U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Field Performance of Heat Pump Water Heaters in the Northeast

Carl Shapiro and Srikanth Puttagunta
Consortium for Advanced Residential Buildings

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Golden, CO 80401

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Prepared by:

Carl Shapiro and Srikanth Puttagunta

Steven Winter Associates, Inc.

of the

Consortium for Advanced Residential Buildings

61 Washington Street

Norwalk, CT 06854

NREL Technical Monitor: Cheryn Metzger

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

Btu	British Thermal Unit
CO_2	Carbon Dioxide
COP	Coefficient of Performance
EF	energy factor
EPRI	Electric Power Research Institute
ERWH	Electric resistance water heater
FHR	First Hour Rating
ft	Foot
gal	Gallon
GE	General Electric
GPD	Gallons per Day
in.	inch
kW	Kilowatt
kWh	Kilowatt-Hour
lbm	Pound Mass
MBtu	Million British Thermal Units
HPWH	Heat Pump Water Heater
quad	Quadrillion British Thermal Units
SWA	Steven Winter Associates, Inc.
therm	100,000 British Thermal Units
Wh	Watt-Hour

Executive Summary

Heat pump water heaters (HPWHs) are finally entering the mainstream residential water heater market. Possible catalysts are increased consumer demand for more energy-efficient electric water heating and a new federal water-heating standard that effectively mandates the use of HPWHs for electric storage water heaters with nominal capacities higher than 55 gal. Compared to electric resistance water heaters (ERWHs), the energy and cost savings potential of HPWHs is tremendous. Converting all ERWHs to HPWHs could save American consumers $7.8 billion annually ($182 per household) in water heater operating costs and cut annual residential source energy consumption for water heating by 0.70 quads.

Steven Winter Associates, Inc., a partner of the U.S. Department of Energy's Building America research team Consortium for Advanced Residential Buildings, embarked on one of the first in situ studies of these newly released HPWH products through a partnership with two sponsoring electric utility companies, National Grid and NSTAR, and one sponsoring energy-efficiency service program administrator, Cape Light Compact. Recent laboratory studies have measured the performance of HPWHs under various operating conditions, but publically available field studies have been less available. This evaluation attempts to provide publically available field data about new HPWHs by monitoring the performance of three recently released products: General Electric (GE) GeoSpring, A.O. Smith Voltex, and Stiebel Eltron Accelera 300. Fourteen HPWHs were installed in Massachusetts and Rhode Island and monitored for more than 1 year. Of these, 10 were GE models (50-gal units), 2 were Stiebel Eltron models (80-gal units), and 2 were A.O. Smith models (1 60-gal and 1 80-gal unit).

Although this study used a small sample size and all the water heaters were in unconditioned basements, the HPWHs studied show great promise. Excluding one site, the monitored units had coefficients of performance (COPs) ranging from 1.5 to 2.6. The excluded site had ambient air temperatures lower than 50°F for much of the year that resulted in excessive electric resistance backup use. The average COP for each model is provided in Table 1.

Table 1. Performance Summary of Monitored HPWHs by Model

Model	Capacity (gal)	First Hour Rating (gal/h)	Measured Average COP	COP Range
GE	50	63	1.82	1.5–2.1
A.O. Smith	60/80	68/84	2.12	2.1
Stiebel Eltron	80	78.6	2.32	2–2.6

The monitored data show that the primary variables that affect HPWH performance are hot water use (daily volume and draw pattern) and ambient temperature. High hot water demand reduces efficiency by increasing auxiliary electric resistance use. Higher ambient temperature increases efficiency by increasing the efficiency of the heat pump and reducing standby losses. The GE unit shows two distinct operating regions that correspond to large and small electric resistance loads: the A.O. Smith and Stiebel Eltron units, which operate entirely in the low electric resistance region. This is most likely a product of the larger tank volumes and the control logic that allows the heat pump to reengage, in the case of A.O. Smith, or operate simultaneously, in the case of Stiebel Eltron.

Despite the slower recovery rate of the heat pump compared to electric resistance elements, all three models delivered hot water at temperatures higher than the minimum acceptable level (110°F) during nearly all draws. The hybrid nature of these systems allows them to deliver hot water reliably.

Unfortunately, the standby losses of the systems are higher than traditional ERWHs. Possible causes are the additional piping, wraparound condensing unit, and inadequate insulation. Installation of HPWHs in confined spaces also reduced efficiency by approximately 16%, which is consistent with other studies.

The HPWH monitoring results were compared to several alternative natural gas, electric resistance, fuel oil, and propane storage tank water heaters. Tankless water heaters were not considered. With the exception of condensing storage natural gas water heaters, annual operating costs and source energy consumption for the monitored HPWHs were lower than the alternative storage tank water heaters considered. The annualized energy-related costs—which are a measure of total lifetime costs and include first costs, operating costs, replacement costs, and the time value of money—of the monitored HPWHs were slightly lower than ERWHs and condensing natural gas water heaters. Annualized energy-related costs for HPWHs were considerably lower than for propane- and fuel-oil-fired systems. Natural gas storage water heaters, with the exception of condensing storage water heaters, had lower annualized energy-related costs than all other options. Space-conditioning interactions for HPWHs, however, may change the relative costs depending on the climate and location of the HPWH. Natural gas water heaters, however, were still the lowest-cost storage water heater option on an annualized energy-related cost basis.

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1 Introduction

A confluence of regulatory and economic factors is rapidly pushing heat pump water heaters (HPWHs) into the mainstream residential marketplace. The primary regulatory catalyst is a new federal water-heating standard that mandates energy factors (EFs) around 2 for all new electric storage water heaters with capacities higher than 55 gal (DOE 2010).[1] This regulation is a major driver of change in residential water-heating technologies (Maynard 2011), because it effectively requires HPWHs in applications that have large hot water loads and where electricity is used for water heating. Also, for energy-conscious consumers who want to decrease energy use, HPWHs are currently the only ENERGY STAR®-qualified electric water-heating products on the market (EPA 2012).

In addition to a changing regulatory environment in the residential electric resistance water heater (ERWH) market, financial factors are also pushing HPWHs into the mainstream. Inflation of residential retail electricity prices significantly outpaced general inflation, as measured by the consumer price index, between 2002 and 2009.[2] While electricity prices have since stabilized due to a slowdown in economic growth and declining natural gas prices (EIA 2012a), the relative increase in electricity prices over the past decade has played an important role in HPWH development. Furthermore, even though HPWHs have higher first costs than traditional ERWHs, many utility companies are offering sizable rebates for HPWH installations[3] in the hopes of making these units more attractive in the residential marketplace.

The move to HPWHs from standard ERWHs is not trivial; energy used by electric water heaters is a substantial fraction of total residential energy consumption, and HPWHs are significantly more efficient than traditional ERWHs. Water heating is the second-largest contributor (2.11 quads or 20% of site energy) to residential energy consumption in the United States after space heating (EIA 2005), and nearly 44% of American households use electricity as their primary water-heating fuel (EIA 2009). To demonstrate the magnitude of the energy consumed through residential water heating, site energy, source energy, and annual operating costs are listed in Table 2.

Table 2. Residential Water-Heating Energy Consumption and Operating Costs (per annum)

Fuel	Number of Households (millions)	Site Energy		Source Energy		Operating Costs	
		Per Household	U.S. Total (quads)	Per Household (MBtu)	U.S. Total (quads)	Per Household ($)	U.S. Total (billion $)
Electricity	43.3	2,813 kWh	0.42	32.3	1.40	330	14.28
Natural Gas	59.8	241 therms	1.44	26.3	1.57	265	15.80
Fuel Oil	4.3	226 gal	0.14	36.6	0.16	887	3.81
Propane	5.8	277 gal	0.15	29.2	0.17	790	4.58

Source: Adapted from EIA (2005).

[1] The regulation specifies the minimum EF as a function of rated storage volume, $EF = 2.057\text{-}0.00113V$, which corresponds to an EF range of 1.92 to 1.99 for rated tank volumes between 55 gal and 119 gal, respectively.
[2] The average residential retail price of electricity increased 36% between 2002 and 2009 (EIA 2012b), while the increase in the consumer price index was 19% over the same period (BLS 2012).
[3] For example, Massachusetts utilities offer up to $1,000 (Mass Save 2012).

Because all new HPWHs have a listed EF of 2 or higher—compared to 0.9–0.95 for ERWHs[4]—if all ERWHs were replaced with HPWHs and these water heaters performed at their rated efficiencies, American consumers could save $7.8 billion annually (average of $182/household) in water heater operating costs and cut annual residential source energy consumption for water heating by 0.70 quads. HPWHs are not appropriate in all circumstances, however, and they may increase space-conditioning loads in some cases, so these figures represent the upper limit of potential savings based on EF ratings associated with the move from ERWHs to HPWHs.

In 2013, five major integrated[5] HPWH products were available in the American market. Key specifications for these HPWHs are shown in Table 3. These specifications include the two U.S. Department of Energy performance metrics—EF and first hour rating (FHR).[6] The EF represents the efficiency of the electric heating elements and tank losses under a specific 24-hour test procedure. The FHR represents the amount of hot water that can be supplied by a fully heated storage water heater during the first hour of operation. Storage tank volume is often used as a proxy for water-heating capacity, but FHR is the more appropriate metric. See Section 4.2 for more details about the EF and FHR test procedures.

Table 3. Key Specifications of Integrated HPWHs Currently Available in the U.S. Market[7]

Model	Capacity (gal)	EF	FHR (gal)	Electric Resistance Elements (kW)
General Electric (GE) GeoSpring	50	2.35	63	Upper: 4.5 Lower: 4.5
A.O. Smith Voltex	60/80	2.33	68/84	Upper: 4.5 Lower: 2
Stiebel Eltron Accelera 300	80	2.51	78.6	Upper: 1
Rheem EcoSense	40/50	2.00	56/67	Upper: 2 Lower: 2
AirGenerate AirTap Integrated	50/66	2.39/2.40	60/75	Upper: 4

1.1 Background

Although regulatory and economic factors may be finally pushing HPWHs into the mainstream residential market, HPWHs are not new. The first patented HPWH dates back to 1935, and they were first commercialized in the 1950s. For more than 50 years, HPWHs have followed a boom-bust cycle of product development and subsequent abandonment that closely follows retail

[4] EF is meant to represent the efficiency of residential water heaters as a fraction. For example, 0.92 EF water heaters are expected to be 92% efficient when tested under the rating procedure. See Section 4.2 for more information about the EF test.
[5] Integrated refers to water heaters in which the heat pump and tank are packaged together as a one-piece, drop-in unit. Add-on HPWHs can be plumbed into existing storage water heaters.
[6] Recovery efficiency (RE) is also used to quantify the efficiency of natural gas, fuel oil, and propane water heaters. RE is an approximate metric of the burn efficiency of the heating device. Because electric resistance elements have an efficiency of 1, RE is not tested or reported.
[7] Any omission of a manufacturer or product is unintentional, and no endorsement of any commercial product or manufacturer is implied.

electricity prices and demonstrates the reliability issues of past products. See Figure 1 for a timeline of the development of HPWHs in the United States and Appendix A for more detailed information.

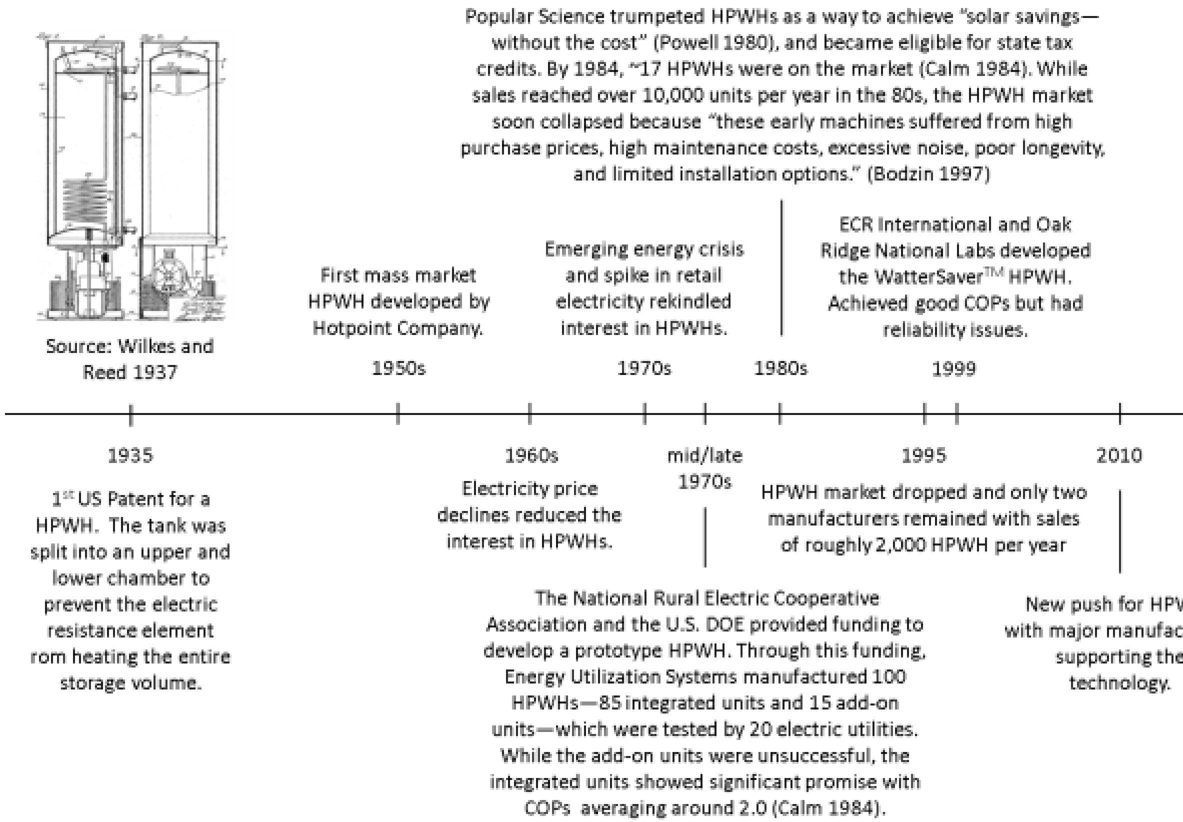

Figure 1. Timeline of HPWH development in the United States

Because of regulatory and financial forces that have converged to push HPWHs into the mainstream residential market and the magnitude of the savings potential represented by this market, Steven Winter Associates, Inc. (SWA), a partner of the U.S. Department of Energy's Building America research team Consortium for Advanced Residential Buildings, embarked on one of the first in situ studies of these newly released HPWH products. Recent laboratory studies have quantified the performance of HPWHs under various operating conditions, but publically available field studies have been less available. This evaluation attempts to provide publically available field data about new HPWHs by quantifying the field performance of three products: GE GeoSpring, A.O. Smith Voltex, and Stiebel Eltron Accelera 300.

