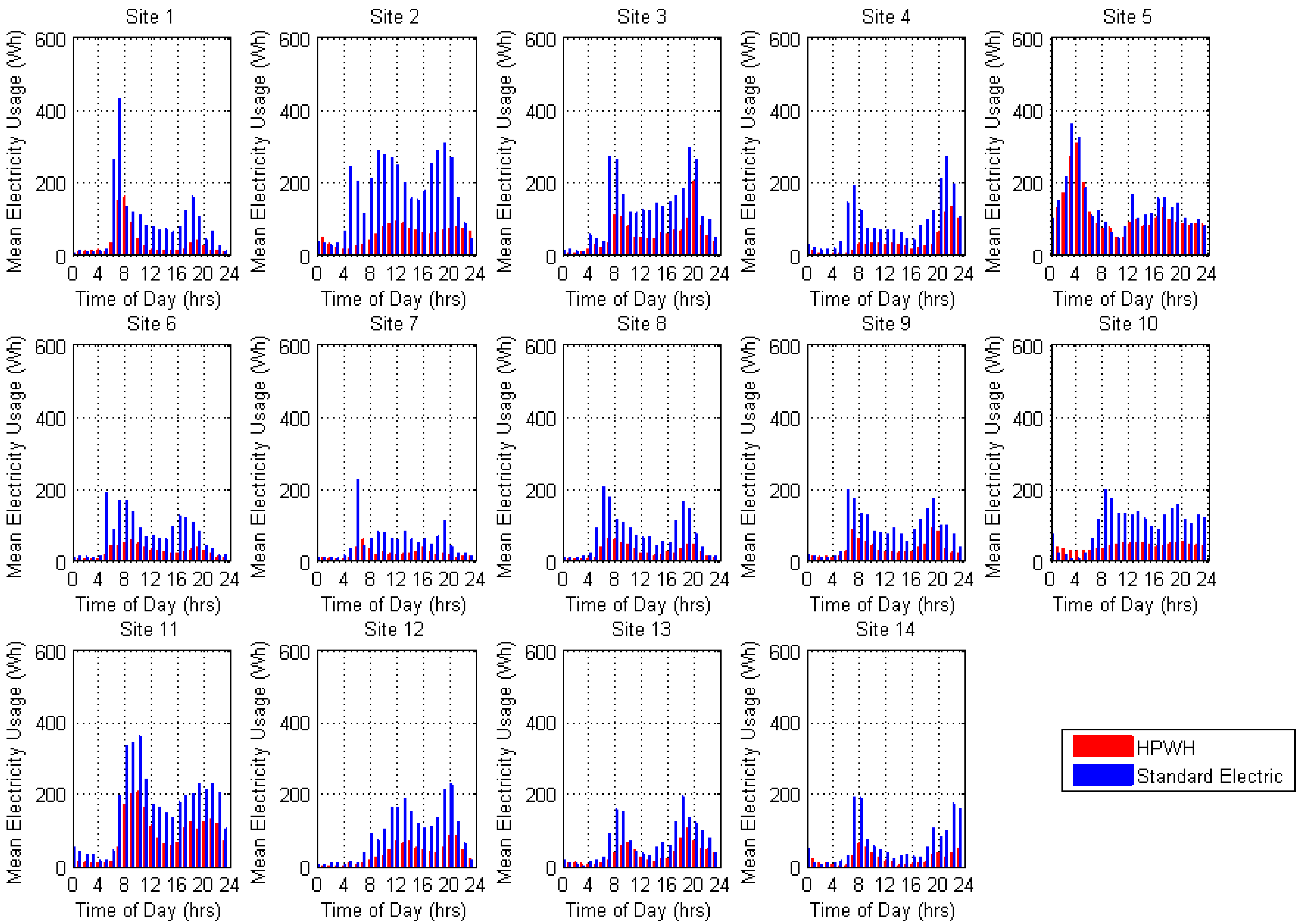

Figure 23. Measured HPWH and modeled traditional electric water heater electricity consumption by hour and site.