Fourteen HPWHs were installed in Massachusetts and Rhode Island and monitored for more than 1 year. 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. Of the 14 units, 10 were GE models (50-gal units), 2 were Stiebel Eltron models (80-gal units), and 2 were A.O. Smith models (1 60-gal and 1 80-gal unit). The 10 50-gal units were intended to be split between the GE and Rheem HPWHs, but the Rheem units were not available during the installation phase of this project.

1.2 How Heat Pump Water Heaters Work

HPWHs are primarily designed as replacements for traditional ERWHs and can achieve higher efficiencies by using the vapor-compression heat pump cycle. Generally speaking, heat pumps are devices—such as air conditioners and refrigerators—that move thermal energy from one location to another. A refrigerator moves heat from the inside the appliance into the kitchen; the heat pump inside an HPWH moves heat from the surrounding air into the hot water storage tank. By moving thermal energy instead of converting electricity to heat, heat pumps are more efficient and usually operate at efficiencies that exceed 200%.

Most HPWHs, however, are hybrid devices that combine a heat pump, backup electric resistance element(s), and a storage tank (Figure 2). Although the heat pumps in these hybrid water heaters can heat water at high efficiencies, their recovery rate is significantly slower than traditional electric resistance heating mechanisms. A typical 4.5-kW electric resistance element can reliably heat more than 20 gal of water per hour. The heat pump has a lower heating rate; GE, for example, publishes a rate of 8 gal/hour at 68°F air temperature (GE 2010). Auxiliary electric resistance elements are thus also installed in HPWHs for reliability and quicker hot water recovery. Most HPWHs use the heat pump whenever possible, but built-in controls switch to conventional resistance heating during times of high hot water demand.

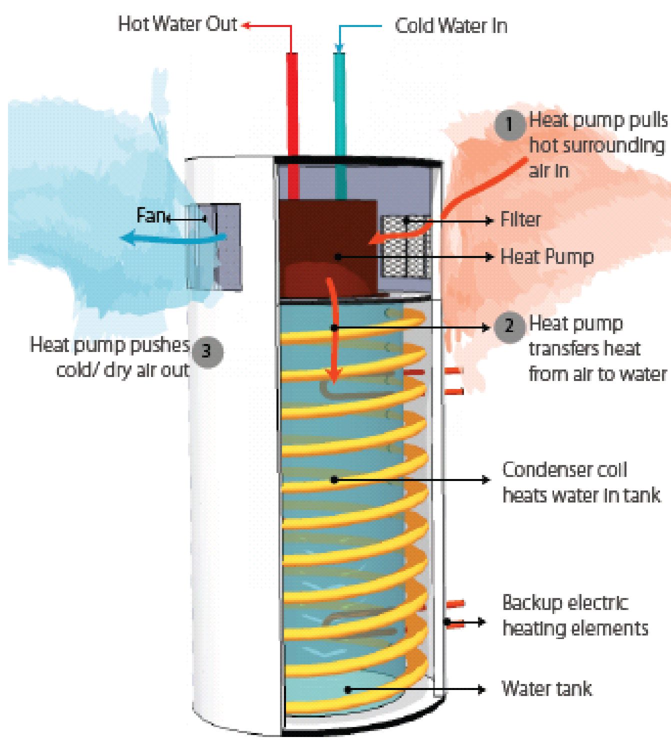

Figure 2. How HPWHs work

Historically, heat pumps have been differentiated into two categories: integrated (or "drop-in") and remote (or "add-on"). These categories describe the relationship between the heat pump and the storage tank. Add-on devices are stand-alone heat pumps that are combined with traditional tank ERWHs. Integrated devices include the heat pump, storage tank, and resistance element(s) in one package and have the advantage of being able to control the operation of the heat pump and resistance elements more precisely. Add-on devices can, however, be used as retrofits to existing water heaters at a lower cost (Ashdown et al. 2004).

Integrated devices come in three configurations of heat exchangers. The most common in the United States is a wraparound condenser. In this configuration, the refrigerant coils are wrapped around the storage tank but are not in direct contact with the potable water inside the tank. The Air Generate AirTap uses refrigerant immersion coils that are directly immersed in the potable water. Finally, coaxial heat exchangers can be used, as with the Rheem EcoSense, wherein the water is pumped through the heat exchanger to transfer energy from the heat pump to the potable water (Sparn et al. 2011).

The most common arrangement of current HPWHs is an integrated water heater with a wraparound condenser and two backup electric elements. Figure 2 illustrates this arrangement and describes the typical components and operation of modern HPWHs in the U.S. market. Among the systems evaluated in this study, the only model to deviate from this configuration is the Stiebel Eltron unit, which has only one smaller (1.7-kW) upper element and always operates in hybrid mode.

1.3 Space-Conditioning Interactions and Installation Considerations

HPWHs move thermal energy from the surrounding air into the storage tank. Therefore, units installed in conditioned spaces directly affect the space-conditioning loads of the building. During the heating season, HPWHs increase loads on space-heating systems. Conversely, HPWHs reduce cooling loads during the cooling season. When HPWHs are installed in unconditioned spaces such as attics and garages (possible in warm climates only), space-conditioning impacts are minimal. When in “quasi-conditioned” spaces—such as uninsulated basements—space-conditioning impacts of HPWHs are very difficult to assess. Because most basements are thermally connected to conditioned space, HPWHs still have an impact on conditioning loads. Finally, by using a vapor-compression system, HPWHs typically remove moisture from the surrounding air, which can be a significant benefit in hot-humid climates and damp basements.

Because these hybrid HPWHs are new to the mainstream market, installation is less straightforward for installers than traditional ERWHs. HPWHs require special attention to airflow around the unit and condensate collection. Furthermore, to improve the efficiency of the units, A.O. Smith and Stiebel Eltron manufacture models that are substantially larger than typical ERWHs. Installers may not be familiar with these units—or with heat pump models in general—and installing these units in existing homes may be difficult.

During installation the team noted specific challenges the installer faced at the various sites. Many of these details are discussed in more depth by Shapiro, Puttagunta, and Owens (2012). Installation considerations are further discussed by SWA (2012). A trifold brochure for consumers (Appendix E) was created for SWA’s rebate programs.

1.4 Model Operation and Control Logic

Although all three monitored HPWHs have similar components, the control logic differs substantially among models. The GE and A.O. Smith tanks have two electric resistance (upper and lower) elements in addition to the heat pump and operate in several modes; the Stiebel Eltron unit has only one mode of operation and uses a small upper element to supplement the heat pump. All three units have wraparound condensers and an integrated storage tank.

1.4.1 General Electric Control Logic

The GE model has two 4.5-kW electric resistance elements, one placed at the top third and one placed at the bottom third of the unit. The unit can operate under five operating modes: Hybrid, eHeat, Standard Electric, High Demand Mode, and Vacation Mode (GE 2009). The control logic for these modes is described below:

- **Hybrid Mode** is the default operating mode. The control logic for the GE unit is proprietary; however, the general operating principle behind the hybrid mode is to balance energy savings and provide hot water at rates that are similar to comparably sized ERWHs. Thus, the control logic tries to meet certain targets for the availability of hot water. The unit uses the heat pump until approximately 75% of the available hot water has been depleted and the heat pump cannot keep up with the hot water demand. Because the unit does not measure average tank temperature or hot water flow rate directly and measures the temperature at the top third of the tank only, the control logic uses the current and previous values of the temperature at the top of the tank as a proxy for available hot water and hot water flow rate. The system uses a closed-form model that employs autocorrelation functions to map upper tank temperature to hot water availability (Tsai 2012).

  In practice, this control strategy results in the electric elements being used in three circumstances.

  - If the ambient air temperature is outside the safe operating range (45°–120°F), the system reverts to standard resistance mode.
  - If the water in the tank is significantly lower than the set point, the upper element operates. The difference between the tank temperature and the set point depends on the circumstances, but it is generally 25°–30°F.
  - If the system senses that the water use is too high, the lower element operates. In general, 25–30 gal within a short time period is considered high water use. Once the lower electric resistance element engages, the entire tank is reheated like a traditional ERWH (Tsai 2011).
- **eHeat Mode** uses only 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 set point temperature. The temperature dead band at the top of the tank that regulates heat pump operation is 1°F (Sparn et al. 2011).
- **Standard Electric Mode** operates like a traditional ERWH.
- **High Demand Mode** is similar to the hybrid mode, but the control logic changes from 75% of the available hot water being depleted to 50% (Tsai 2012).
- **Vacation Mode** is similar to eHeat Mode but with a temperature set point of 50°F.

1.4.2 A.O. Smith Control Logic

The A.O. Smith model has two electric resistance elements: a 4.5-kW upper element and a 2-kW lower element. The A.O. Smith model has four operating modes: hybrid mode, efficiency mode, electric mode, and vacation mode (A.O. Smith 2010). The control logic of the A.O. Smith unit, however, is quite different than that of the GE unit:

- **Hybrid Mode** of the A.O. Smith model uses a simple temperature dead-band algorithm. If the average tank temperature—which is the weighted average of the upper and lower thermostats, where the upper thermostat receives 75% weighting (Sparn et al. 2011)—drops 9°F below the set point, the heat pump is turned on to heat the water back to the set point. If, however, the heat pump fails to heat the water sufficiently, and the average tank temperature drops more than 20°F below the set point, the upper element replaces the heat pump as the heating source. The lower element is not used in hybrid mode (A.O. Smith 2011). Unlike the GE unit, the heat pump may reengage during the reheat cycle after the electric resistance elements have been operating.
- **Efficiency Mode** does not use the electric resistance elements, unless the ambient temperature is outside the safe operating range (45°–109°F) of the heat pump (A.O. Smith 2011).
- **Electric Mode** operates like a traditional ERWH. The upper element is used first to heat the top of the tank, then the lower element is used to heat the bottom of the tank (A.O. Smith 2010).
- **Vacation Mode** is identical to efficiency mode with a set point of 60°F (A.O. Smith 2010).

1.4.3 Stiebel Eltron Control Logic

The Stiebel Eltron has only one operating mode. The hot water temperature set point is factory set at 140°F and is not easily adjustable by the user. The unit has one 1.69-kW electric resistance element installed vertically at the top of the tank and operates under a fixed mode. The heat pump is turned on when the temperature 16 in. from the top of the internal tank drops more than 4°F below the set point. If the heat pump cannot meet the demand and the temperature at the top of the tank drops lower than 112°F, the upper element is used as a backup heat source. The upper element heats only the top third of the water heater tank (approximately 27 gal). The Stiebel Eltron unit is the only unit that allows simultaneous operation of the heat pump and booster resistance heater (Megliola 2011).

2 Recent Studies

Since the introduction of the most recent line of HPWHs, a growing body of literature has been devoted to measuring the performance, energy and cost savings potential, and reliability of these products.

Unfortunately, robust and publically available field-test results for the new HPWHs have been less available than laboratory testing results. Pacific Gas & Electric monitored one GE HPWH in Sonora, California. The unit was placed in an unconditioned basement with a floor area of approximately 400 ft^2. The average COP was 1.29 with average operating conditions of 68.6°F ambient temperature, 62% relative humidity, 70.5°F inlet water temperature, 1.3 gal/minute flow rate, 18.6 draw events per day, and 18.3 GPD (Hu and Davis 2011).

Electric Power Research Institute (EPRI) has worked with four electric utility companies—Bonneville Power Administration, Kansas City Power & Light, Tennessee Valley Authority, and Southern Company—to test 160 water heaters across the United States, mostly GE, A.O. Smith, and Rheem HPWHs, but several ERWHs were installed as control units. EPRI has provided preliminary results from the study, but the results are identified only as Model A, Model B, and Model C. The COPs of these units were 0.7–2.7; their performance varied significantly. Their reliability has been high so far, but EPRI saw only minimal peak demand savings (Amarnath and Bush 2012).

A 2009 Pacific Gas & Electric HPWH study (PG&E 2009) concluded that, in terms of source energy[8] efficiency, an HPWH was more efficient (67%) than a standard natural gas (57%) or electric (29%) tank water heater when the heating, ventilating, and air-conditioning interaction of the HPWH is ignored. If this interaction is included, HPWHs are significantly more efficient (104% source energy efficiency) than both standard systems in the cooling season and less efficient (44% source energy efficiency) than natural gas tank water heaters in the heating season.

According to Franco et al. (2010), HPWHs have the lowest life cycle cost in roughly half of all single-family homes that heat water with electricity. This study assumed that some houses need venting for successful HPWH installation; thus, HPWHs could not be cost-effectively installed in many older homes. Furthermore, HPWHs demonstrated a greater cost benefit in new, single-family homes.

Hudon et al. (2012) modeled HPWH performance against gas water heaters and ERWHs in six U.S. cities. HPWHs saved source energy compared to traditional ERWHs 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.

[8] See Section 5 for discussion of source energy.

3 Technical Approach

This evaluation of HPWHs provides valuable information that can be used to advise consumers and builders about efficient methods to provide electric water heating. This information can also be used as validation by utilities and other program implementers throughout the United States that are attempting to develop incentive programs for this technology. Although this study is primarily applicable to colder climates, the measured performance of the HPWH units is relevant in many climate zones. Even though the sample for this evaluation was relatively small, some clear results were consistent with other ongoing field-testing across the country.

3.1 Research Questions

This research effort focused on answering the following questions about the efficiency, reliability, and performance of each model evaluated:

- What is the measured efficiency of an HPWH located in unfinished basements of cold-climate homes?
- What are the critical criteria that affect the installed performance of HPWHs, and how do they impact the performance of each HPWH model?
- What are the standby losses for these HPWHs, and how do they compare to traditional ERWHs?
- Does each model evaluated in this study effectively deliver hot water at the set point temperature?
- Are homeowners satisfied with hot water delivery, efficiency, noise, and other characteristics?

3.2 Measurements

Long-term performance data were 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 annual efficiency and performance of each unit. These measurements included water temperatures, flow rates, and electricity consumption. Sensors were sampled at 5-second intervals and output at 15-minute intervals in the forms of averages, minimums, maximums, and/or totals over that time period, depending on the desired outputs. An additional data table captures the duration and volume of each hot water draw.

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

- Inlet water temperature (°F)
- Outlet water temperature (°F)
- Ambient air temperature (°F)
- Ambient air relative humidity (%)
- Hot water flow (gal)
- Compressor energy consumption (Wh)

- Energy consumption of each electric resistance heating element (Wh)
- Entire system energy consumption (Wh).

At each 5-second interval, thermal heat delivered by the water heater was calculated based on water flow and temperature differential.

The following values were output 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 use (gal)
- Domestic hot water energy (Btu)
- Total compressor energy consumption (Wh)
- Total upper heating element energy consumption (Wh)
- Total lower heating element energy consumption (Wh)
- Total system energy consumption (Wh)
- Total heat pump energy (Wh)
- Total standby energy consumption (Wh)

The start time, volume, and duration of each hot water draw were also recorded. Details on how a heating event was defined for this study is provided in Appendix D

3.3 Equipment

As shown in Figure 3, a Campbell-Scientific CR-1000 data logger and various sensors (Table 4) were used at each site to take measurements. A wireless modem was used to remotely download data for evaluation throughout the monitoring period. Thermistors were used for all temperature measurements. Cold water inlet and hot water outlet water temperatures were measured using an Omega tubular immersion sensor with a 4.5-in. probe length and National Pipe Thread tapers. The HPWH installer installed these directly in the water flow. Omega FTB4607 low-flow (0.22–20 gal/minute) turbine-type flow meters were used to measure domestic hot water flow. All flow meters were 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 located to minimize heat transfer from radiation and surrounding equipment. All electrical energy consumption measurements used a Continental Control Systems WattNode and right-sized current transformers. The WattNodes are true-root mean squared, alternating current, watt-hour transducers with pulse outputs.

Table 4. Installed Monitoring Equipment

Measurement	Equipment
Record and Output Measurements	Campbell-Scientific CR-1000 data logger
Inlet and Outlet Water Temperatures	Omega ON-910-44006 National Pipe Thread pipe plug thermistor
Inlet Air Temperature and Relative Humidity	Humirel HTM2500 Probe
Compressor Energy, Heating Element Energy, and System Energy	Continental Control Systems WattNode WNB-3D-240-P watt-hour transducer with appropriately sized current transformers
Hot Water Flow	Omega FTB4607 low-flow, turbine-type flow meter

Figure 3. Example of an HPWH monitoring system installation

3.4 Analysis

The COP has been defined differently in numerous studies (AIL Research 2001, AIL Research 2002, Murphy and Tomlinson 2002, and Zogg 2002). For this evaluation the standard definition of COP, which is the net heat delivered by the water heater to the domestic water load divided by the total electrical energy consumed over a period of time was used:

$$COP = \frac{\text{useful heating energy}}{\text{net energy input}} = \frac{Q_{DHW}}{W_{DHW} \times 3.413 \text{ Btu/Wh}}, \tag{1}$$

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 data logger every 5 seconds using measured data. These energy values were summed and logged at 15-minute intervals.

$$Q_{DHW} = \rho C_p \dot{V}\left(T_{out} - T_{in}\right), \tag{2}$$

where

T_{out}	=	outlet water temperature (°F)
T_{in}	=	inlet water temperature (°F)
$\dot{V}$	=	hot water volumetric flow rate (ft^3/h)
C_p	=	specific heat of water (Btu/lbm·°F)
ρ	=	density of water (lbm/ft^3).

4 Performance Results

Measured performance, rated capacity, EF, and FHR for each monitored model are shown in Table 5. All systems were set to hybrid mode, but set point temperatures varied. The electric resistance percentage represents the fraction of electricity consumed by the electric resistance elements (rather than the heat pump, controls, or peripherals). This is a small sample and many variables affect water heater performance; however, the values do provide insight into some differences between the units.

Table 5. Summary Statics of Performance by Model

Model	Capacity (gal)	FHR[a]	Measured Average COP	COP Range	% Electric Resistance
GE	50	63	1.82[b]/1.61	1–2.1	32.7%[b]/44%
A.O. Smith	60/80	68/84	2.12	2.1–2.1	5.6%
Stiebel Eltron	80	78.6	2.32	2–2.6	5.5%

[a] FHR is measured in gal/hour.
[b] Average COP calculation for the GE units does not include Site 5 (cold air = high electric resistance use)

Average COPs over the entire monitoring period were influenced heavily by storage volumes, set point temperature, and the ability to meet high demand over short periods of time. While the A.O. Smith and Stiebel Eltron units used the heat pump to provide the vast majority of the load (approximately 95% of the total electricity was consumed by the heat pump), the electric resistance elements in the GE units consumed almost one-third of the measured electricity (excluding Site 5, where low ambient temperatures forced the unit into resistance mode most of the time). The A.O. Smith and Stiebel Eltron models benefit from larger storage tanks, and the Stiebel Eltron model benefits from a factory-set set point temperature of 140°F, which increases the availability of hot water. Increased hot water availability can increase COP by minimizing electric resistance use.

More detailed summary statistics for each site, which include operational conditions and efficiency values, are shown in Table 6. Although the two A.O. Smith units had remarkably similar COPs, the COPs of the Stiebel Eltron and GE 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 draws at the two sites. The residents at Site 2 used an average of 73 GPD with a COP of 2.6; the residents at Site 10 used an average of 41 GPD with a COP of 2. Larger hot water draw volumes dilute the impact of tank thermal losses and elevate the COP of the unit—as long as larger draws do not increase use of resistance heating. The differences between the measured COPs at the sites with GE units were significantly larger than those of the other units. With a smaller tank, the GE model seems to require more electric resistance heating to meet the demand.

Analysis of the data collected during the year of monitoring uncovered key variables that affect HPWH 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 affected water heater performance. These variables, particularly the effect of hot water use and electric resistance element operation, can have different impacts on different HPWH models.

Table 6. Summary Table of Performance by Site

Site	HPWH Model	Adults + Children	Water Heater Set Point Temp (°F)	Days Monitored	Avg. Daily Hot Water Use (gal)	Avg. Cold Water Temp. (°F)	Avg. Hot Water Temp. (°F)	% of Electricity Consumption from Electric Resistance[b]	Avg. Air Temp. (°F)[a]	Avg. Relative Humidity (%)[a]	Avg. Wet Bulb (°F)[a]	Total COP
1	A.O. Smith-80	2 + 1	120	454	44	54	119	0%	59	47%	49	2.1
2	Stiebel Eltron	5 + 0	140	438	73	57	136	8%	71	45%	58	2.6
3	GE	2 + 1	125	469	60	53	121	48%	64	38%	51	1.8
4	A.O. Smith-60	3 + 0	120	445	45	53	119	11%	63	56%	54	2.1
5	GE	2 + 0	129	460	64	52	127	78%	53	62%	46	1
6	GE	2 + 0	122	475	35	53	118	5%	62	55%	53	2.1
7	GE	2 + 0	125	450	23	58	123	11%	66	49%	55	1.8
8	GE	2 + 1	125	430	33	55	122	15%	66	44%	54	2.1
9	GE	2 + 2	120	468	41	55	122	22%	62	48%	52	2
10	Stiebel Eltron	2 + 0	140	424	41	57	138	2%	68	55%	58	2
11	GE	2 + 3	140	459	72	58	136	58%	76	34%	58	1.5
12	GE	2 + 1	130	492	42	56	128	29%	71	46%	58	1.9
13	GE	2 + 0	130	388	32	59	126	15%	70	57%	60	1.4
14	GE	2 + 0	120	433	32	53	119	15%	62	52%	52	1.9

[a] Average of daily averages
[b] Electric resistance percentage = % of total electricity kilowatt-hours that was used by electric resistance, NOT the thermal energy fraction provided by electric resistance.

4.1 Impact of Water Use on Efficiency

As previously discussed, the smaller volume GE units used the electric resistance elements to provide a much larger percentage of the needed energy than the other models. Figure 4 shows seven days of operation for the GE unit at Site 9. These days are representative of typical operation across many sites. During day 1 and days 3–6, the water draws from the tank were distributed throughout the day and/or were relatively small. The heat pump could thus meet recovery needs for those days. During 11/22 and 11/27, the water draws were more concentrated, and the electric resistance element was needed to provide additional hot water.

Figure 4 shows how large and concentrated draws can reduce the efficiency of the unit; however, low water use can also result in low COPs (Figure 5). In this figure, although the heat pump was used to meet the entire hot water demand, the low load and relatively high standby losses resulted in low daily COPs.

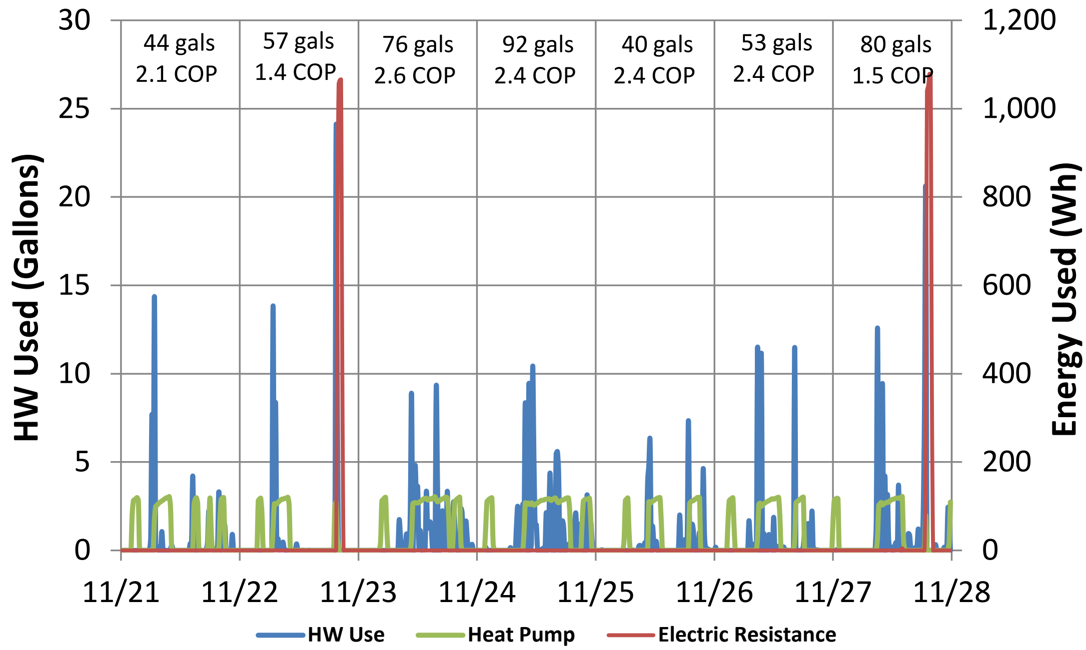

Figure 4. Ideal operation of the GE HPWH in hybrid mode (Site 9)[9]