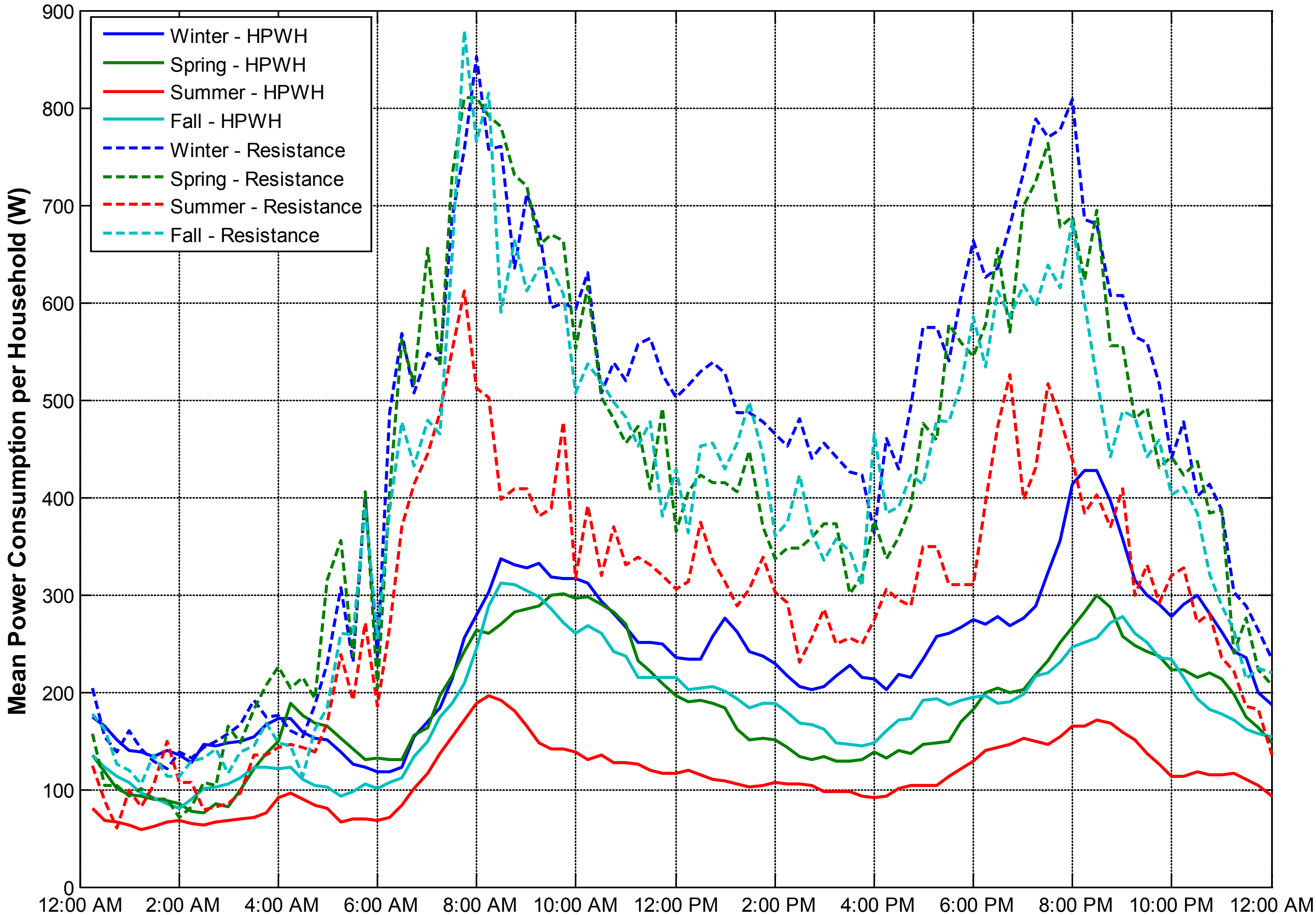

Figure 24. Seasonal load profiles of HPWH and traditional electric resistance water heater.