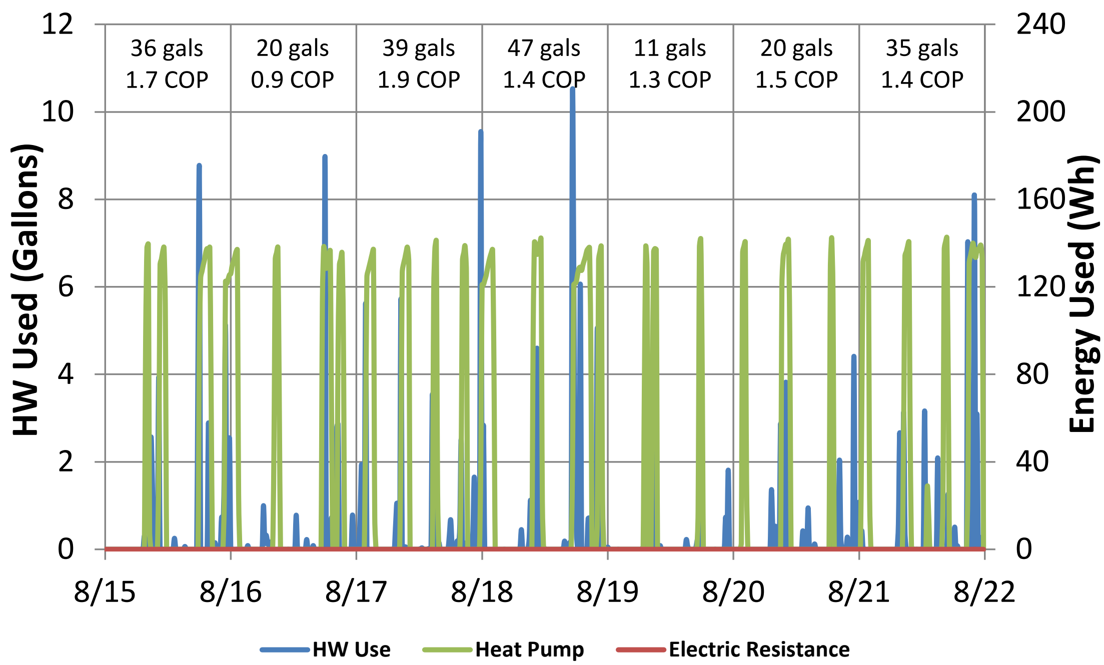

Figure 5. Low water use can reduce the overall benefit of an HPWH when the cost benefit is assessed.

Scatter plots of the daily hot water use[10] versus the daily COP are shown in Figure 6. Each daily observation is also color coded by the electric resistance fraction, where blue is zero electric

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[9] For this and similar figures, the vertical axes show discrete values for 15-minute intervals.

[10] Daily values are misleading because the net energy content of the water in the tank can change throughout the day. Thus, heating events with zero net tank energy change are identified from the 15-minute raw data. All heating events are normalized to daily values and displayed graphically. See Appendix D for more information.

resistance use, and red is when the electric elements are used to reheat the entire recovery load. The GE unit has the most observations; therefore, the operational patterns can be most directly observed in the scatter plot. For the GE unit, the data could be interpreted as lying between two exponential curves, where the upper curve has no electric resistance use and the lower curve is entirely electric resistance operation. The scatter plot of the GE unit operation also shows that the electric resistance fraction has a strong correlation with the hot water use. Days of lower hot water demand are far less likely to have instances of electric resistance heating (e.g., less than 30 GPD). On the other hand, days with high hot water demand are far more likely to have instances of electric resistance heating.

Although the scatter plots for the Stiebel Eltron and A.O. Smith units have fewer apparent trends—because fewer sites were monitored—the scatter plots appear to agree with the trend observed for the GE units, with one primary distinction. The GE unit shows two distinct operating regions that correspond to large and small electric resistance loads, and the A.O. Smith and Stiebel Eltron units operate entirely in the low electric resistance region. This is most likely a product of the larger tank volumes and the control logic that allows the heat pump to reengage, in the case of A.O. Smith, or operate simultaneously, in the case of Stiebel Eltron.

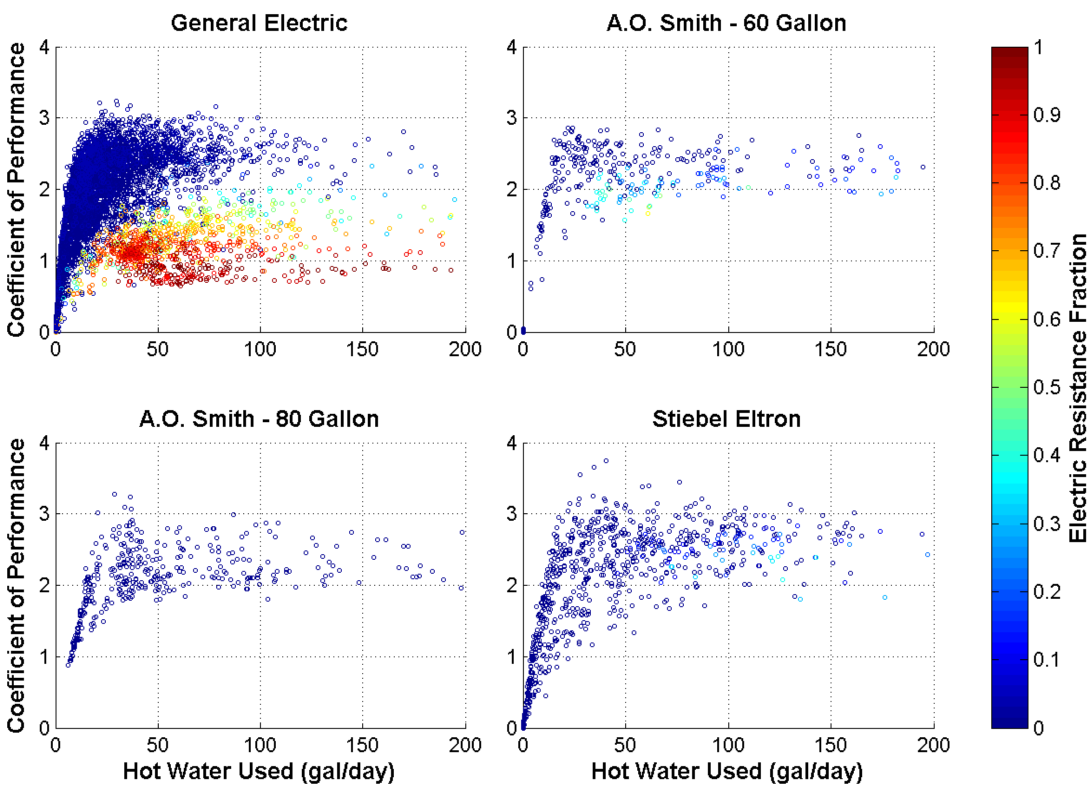

Figure 6. Scatter plots of daily hot water use versus COP color coded by electric resistance fraction

4.2 Impact of Air Temperature on Efficiency

Although hot water demand is a primary driver of efficiency, other factors still play a prominent role (Figure 6). The efficiency of the heat pump is primarily a function of the ambient temperature in the space. Two sites with cold and hot operating environments are compared to give a sense of how ambient temperature affects overall efficiency. At Site 5, the HPWH was installed in a cold basement with ambient air temperatures dropping lower than 50°F from December through April. These temperatures are close to the cut-off temperature of the heat pump in the GE unit. As a result, the HPWH at Site 5 operated like a traditional ERWH, as shown in Figure 7, but with an added parasitic of the heat pump cycles on and off at the cut-off temperature of the unit.

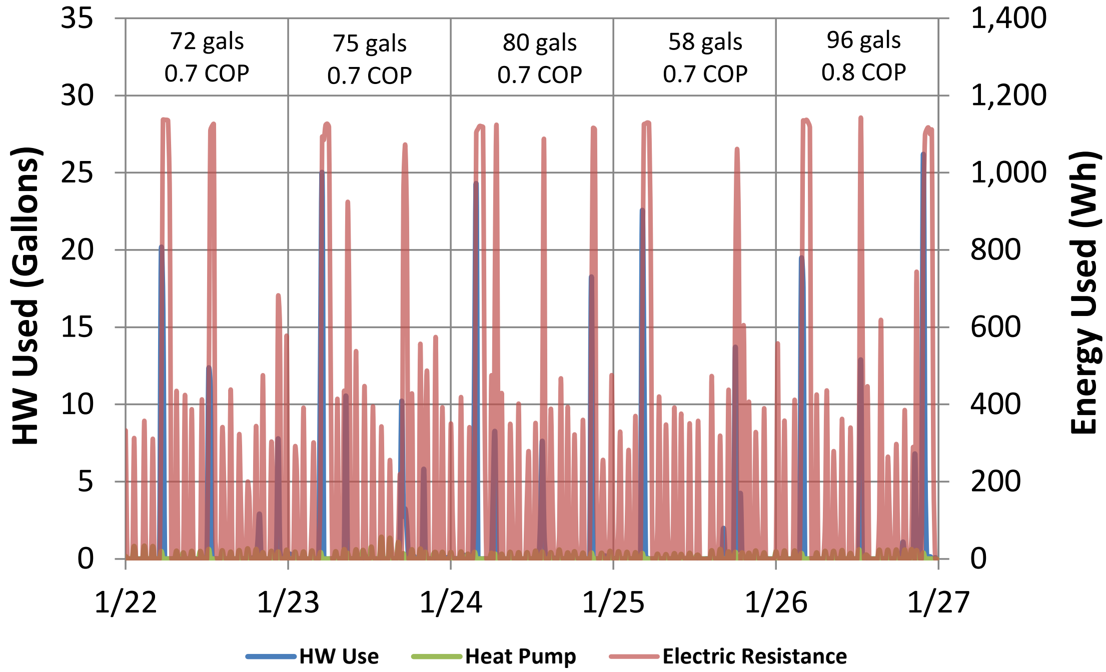

Figure 7. Because the Site 5 basement was too cold, this GE HPWH switched primarily to electric resistance mode during the winter months.

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 9) with ambient temperatures around 80°F (Figure 8). At the beginning of January, the unit was able to supply hot water in large quantities with high COPs higher than the rated EF of 2.35 (Figure 10). On 2 days during this week of data, high water use concentrations resulted in electric resistance operation to meet demand. Furthermore, some periods had low hot water draws. As discussed in Section 4.2, lower draw quantities can decrease overall COP, because standby losses account for a larger percentage of the recovery load. The high ambient temperatures boost the efficiency of the heat pump and increase the corresponding overall COP of the unit during these periods.

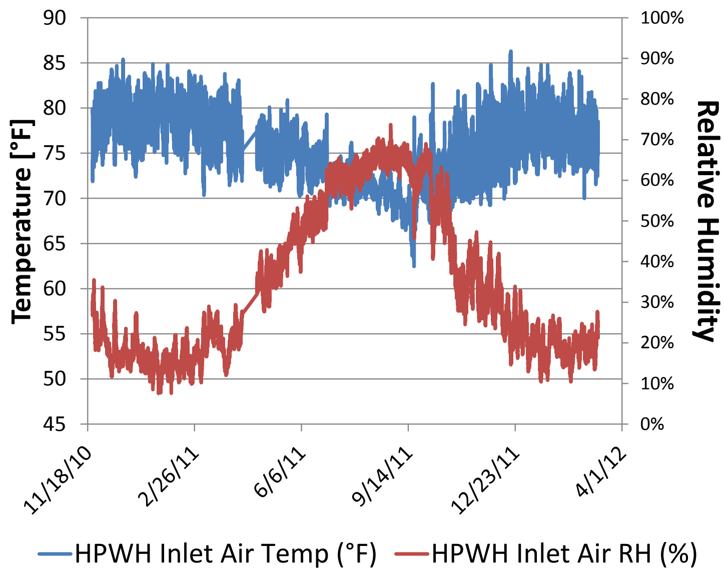

Figure 8. Ambient temperature at Site 11

Figure 9. This HPWH benefited from the waste heat of the boiler used for space heating.

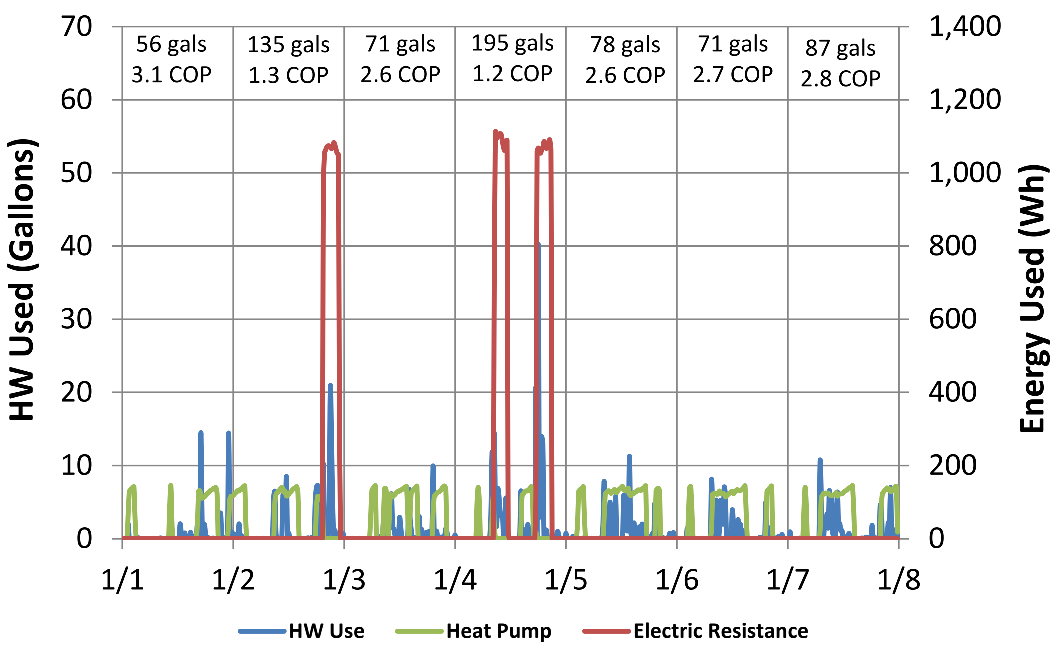

Figure 10. Typical winter performance of the GE HPWH in the Site 11 warm mechanical room

To demonstrate the relationship between ambient temperature and efficiency, daily scatter plots similar to those in Figure 7, but color coded by average ambient temperature, are shown in Figure 11. Periods with electric resistance fractions greater than 0.04 were excluded, as were data from Sites 5 and 13, which had lower heat pump COPs than the other units. The scatter plots show a strong correlation between ambient air temperature and efficiency. Everything else being equal, higher ambient temperatures improve efficiency. At a 50 GPD recovery load increasing the ambient temperature from 50°F to 80°F can increase the COP of the GE and A.O. Smith units from around 2 to nearly 3.

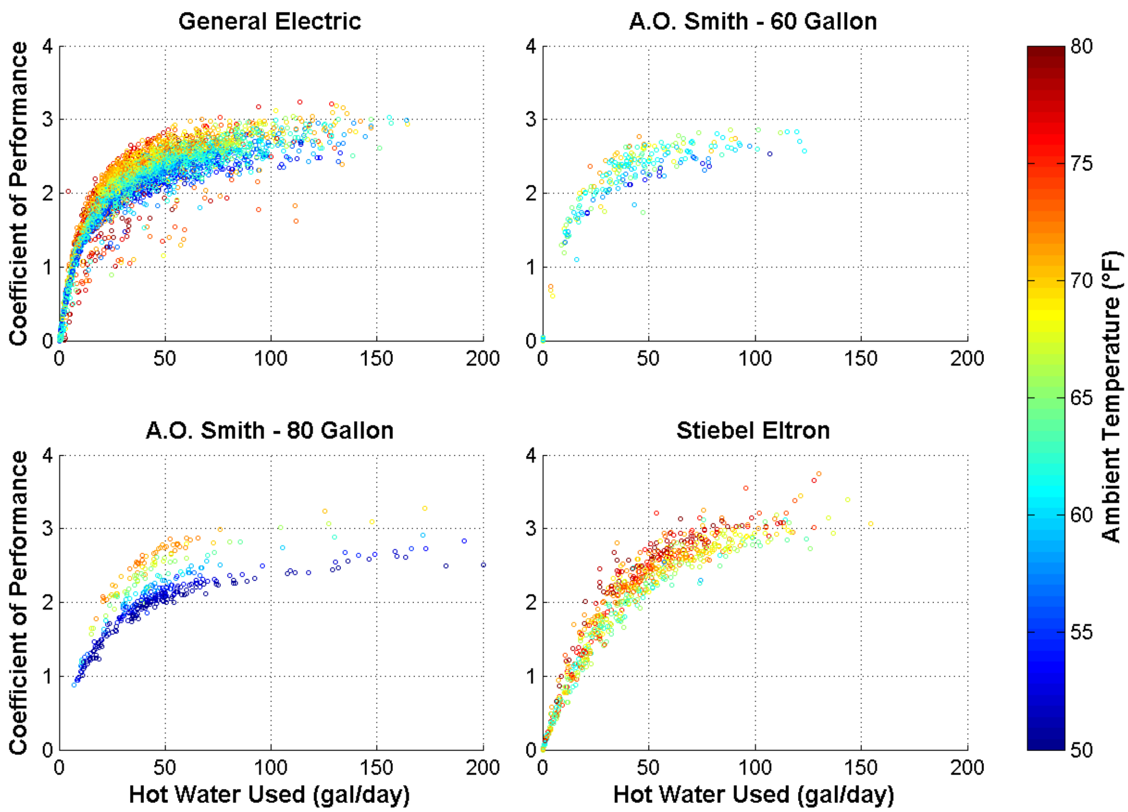

Figure 11. Scatter plots of COPs versus daily hot water use color coded by ambient temperature. Periods with electric resistance fractions greater than 0.04 and Sites 5 and 13 were excluded.

4.3 Delivered Water Temperature

The efficiency of water heating is important from a performance standpoint; however, the temperature of delivered water from the HPWH is also important for customer satisfaction. Surprisingly, graphing several days of high water use at a site with a Stiebel Eltron HPWH revealed that this unit was able to meet very large hot water demands at surprisingly high COPs, as shown in Figure 12. While the electric resistance element was needed to supply additional heating, the unit performed with COPs higher than 2.6 for the 4 days of high hot water use. 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 4 days of high hot water demand (Figure 13). The higher COPs for the Stiebel Eltron unit are probably a result of the large tank size and the ability of the unit to only heat water for the load directly when the heat pump cannot meet the load rather than heating the entire tank.

To determine the ability of the HPWHs to deliver water at an acceptable delivery temperature, normalized histograms of maximum delivered water temperature for 15-minute periods with draws larger than 1 gal were plotted for each site (Figure 14). The red and green vertical lines represent the set point temperature and minimum acceptable delivery temperature of 110°F (Hendron and

Engebrecht 2010), respectively. The percentage of occurrences lower than the minimum acceptable delivery temperature is shown in the upper left corner of each plot. The normalized histograms show that all three units deliver water hotter than 110°F at a variety of set point temperatures. However, many units did not maintain set point for all draw occurrences, and temperatures dropped more than 10°F lower than set point for a significant fraction of the 15-minute periods.

Unfortunately, the aforementioned method of determining whether the HPWHs can maintain the delivered water at a minimum acceptable temperature has flaws related to the 15-minute recording interval used in this study. Because the average delivered water temperature includes water inside the pipe before the draw, the maximum delivered water temperature for the interval must be used. Thus, this analysis looks only at the delivery temperature at the beginning of the draw or at the beginning of a 15-minute interval. If the water heater runs out of hot water, the user may end the draw and the run-out may not be recorded using this method. However, the very small percentage of run-outs recorded at the 110°F minimum acceptable delivery criteria means that delivery temperature is probably not dropping significantly lower than usable temperatures.

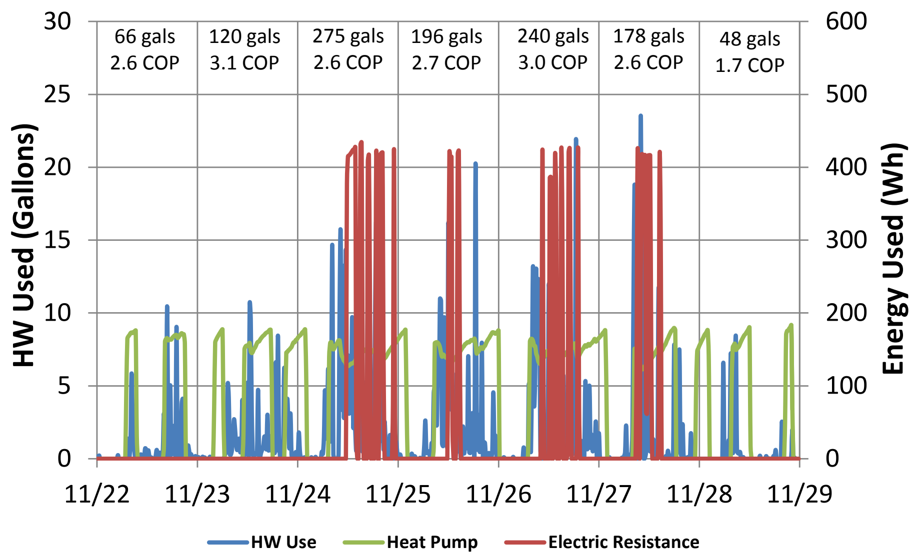

Figure 12. This Stiebel Eltron HPWH was able to maintain high COPs during high water demand.

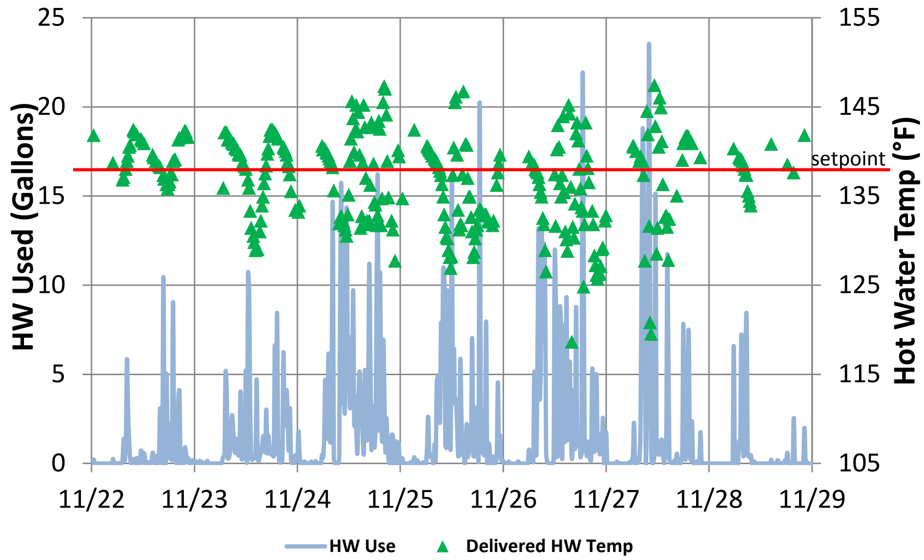

Figure 13. Even with high water demand, the hot water temperature dropped only as low as 118°F.

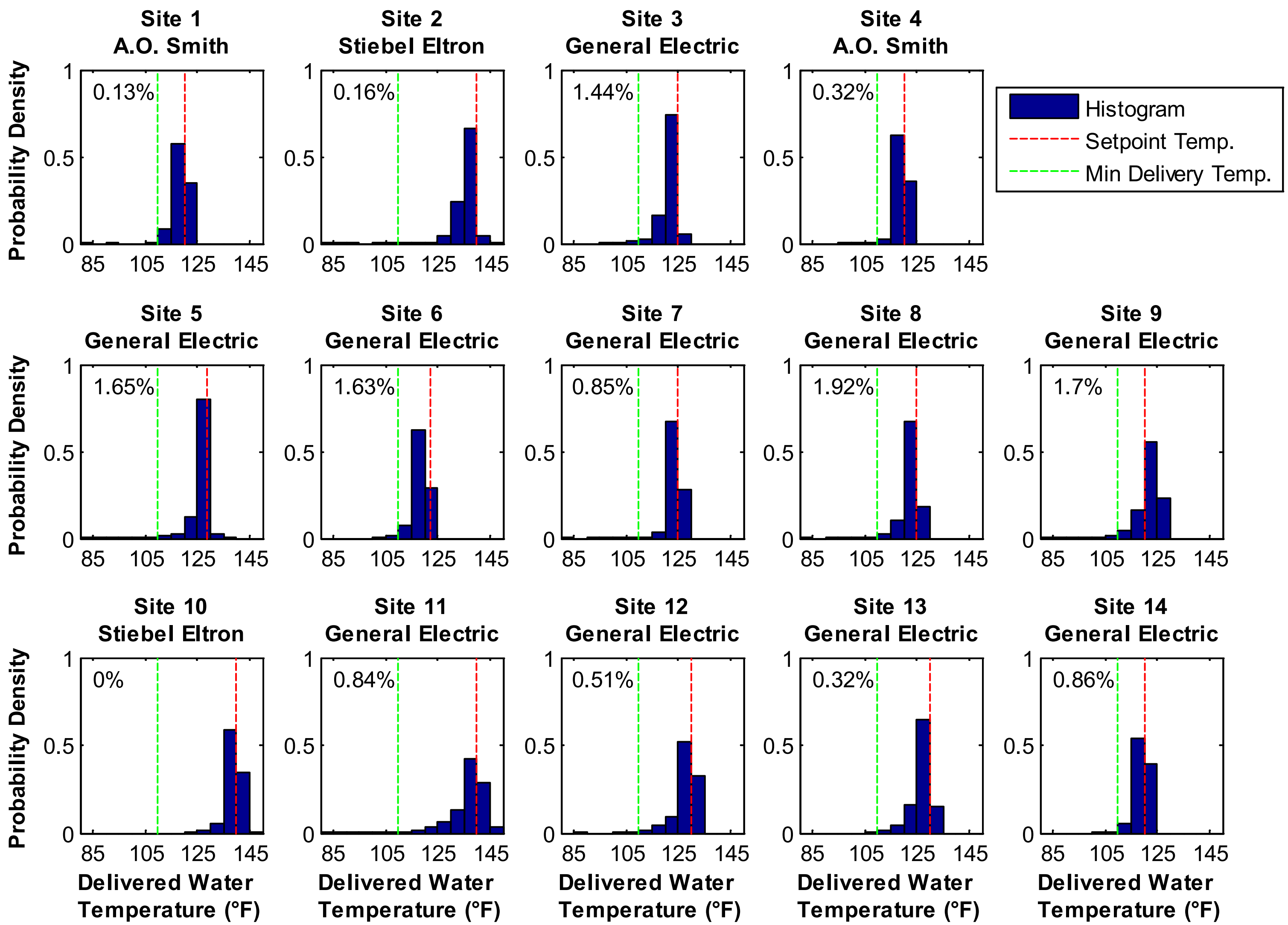

Figure 14. Normalized histograms of delivered water temperature. Red line indicates set point temperature. Green line indicates minimum delivery temperature (110°F). The percentage of occurrences with water temperatures lower than 110°F is shown.