11 Standby Losses

Tank losses to the ambient are an important contributor to tank inefficiency. Unfortunately, tank losses are hard to quantify, and thermal losses could not be measured directly. Instead of measuring thermal losses, the electricity required to return a tank to the setpoint temperature after an idle period was estimated.

To measure the electric power necessary to recover from standby losses, idle periods followed by heat pump operation with no hot water demand were identified from the 15 minute data. These periods satisfied the following conditions:

1. No draw over the period
2. Period begins with the termination of heating (lower element is excluded)
3. Period ends with the termination of a heat pump operation.
4. The overall period must be over 3 hours.
5. Noise (<1W) in the upper element is ignored.

The losses are calculated as the energy input by the heat pump divided by the total idle period (including heating period). The energy delivered to the water tank was estimated using the performance model described in Section 0. While there was enough data for the GE models to analyze the tank standby losses, the data available for the other two models were insufficient to calculate the overall heat transfer coefficient of these tanks.

$$Q_{s\tan dby} = UA\left(T_{setpo\mathrm{int}} - T_{ambient}\right)$$

The standby losses of the tank are determined by the equation above, where UA is the overall heat transfer rate of the tank in BTU/hr-°F. By plotting the standby losses against the difference between the setpoint and ambient temperature, the UA of the tank can be calculated. A linear regression was performed to find a UA of 5.31 BTU/hr-°F. The R^2 was 0.782, which means that 78.2% of the scatter in the model was explained by the equation above. Assuming a setpoint temperature of 120°F and an ambient temperature of 67.5°F the UA of the tank equals approximately 716 kWh of additional thermal energy demand.

A plot of the data and method described above is shown in Figure 25. Each scatter point represents a period of standby recovery, which was identified using the method described above. Each scatter point is colored by the site at which the recovery occurred. The regression line is shown in blue, and the equation and R^2 values are shown on the graph. There is a clear trend, as expected, between tank standby losses and the ambient temperature of the space in which the HPWHs are located.