4.4 Calculating Standby Losses

Tank losses to the ambient are important contributors to tank inefficiency; indeed, for ERWHs, tank losses represent the entirety of water heat site energy inefficiencies. Unfortunately, tank losses from HPWHs are hard to quantify without precise laboratory equipment. The data from this study, in conjunction with laboratory HPWHs tests conducted by Sparn et al. (2011), can be used to estimate the tank heat loss coefficient. This analysis was possible for the GE unit only, because the Stiebel Eltron and A.O. Smith units did not provide enough data points to perform this analysis.

The following analysis differs from the methods outlined in the U.S. Department of Energy's test procedure (DOE 1998) and the National Renewable Energy Laboratory's field-testing protocol (NREL 2012c). These methods measure the change in the average tank temperature during a period of no draws. The National Renewable Energy Laboratory specifies that this period should begin 10 minutes after the heat pump has shut off, because the condensing coil still gives off heat immediately after the reheat period.

Because internal tank temperatures were not measured in this study, a different procedure was used to measure standby losses. The basic procedure identified idle periods during which the tank begins fully heated, experiences no water draws, and is finally reheated. The tank losses during that period are simply the ratio of the thermal energy input to the product of the time elapsed since the last reheat and the temperature difference between the tank and the ambient air.

$$UA = \frac{Q_{standby}}{\Delta t\left(T_{tank} - T_{amb}\right)}, \tag{3}$$

where

UA	=	overall heat transfer coefficient of the tank (Btu/h-°F)
$Q_{standby}$	=	thermal energy to recover tank to set point (Btu)
T_{tank}	=	average tank temperature (°F)
T_{amb}	=	ambient temperature (°F)
Δt	=	time elapsed since the last reheat (h).

The average tank temperature was assumed be 2.5°F lower than the temperature set point, which is equivalent to assuming an average tank temperature dead band of 5°F for recovery from an idle period. For example, if the tank set point were 135°F, the tank would presumably start the period at 135°F, drop to 130°F due to standby losses, and finally return to 135°F through the recovery process. The average temperature would be 132.5°F, which is 2.5°F lower than the set point temperature. This dead band temperature is consistent with graphs of the EF testing of the GE unit by PG&E (2010) and other studies.

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

- No water was drawn during the period.
- The period began and ended with the termination of heat pump operation to ensure similar stratification.
- The overall period exceeded 3 hours.

For ERWHs the electricity used is directly converted to thermal energy; for HPWHs, however, the electricity input does not directly correspond to the thermal energy input into the tank. Thus, laboratory performance maps discussed by Sparn et al. (2011) were used to convert electricity energy used by the heat pump to the thermal energy delivered to the storage tank. The equation for the efficiency of the GE heat pump is:

$$COP_{hp} = COP_{hp,rated}\left(C_1 + C_2 T_{wb} + C_3 T_{wb}^{\ 2} + C4T_{tank} + C_5 T_{tank}^{\ 2} + C_6 T_{wb} T_{tank}\right), \qquad (4)$$

where

COP_{hp}	=	efficiency of the heat pump (Btu/Btu)
$COP_{hp,rated}$	=	rated COP_{hp} at 57°F wet bulb and 120°F tank temperature (2.76)
T_{tank}	=	average tank temperature (°F)
T_{wb}	=	ambient wet bulb temperature (°F)
C_1	=	1.192E+00
C_2	=	4.247E-02
C_3	=	–3.795E-04
C_4	=	–1.110E-02
C_5	=	–9.400E-07
C_6	=	–2.657E-04.

The tank lost during the standby period is

$$Q_{standby} = C\left(E_{res} + E_{hp} COP_{hp}\right), \qquad (5)$$

where

$Q_{standby}$	=	thermal energy to recover tank to set point (Btu)
COP_{hp}	=	efficiency of the heat pump (kWh/kWh)
E_{res}	=	electricity used by the resistance elements (kWh)
E_{hp}	=	electricity used by the heat pump (kWh)
C	=	conversion factor for kWh to Btu (3.412 Btu/kWh).

The estimated time of electricity cutoff was determined by examining the previous data logging period to correct for the error inherent in the 15-minute data logging interval. If the electricity draw for the last interval *i* before cutoff was smaller than the previous interval *i-1*, the runtime fraction for the cutoff interval was set as the ratio of the electricity draws, as shown in Eq. (6).

$$f = \begin{cases} \dfrac{E_i}{E_{i-1}} & \text{for} \quad E_i < E_{i-1} \\ 1 & \text{for} \quad E_i \geq E_{i-1} \end{cases} \qquad (6)$$

Robust regression[11] analysis was used to estimate the thermal heat transfer coefficient of the tank:

$$Q_{standby} = UA\Delta t\left(T_{tank} - T_{amb}\right). \tag{7}$$

Regressions using Eq. (7) were performed with and without a constant (i.e., nonzero intercept). Although the idle periods were chosen such that the water heater tank could be assumed to have no net energy change from the beginning of the period to the end of the period, the inclusion of the constant in one of the regressions is used to test whether this assumption is valid. Regression results with and without a constant are shown in Table 7 and Table 8, respectively, and Figure 15 shows the two regression lines plotted against the observed data. Although the intercept estimate is significant at the 95% confidence level and the tank loss coefficient is similar to that of other studies, the model without the constant is arguably preferable.

Table 7. Tank Heat Loss Robust Regression Results with Constant (number of observances = 113, degrees of freedom = 111)

Coefficient	Estimate	95% Confidence Interval	t Statistic	p Value
Intercept	52.821	(4.2826,101.3604)	2.1564	0.033211
Overall Heat Transfer Coefficient	3.5008	(2.7034, 4.2982)	8.6994	3.4555E-14

Table 8. Tank Heat Loss Robust Regression Results without Constant (number of observances = 113, degrees of freedom = 112)

Coefficient	Estimate	95% Confidence Interval	t Statistic	p Value
Overall Heat Transfer Coefficient	4.369	(4.3169,4.4211)	166.15	6.907E-136

[11] Robust regression is similar to a simple linear regression in this case, except points with high leverage are given less weight in the regression analysis (Chatterjee and Price 1991). Two points (see Figure 15), which appeared to be outliers, did not qualify for exclusion under the leverage criteria of *2/N* (Chatterjee and Price 1991)—where *N* is the number of observations—but did have a Cook's distance greater than 4/N (Bollen and Jackman 1985), which suggests that these have a large impact on the regression results. Robust regression allows these points to have lower weights.

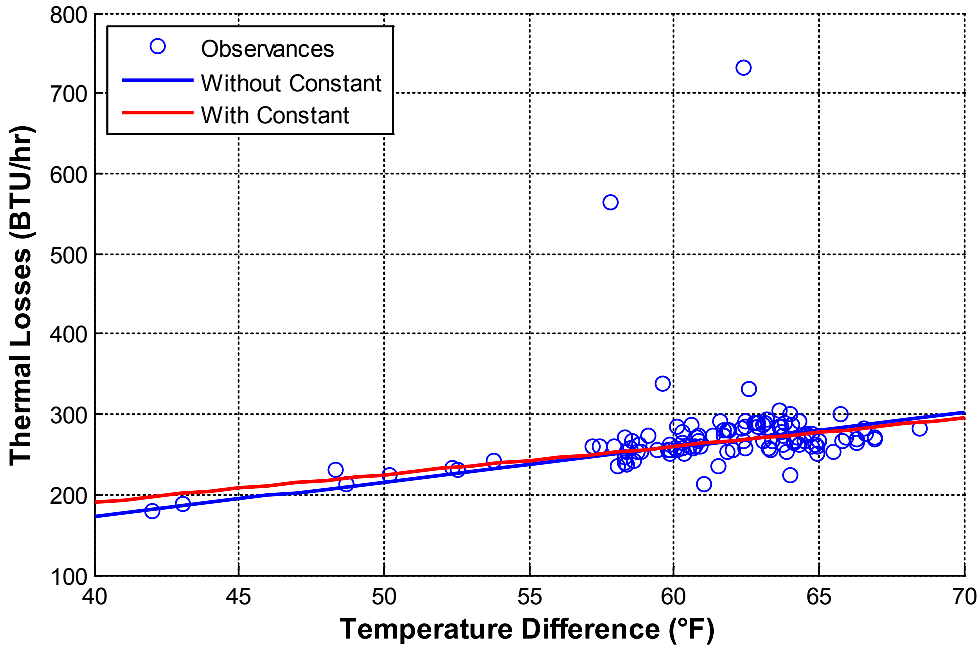

Figure 15. Regression results and data points for GE standby losses. Temperature difference is between the tank average temperature and ambient air.

Because the estimate of the heat loss coefficient is the desired result from the regression, the model with the more confined confidence interval for the slope coefficient is preferred. By including the constant in the model, the error of the heat loss coefficient estimate at the 95% confidence level is ±22.8%, meaning that calculations using this coefficient have an acceptably higher error. The corresponding error for the model without the constant is only ±1.2%, which is far more acceptable for energy balance calculations. One could also argue that a higher confidence level should be used in this analysis, because the model represents a physical system with a well-known response and should follow a well-described deterministic phenomenon. The heat transfer coefficient for the model without the constant is 4.312 Btu/h-°F.

4.5 Impact of Confined Spaces

Because HPWHs remove heat from the ambient air, a sufficient volume of available air is needed to ensure proper performance of the unit. Several laboratory studies have attempted to quantify the impact of installing HPWHs in spaces without proper air volume. All these tests were performed on the GE GeoSpring. Advanced Energy compared two HPWHs, one placed in a 220.5-ft^3 uninsulated space and another subjected to the default operating conditions. GE recommends a volume of 750 ft^3 (GE 2010). The efficiency of the unit in the confined space was 10% lower than the control unit (Fitzpatrick and Murray 2011). The Florida Solar Energy Center also tested an HPWH in a confined space (92.5 ft^3) and saw a reduction in efficiency of 13% (Colon 2012). The National Renewable Energy Laboratory's laboratory tests included blocking the airflow of the unit with tape. Blocking the airflow by 33% and 67% had only a minor impact on the performance of the unit, most of which was attributable to the increased fan energy use (Sparn et al. 2011). This suggests that the volume of air available to the unit is more important than constriction of airflow.

The HPWH at Site 13 was installed in a confined space with approximately 400 ft^3 of available air. The heating event shown in Figure 16 resulted in a measured COP of 2.02; the resulting performance drop was approximately 15.8% lower than an approximate expected COP of 2.4 at a set point temperature of 130°F. The performance reduction is similar to those found by Fitzpatrick and Murray (2011) and Colon (2012).

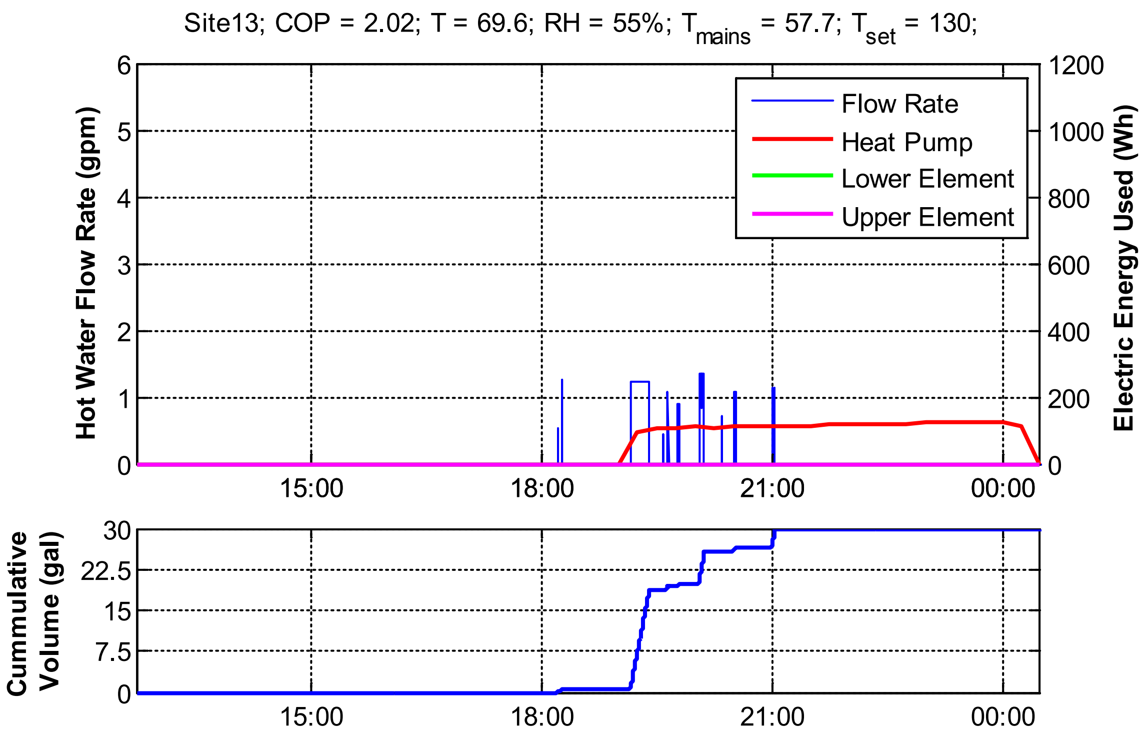

Figure 16. Performance of the HPWH at Site 13 in a confined space

4.6 Impact on Space-Conditioning Systems

Because HPWHs move heat from the air surrounding the water heater into the storage tank, HPWHs have an impact on space-conditioning loads. HPWHs in conditioned space have a very direct effect on space-conditioning loads. In the summer, HPWHs reduce the cooling load of the building; conversely, the heating load increases in the winter. The combined impact of the HPWH energy consumption and its impact on the space conditioning systems rely heavily on climate, home configuration, HPWH location, and the space-conditioning systems used. For more information about these impacts see the modeling results described by Hudon et al. (2012). A less complex analysis was also presented by Shapiro, Puttagunta, and Owens (2012).

For HPWHs installed in unconditioned or “semiconditioned” spaces such as basements, the space-conditioning impacts are harder to determine. These spaces act as buffers, so the heat transferred from the space into the storage tank is not necessarily transferred from the conditioned spaces. Air infiltration into the buffer space, ground coupling, solar gains, and heat transfer from mechanical equipment can all affect heat transfer between the buffer space and conditioned space. The transient effects of these heat transfer processes mean that the HPWH space-conditioning impacts are potentially reduced.

Because these transient heat transfer interactions cannot be directly addressed for the HPWHs installed in unconditioned basements in this study, the space-conditioning impacts are addressed as the maximum potential impact. The impact on the space-conditioning equipment is defined as (NREL 2012c):

$$Q_{net,space} = Q_{input} - Q_{dhw}, \tag{8}$$

where

$Q_{net,space}$	=	maximum potential thermal impact on space (Btu)
Q_{input}	=	electric energy used by the water heater (Btu)
Q_{dhw}	=	thermal energy removed from storage tank (Btu).

The maximum potential thermal impact on the space-conditioning equipment on the space is negative when thermal energy is being removed from the space and positive when the energy is being added to the space. In the case of standard water heaters, $Q_{net,space}$ is positive, but for HPWHs the net energy to the space is negative.

Although the HPWHs remove energy from the space, the impact on the space-conditioning loads depends on the season. For this analysis, the cooling season for these sites was considered to be June through September, and all other periods were considered the heating season. Box plots of the hourly load and seasonal space-conditioning impacts are shown in Figure 17 (negative values reduce the space-conditioning loads and positive values increase the space-conditioning loads). Box plots display the range of data for each of the categories. In the plots, the boxes represent the inner two quartiles—also called the *inner quartile range*—where the lower quartile is the bottom of the box and the upper quartile is the top of the box. The red line in the middle of the box represents the median. At the top and bottom of the boxes are whiskers that represent the smallest and largest observations within the 1.5 inner quartile range. Outliers are represented by a red plus, and the mean is represented by a black plus.

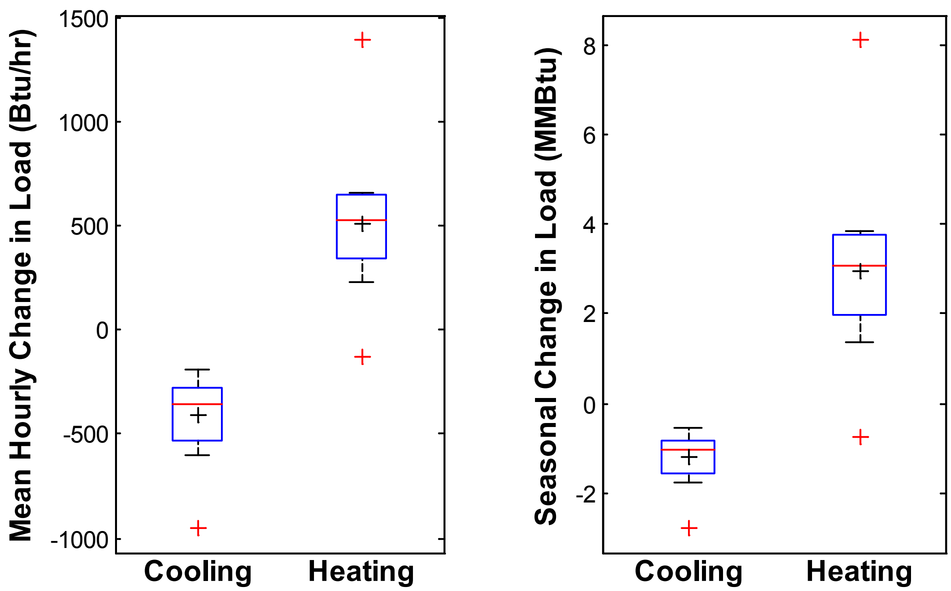

Figure 17. Box plots of maximum potential space-conditioning impacts for monitored HPWHs

As shown in the box plots, the magnitude of the mean hourly heating impact is slightly higher than that of the mean hourly cooling impact. Similarly, the magnitude of total heating seasonal impact is nearly twice that of the total cooling seasonal impact. These box plots show that the homes in this study, which are all in northern climates, had maximum potential seasonal cooling load reductions of approximately 1.5 MBtu and heating load increases of approximately 3 MBtu.

5 Energy and Cost Analysis

Energy and cost savings potentials of HPWHs were investigated against eight alternative storage tank water heaters: electric resistance; standard natural gas, fuel oil, and propane; premium natural gas, fuel oil, propane; and condensing natural gas. Tankless water heaters were not considered, because a more complicated modeling procedure to account for the transient response of these water heaters would be necessary. The assumed EFs, recovery efficiencies, and pilot light energy are listed in Table 9, where all standard and premium fossil-fuel-based systems are assumed to have the same operating characteristics except for the energy source used to provide the heating energy.

Table 9. Alternative Water Heaters

Water Heater	Fuel Types	EF	Recovery Efficiency	Pilot Light Energy (Btu/h)[a]
Electric Resistance	Electricity	0.92	100%	0
Standard Fossil Fuel	Natural gas, fuel oil, and propane	0.59	78%	400
Premium Fossil Fuel	Natural gas, fuel oil, and propane	0.67	82%	400
Condensing Fossil Fuel	Natural gas	0.83[b]	95%[b]	0

[a] WATSMPL default (EPRI 2000)
[b] Efficiencies from laboratory testing by PG&E (2008)

The alternative water heaters were simulated using the equations underlying the WATSMPL simplified water heater software (EPRI 2000). The daily operating conditions at each site—set point temperature, mains temperature, volume of water drawn, and ambient temperature—were simulated for each using the equations in Appendix B. The monitored (in the case of the HPWHs) and simulated energy consumption (in the case of the alternative water heaters) were normalized to yearly energy consumption. The normalization procedure accounts for the fact that the monitoring period at each site was different and some overlap occurred in the days that were monitored.

Although energy use is usually measured in site energy—which is the energy used at the home and is typically measured at a utility meter in kilowatt-hours (electricity)—therms (natural gas), or gallons (fuel oil or propane), a better metric for measured energy use is source energy, which is the sum of energy used at the home and the energy lost to extraction, conversion, or transmission. Site energy is easily converted to source energy using site-to-source ratios (Deru and Torcellini 2007), which are defined to the fuels studied in Table 10. Energy use is thus reported in source energy and cost to consumers. The site energy consumption for each water heater-site combination was converted to source energy and cost using the values listed in Table 10.

Table 10. Fuel Prices and Characteristics for Energy and Cost Analysis

Energy Source	Site-to-Source Ratio[a]	Cost[b]	Energy Content[c]
Electricity	3.365	$0.1172/kWh	3,412 Btu/kWh
Natural Gas	1.092	$1.10/therm	100,000 Btu/therm
Fuel Oil	1.158	$3.93/gal	140,000 Btu/gal
Propane	1.151	$2.85/gal	91,600 Btu/gal

[a] Deru and Torcellini (2007)
[b] Prices obtained from EIA (2012b, 2012c, 2012d). Electricity and natural gas prices represent average national prices for 2011. Fuel oil and propane prices are the average national prices for October 2011 through March 2012.
[c] Thumann and Mehta (1991)

To compare the installed HPWHs and the simulated alternative water heaters, box plots of annual source energy consumption and annual operating costs are shown in Figure 18 and Figure 19 (data tables provided in Appendix C). Figure 18 shows that HPWHs have significantly lower operating costs than electric resistance, oil, and propane, and comparable operating costs to natural gas systems. Furthermore, HPWHs have the lowest mean and median operating costs of all water-heating systems except condensing natural gas. In terms of source energy consumption, Figure 19 shows that HPWHs have the second-lowest source energy consumption of all water-heating products (a natural gas condensing tank unit is the lowest). Unlike ERWHs, which have the highest source energy consumption of all products by far, HPWHs can counteract the source energy penalty of using electricity to provide water heating. The outlier for the HPWHs in both plots is Site 5, which was operating in electric resistance mode throughout the winter months and therefore has operating costs similar to the ERWH category.

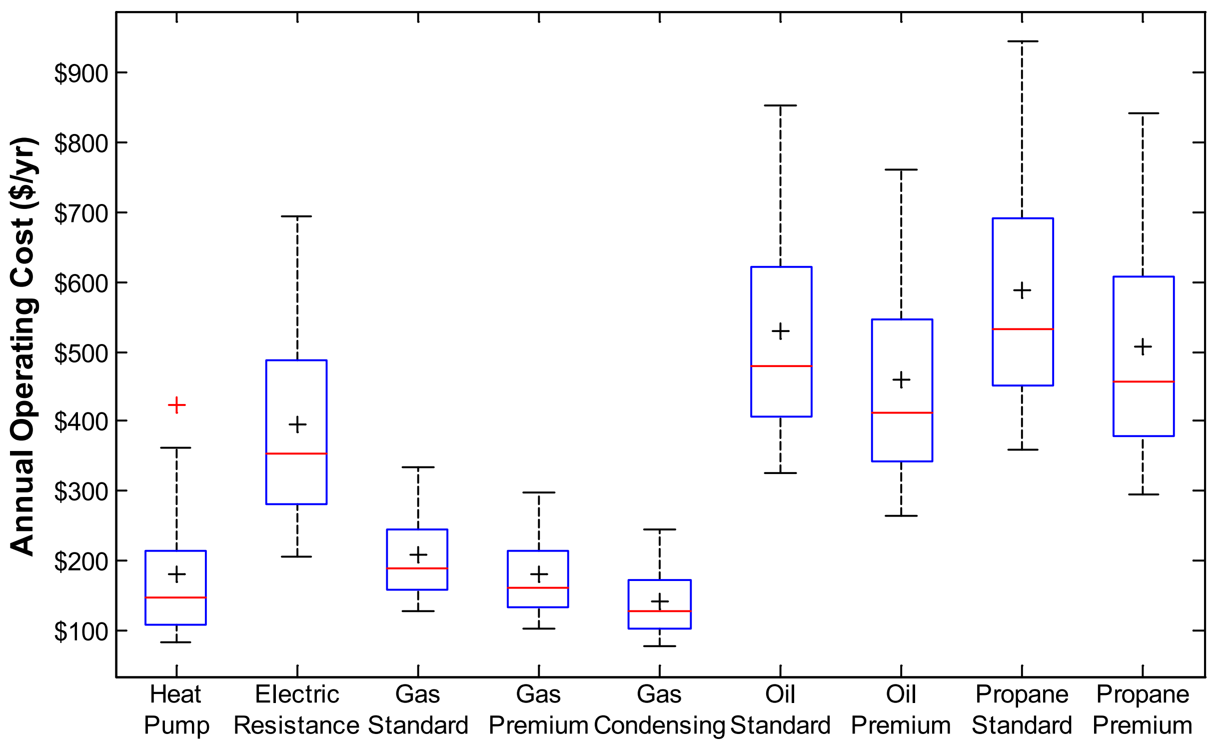

Figure 18. Annual operating cost of monitored HPWHs and alternative water heaters

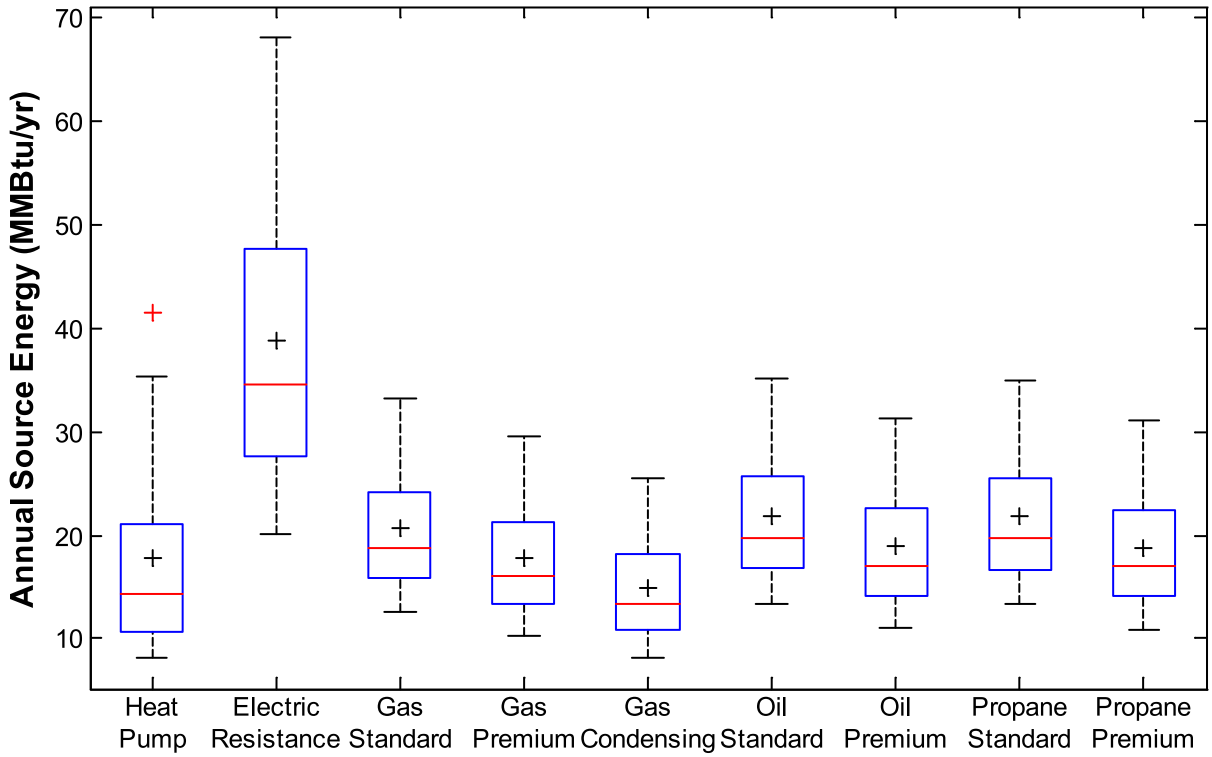

Figure 19. Annual source energy of monitored HPWHs and alternative water heaters

Although HPWHs have the second-lowest operating costs and source energy use of the water heaters considered in this study, installation costs have an impact on the overall financial outcome of HPWHs versus alternative water heaters. The cost analysis was performed as described by Polly et al. (2011). The assumptions and results are listed in Table 11. The costs were assumed to be wrapped into a 30-year mortgage at a 4.42% interest rate. These assumptions are based on wrapping the cost of the water heaters into the cost of buying a new house or mortgage refinance.