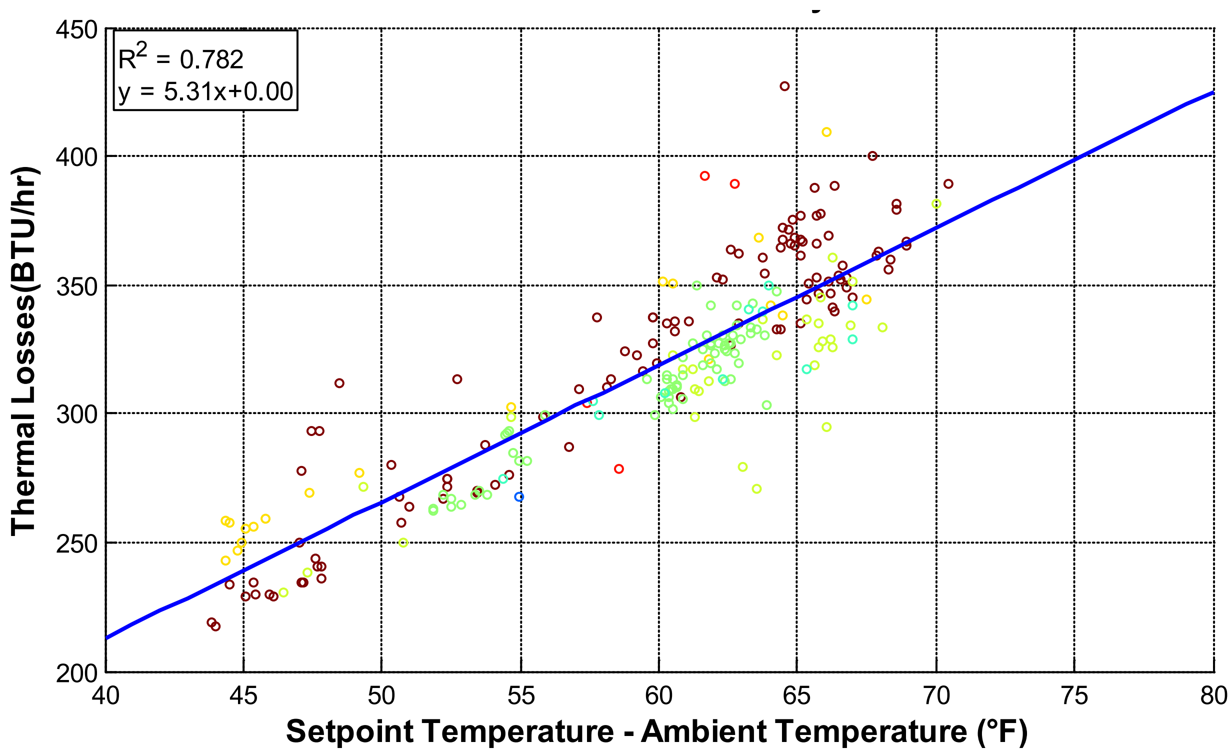

Figure 25. Standby Losses for General Electric Units.

12 Performance Model

A non-linear regression model was used to predict the daily performance of the heat pump water heaters under idealized conditions where there was no electric resistance operation. Four input variables were considered as major factors affecting HPWH performance: (1) ambient dry bulb temperature; (2) volume of water; (3) setpoint temperature; and (4) water mains temperature. The relationship between these variables for the General Electric unit is shown in Figure 26 through Figure 28. Other units have similar relationships between these four variables.

Domestic hot water demand has the largest influence on total COP of the unit because larger hot water loads reduce the influence of tank losses on the COP of the unit. Higher ambient temperatures increase the efficiency of the heat pump and reduce total tank losses. Higher mains temperatures decrease the efficiency of the unit by decreasing the temperature difference across the heat pump heat exchanger, but the overall energy usage is increased by lower mains temperatures because more energy is needed to heat the water to setpoint. Higher setpoint temperatures decrease the efficiency of the unit by increasing tank losses.

These plots provide useful information about the efficiency of the water heater under idealized conditions where there is no electric resistance usage. These plots, however, may be misleading about the efficiency of the unit under typical operation. For example, while idealized efficiency increases with hot water usage, real-world efficiency will decrease at some point because the electric resistance elements will operate more frequently.

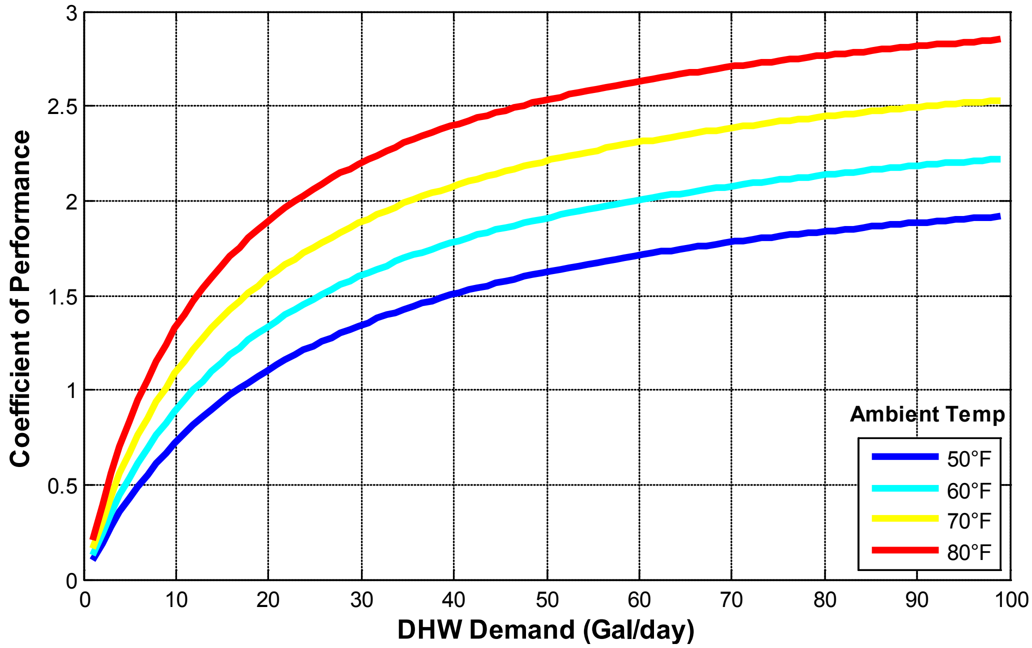

Figure 26. Idealized coefficient of performance for heat pump only mode of the GE HPWH by DHW demand and ambient temperature.

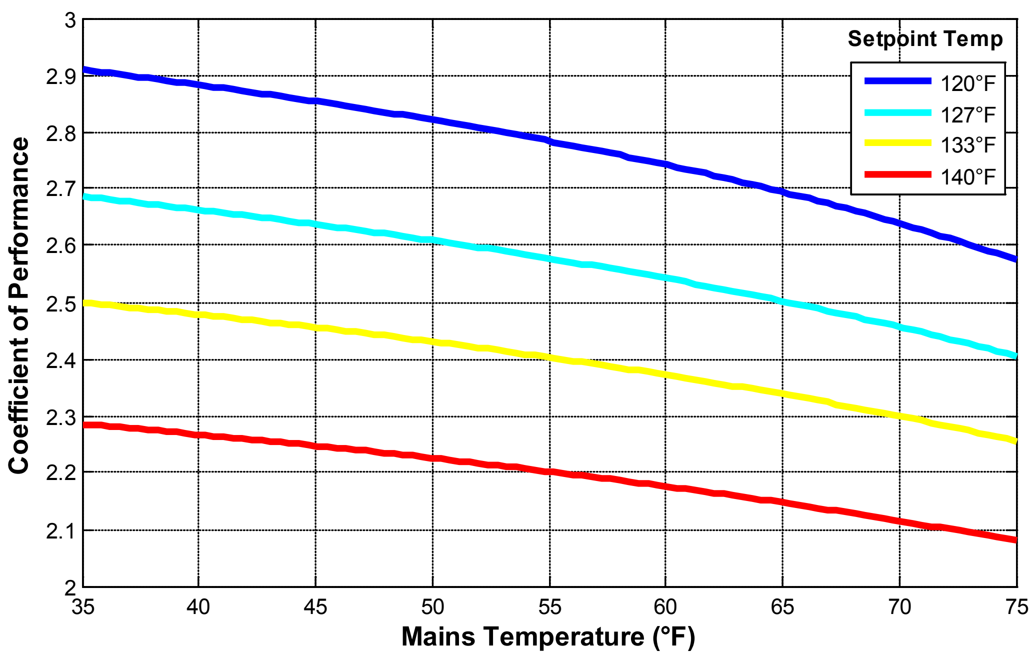

Figure 27. Idealized coefficient of performance for heat pump only mode of the GE HPWH by mains and setpoint temperatures.

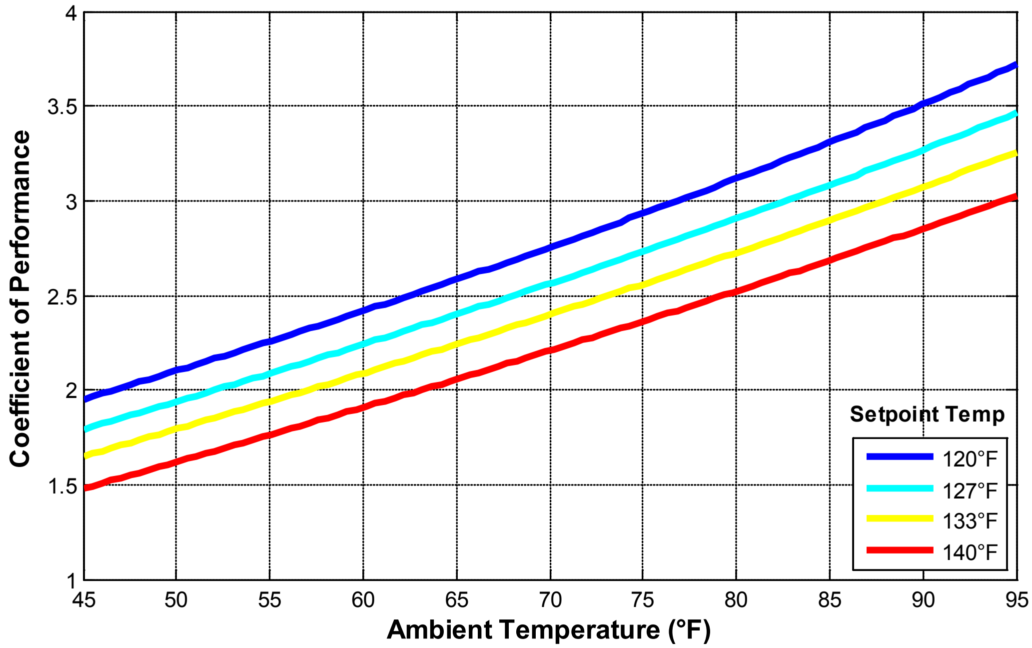

Figure 28. Idealized coefficient of performance for heat pump only mode of the GE HPWH by ambient and setpoint temperatures.

13 Customer Surveys

After complete monitoring of the HPWHs, residents at the 14 sites were surveyed about their satisfaction with the HPWHs. All of the homeowners were satisfied with the HPWH. The majority (70%) noticed cooling and/or dehumidification. Some noted that noise was an issue (18%). Some homeowners experienced running out of water (36%), though these were isolated incidences and weren't a significant concern to the homeowners. The vast majority (73%) noticed lower utility bills. One "No" response was that the homeowner switched from oil and did not know how to do the cost comparison. Another "No" response was that the homeowner was not sure if the savings were a result of HPWH or lower electric rate (the savings were indeed due to the HPWH). Detailed survey results are shown in Table 10 and Table 11.

Table 10. Survey Results of Homeowners (The Ideal Response is Highlighted in Green).

	GE		AO		SE		All	
	Y	N	Y	N	Y	N	Y	N
Have you ever run out of hot water?	4	4	0	1	0	2	4	7
Has the water been hot enough?	8	0	1	0	2	0	11	0
Have you noticed a difference in your energy bills since the water heater was installed?	6	2	1	0	1	1	8	3
Have you noticed the water heater cooling and/or dehumidifying the space?	6	2	0	1	1	0	7	3
Has the water heater's operating noise been a problem?	1	7	0	1	1	1	2	9
Has this water heater changed how you use hot water?	2	6	0	1	0	2	2	9
Are you satisfied with your HPWH's performance?	8	0	1	0	2	0	11	0
Have you read your HPWH's manual?	6	2	1	0	1	1	8	3
Do you know how to change the settings on your HPWH?	7	1	1	0	0	0	8	1
Have you ever changed the settings of the water heater?	5	3	1	0	0	2	6	5
Do you know what operating mode your HPWH is set to?	5	2	1	0	0	0	6	2
Has the water heater required servicing?	1	7	0	1	2	0	3	8

Table 11. Survey Results of Whether the Homeowner or a Qualified Professional Performed any Preventive Maintenance Procedures (The Ideal Response is Highlighted in Green, It was not Expected that the Questions Highlighted in Gray Would be Addressed as these Units have not been Installed Long Enough to Warranty this Level of Maintenance).

	GE		AO		SE		All	
	Y	N	Y	N	Y	N	Y	N
Testing the Temperature & Pressure-Relief Valve?	0	8	0	1	0	2	0	11
Flushing and/or draining the tank?	0	8	0	1	0	2	0	11
Periodically inspecting and clearing the condensate strainer and drain lines?	5	3	1	0	0	2	6	5
Visually inspecting the surrounding floor area, or the drain pan for signs of water leakage?	3	5	1	0	2	0	6	5
Cleaning the air filter?	4	3	1	0	0	0	5	3
Cleaning the evaporator?	0	8	0	1	0	2	0	11
Checking the condition of the sacrificial anode rod?	0	8	0	1	0	2	0	11
Checking and descaling the heating elements?	0	8	0	1	0	2	0	11
Would you encourage a friend or family member to buy the same water heater?	8	0	1	0	1	1	**10**	1

14 Conclusion

Though a small sample set, the overall performance of these 14 HPWHs has been enlightening and show great promise for this technology. To date, there has only been one instance in which a compressor for a HPWH unit had to be replaced. It is unclear as to the cause of this failure. No other major issues have been identified regarding durability and reliability of these units, but this is something that will need to be followed up as these systems age.

This evaluation was successful in answering the initial research questions asked at the start of this field monitoring project:

- What are the critical criteria of the installation to assure that the installed efficiency of the heat pump water heater meets expectations? What specific installation conditions should be avoided?
    - Several of these issues have been discussed in this report and include ambient air temperature/relative humidity and water usage (overall consumption and concentration of draws).

- HPWHs should not be seen as a direct size-for-size replacement of an electric resistance tank water heater. Although general sizing guidelines will allow HPWHs to provide adequate hot water, the HPWH may rely on auxiliary electric resistance elements to meet the load at significantly lower efficiencies than advertised by the energy factor test. As a result, sizing requirements for HPWHs to meet optimal efficiency are significantly different due to their lower recovery rates. As a general rule for HPWHs, size big (80 gals) and set high (140°F temperature set point with a tempering valve downstream). This will enable the HPWH to meet hot water demand while minimizing reliance on electric resistance back-up heat. The efficiency benefits of the heat pump will typically exceed the energy penalty of maintaining a higher set point and the standby loss of having the larger tank.
- This topic is further discussed in a Selection and Quality Installation Guide for HPWHs that SWA worked on with the Sponsors of this evaluation for use in their rebate programs.

- What information do homeowners need to understand whether this technology is right for them and, if they have one, what do they need to know to achieve and maintain efficient operation?
    - As mentioned above, homeowners need to aware that these integrated HPWHs often are not a direct size-for-size replacement for existing water heaters due to their lower heat recovery rates. Although HPWHs can meet hot water loads of the same size as an equally sized electric resistance water heater, the HPWH may rely on electric resistance elements to the detriment of efficiency.
    - Key points are that manufacturer's minimum space requirements need to be adhered to and depending on air conditions in the water heater location, expectations of the efficiency performance of these units need to be adjusted.
    - To ensure proper operation of a HPWH, filters need to be cleaned regularly, condensate drains need to be checked periodically, and water should be drained to flush the tank of potential sediment deposits per manufacturer's specifications.
    - Based on the findings from this research effort, SWA worked with the Sponsors on a tri-fold brochure to educate homeowners on HPWHs.

- What is the expected efficiency of a HPWH located in unfinished basements of cold climate homes?
    - In general, these HPWHs were more than twice as efficient as a traditional electric resistance tank water heater.

HPWH model	Capacity (gal)	Rated Energy Factor**	Avg. COP	COP Range
General Electric	50	2.35	1.82*/ 1.61	1.0-2.1
AO Smith	60/80	2.33	2.12	2.1-2.1
Stiebel Eltron	80	2.51	2.32	2.0-2.6

    - Overall efficiency is dependent on ambient temperature/relative humidity, mains temperature, hot water setpoint temperature, and water usage (consumption and concentration). Sizing and location of the HPWH in these test homes was not specified by SWA prior to monitoring, the HPWHs were installed based on preference of the homeowner and the size of the existing water heater. Three of the units did not meet the manufacturer's minimum volume recommendations, two of the units did not provide a proper air stream path from the heat pump exhaust air, and several of the HPWHs were undersized based on daily consumption averages for the household.

- How do ambient temperature, temperature setpoint, inlet water temperature, and hot water demand affect the performance of each HPWH model?
    - Higher ambient temperature improves the amount of energy that the heat pump can extract and transfer to the domestic water.
    - Higher hot water temperature setpoint reduces overall efficiency of the heat pump mode, but can increase the efficiency of the overall unit in hybrid mode as the heat pump will have a longer time to recover rather than switching to electric resistance mode to meet demand
    - Higher mains temperatures decrease the efficiency of the unit by decreasing the temperature difference across the heat pump heat exchanger, but the overall energy usage is increased by lower mains temperatures because more energy is needed to heat the water to setpoint.
    - Hot water demand has a large impact on whether the HPWH runs in heat pump mode or electric resistance mode during recovery from hot water events. The use of low-flow faucets/showers and the spacing of hot water events throughout a day will improve system performance.

- Does each model evaluated in this study effectively deliver hot water at the setpoint temperature?
    - Four of the test sites noted instances of running out of hot water. In discussions with the homeowners, these instances were rare. These homeowners did not believe that this was an issue with the HPWH, but rather a result of unusually high hot water demands. All of these sites happened to be the smaller 50 gal GE units. Based on the daily hot water consumption of these test sites, a larger HPWH should have been installed.

- Are homeowners satisfied with hot water delivery, efficiency, noise, and other characteristics?
    - 10 out of the 11 survey respondents said that they would recommend a HPWH to a friend or family member. One homeowner had issue with the noise of the HPWH as they had a home office in the room adjoining the basement mechanical room.

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Appendix A: Comparison of Water Heater Energy Use

Table 12. Comparison of Monitored HPWH Energy Use Vs. Other Water Heating Technologies.

Site	HPWH (Monitored) (kWh)	Electric Resistance (EF = 0.91) (kWh)	Fuel Oil (EF = 0.56, RE = 0.78) (gal)	Fuel Oil (EF = 0.67, RE = 0.82) (gal)	Natural Gas (EF = 0.56, RE = 0.78) (therms)	Natural Gas (EF = 0.67, RE = 0.82) (therms)	Propane (EF = 0.56, RE = 0.78) (gal)	Propane (EF = 0.67, RE = 0.82) (gal)
1	1,493	3,868	169	135	234	188	894	718
2	2,447	7,290	279	238	387	331	1,479	1,263
3	2,599	5,600	223	187	309	259	1,182	989
4	1,545	3,966	166	135	230	187	878	714
5	5,080	6,103	255	211	353	292	1,349	1,116
6	1,213	3,459	154	121	214	168	817	641
7	906	2,340	115	85	159	118	607	451
8	1,126	3,056	136	106	188	147	719	563
9	1,608	3,787	159	128	221	177	845	676
10	1,738	4,133	178	142	247	197	943	752
11	3,961	7,309	282	242	390	335	1,492	1,280
12	1,858	4,442	185	150	256	207	978	793
13	1,447	2,715	121	94	168	131	643	500
14	1,164	2,855	129	100	179	139	683	529
Mean	**2,013**	**4,352**	**182**	**148**	**253**	**205**	**965**	**785**