Table 11. Cost Analysis Assumptions

Cost Metric	Assumption
Analysis Period	30 years[a]
Inflation Rate	3%[a]
Real Discount Rate	3%[a]
Real Fuel Escalation Rate	0%[a]
Mortgage Rate	4.42%[b]
Mortgage Period	30 years[b]
Marginal Income Tax Rate	28%[a]

[a] Building Energy Optimization defaults (NREL 2012b)
[b] Average rate for 2011 (Freddie Mac 2012)

Table 12 lists the installation costs and typical lifetimes of the various water-heating products considered. Using these values, the annualized energy-related cost of each water-heating unit was calculated. The annualized energy-related cost represents the equivalent annual cost of the complex cash flow and represents an equivalent annual cost of operating the water heater in present dollars.

Table 12. Installation Costs and Lifetimes of Water-Heating Products

Water Heater	Installation Cost[a]	Typical Lifetime (years)[c]
Heat Pump (80 gal)	$3,300	10
Heat Pump (50-60 gal)	$2,100	10
Electric Resistance	$590	13
Standard Natural Gas	$700	13
Premium Natural Gas	$880	13
Condensing Natural Gas	$4,500[b]	15[c]
Standard Fuel Oil	$820	13
Premium Fuel Oil	$960	13
Standard Propane	$890	13
Premium Propane	$1,400	13

[a] From National Residential Efficiency Measures Database (NREL 2012a).
[b] From American Water Heaters (2008)
[c] Estimated lifetime based on National Residential Efficiency Measures Database values for gas storage and condensing tankless heaters.

The installation costs for the cost analysis were derived from the National Residential Efficiency Measures Database, but HPWH installation costs reported for this study (Table 13) were generally in line with the costs reported in the National Residential Efficiency Measures Database. These reports show shorter lifetimes for the HPWHs than the other water heater technologies, which is probably caused a desire to be conservative and rate the lifetime equal to the product warranty period. The reliability of these units is as yet undetermined, however, so the lifetime of HPWHs may be similar to other water heaters.

Table 13. 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

A boxplot showing the spread of the annualized energy-related cost for the nine water-heating technologies is shown in Figure 20. The HPWHs have lower annual energy-related costs than the electric resistance, fuel oil, and propane water heaters, although the annualized energy-related cost reduction over ERWHs is smaller than the annual operating cost savings due to the increased first cost of HPWHs. As expected, the noncondensing natural gas water heaters are still the lowest-cost option on a total life cycle basis. Space-conditioning interactions may change the relative costs of HPWHs in relation to other water heaters, depending on the climate. These interactions could not be measured in this study. Condensing tankless water heaters, which were not investigated in this analysis, have lower operating costs than even condensing storage water heaters, but the analysis method employed here does not account for the transient behavior of tankless water heaters. Tankless units have other issues, so a direct comparison may not be appropriate.

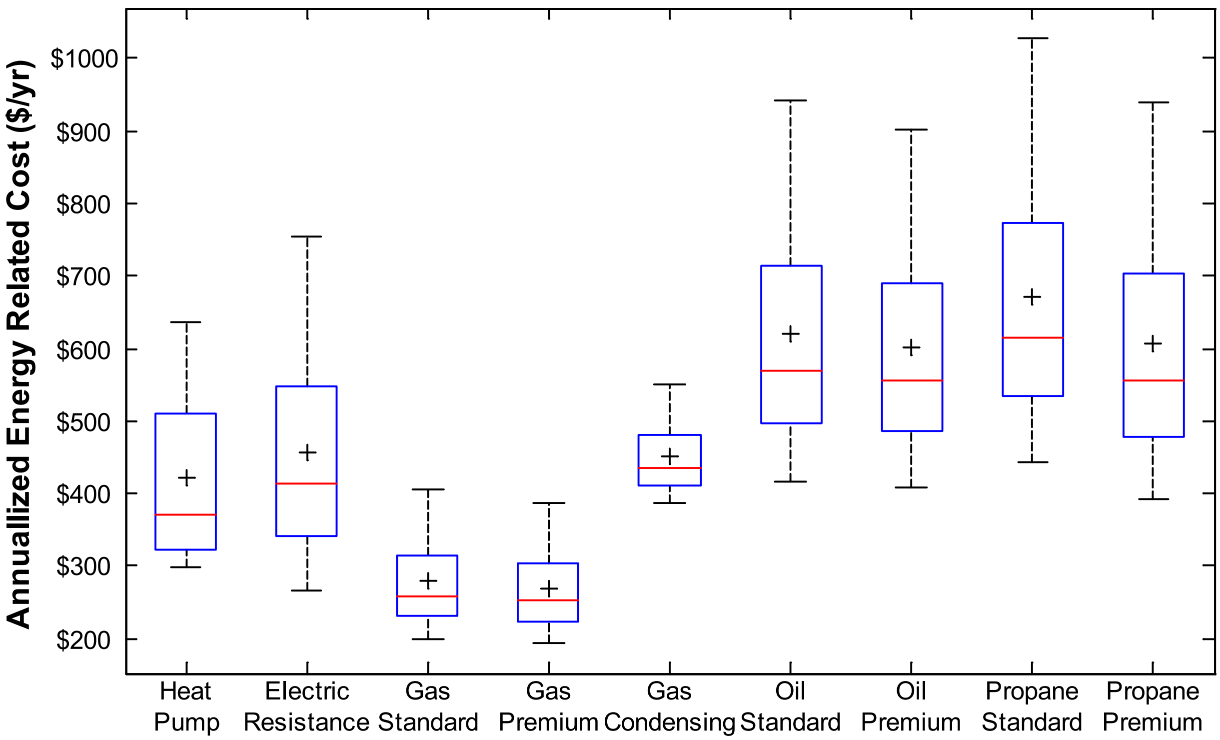

Figure 20. Annualized energy-related costs of monitored HPWHs and alternative water heaters

6 Homeowner Surveys

After complete monitoring of the HPWHs, residents at the 14 sites were surveyed about their satisfaction with the units. All the homeowners were satisfied. 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 were not a significant concern. The majority (73%) noticed lower utility bills. One "No" response to noticing utility bill savings was because 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 electricity rate (the savings were indeed due to the HPWH). Detailed survey results are shown in Table 14 and Table 15.

Table 14. Survey Results of Whether the Homeowner or a Qualified Professional Performed any Preventive Maintenance Procedures

	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

The ideal response is in green text and nonideal response is in red text. Questions in gray were not expected to be addressed because these units have not been installed long enough to warranty this level of maintenance

Table 15. Survey Results of Homeowners

	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

The ideal response is in green text, nonideal response is in red, and questions without an ideal response are in blue.

7 Recommendations

Based on the results of this report, the Consortium for Advanced Residential Buildings provides several recommendations for successful installation of HPWHs. The efficiency of HPWHs is profoundly affected by hot water use. When large quantities of hot water are used in clusters, HPWHs revert to electric resistance mode, which reduces the efficiency of the unit. A homeowner can reduce this effect by purchasing a larger HPWH, increasing the set point temperature (only for high water draw users, low water draw users will be negatively impacted by the higher standby loss resulting from a higher set point temperature), or changing behavior. By increasing the size and temperature of an HPWH, more hot water can be delivered at a given time before the resistance elements are needed. Spreading the water load over a longer period of time may also provide similar benefits and reduce standby losses.

The location of an HPWH is also an important factor to consider during installation. HPWHs operate at higher efficiencies when they are subjected to higher ambient temperatures. If possible, HPWHs should not be installed in cold locations, such as garages in northern climates. Furthermore, HPWHs require additional space to operate at peak efficiency. In this and other studies, an efficiency reduction of more than 10% was observed when HPWHs are installed in confined spaces. Finally, HPWHs remove heat from the surrounding air and can therefore affect the space-conditioning loads of a building. In cold climates, this heat removal is typically undesired, and installing an HPWH in a buffer space such as an unconditioned basement can temper the space-conditioning affects. In hot climates, removing heat can be beneficial, and the total building energy consumption can be reduced by placing HPWHs in the conditioned space.

Although HPWHs are a promising technology that may finally be here to stay, installers must still address some hurdles. Successful installation requires careful consideration of clearance and weight. With additional heating mechanisms, these HPWHs are markedly larger than ERWHs with identical storage volumes. Because HPWHs remove humidity from the air, drain pans and condensate pumps may be necessary to protect them and the floor from excess moisture. Finally, the inclusion of a heat pump means that filters must be cleaned regularly and noise could be a problem for some installations. Many of these details are discussed in more depth by Shapiro, Puttagunta, and Owens (2012) and SWA (2012).

8 Conclusion

Though the study used a small sample set, the overall performance of these 14 HPWHs has been enlightening and shows promise for this technology. To date, only one compressor for an HPWH unit had to be replaced; the cause of this failure is unclear. No other major issues have been identified about the durability and reliability of these units, but this will need to be followed up as these systems age. This evaluation successfully answered the following research questions:

- What is the measured efficiency of an HPWH located in unfinished basements of cold-climate homes?

  Even when installed in unfinished basements of cold-climate homes, the measured efficiency of these units was much higher than that of conventional ERWHs (Table 16). Except for one unit that was placed in a basement with very low ambient temperatures, the monitored units had COPs higher than 1.5, which represents more than a 50% reduction in energy consumption compared to an ERWH. The highest COP was 2.6.

  Table 16. Summary of Test Results by Model

Model	Units Monitored	Capacity (gal)	Measured Average COP	COP Range
GE	10	50	1.82	1.5–2.1
A.O. Smith	2	60/80	2.12	2.1
Stiebel Eltron	2	80	2.32	2.0–2.6

  Annual operating costs and source energy consumption for the monitored HPWHs were lower than those for the alternative storage tank water heaters considered. Annualized energy-related costs for HPWHs were slightly lower than those for ERWHs and considerably lower than those for propane- and fuel-oil-fired systems. Natural gas storage water heaters, however, were still the lowest-cost storage water heater on an annualized energy-related cost basis. Tankless water heaters were not considered here because of their more complex modeling requirements.

- What are the critical criteria that affect the installed performance of HPWHs, and how do they impact the performance of each HPWH model?

  Determining the key variables that affect performance was based on the results of the study data.. Domestic hot water use (daily volume and draw pattern) is the primary driver of efficiency, but ambient temperature plays a considerable role in expected efficiency. Lower water demand reduces the overall efficiency of the water heater by increasing the fraction of the recovery load that is standby losses. High water demand also reduces efficiency by requiring more electric resistance use. Higher ambient temperatures increase the efficiency of the heat pump and reduce standby losses.

  Although the GE unit shows two distinct operating regions that correspond to large and small electric resistance loads, the A.O. Smith and Stiebel Eltron units operate entirely in the low electric resistance region. This is most likely a product of the larger tank volumes and the control logic that allows the heat pump to reengage, in the case of A.O. Smith, or operate simultaneously, in the case of Stiebel Eltron. The Stiebel Eltron unit's higher factory-set set point temperature may also play a role.

- Does each model evaluated in this study effectively deliver hot water at the set point temperature?

  Despite the slower recovery rate of heat pump compared to electric resistance elements, the HPWHs were surprisingly able to meet very high hot water demands. The Stiebel Eltron unit in particular was able to meet large loads around 200 GPD of hot water at high COPs. The outlet water temperature during these periods never dropped below the minimum accepted water temperature of 110°F.

- What are the standby losses for these HPWHs, and how do they compare to traditional ERWHs?

  HPWHs are significantly more efficient than ERWHs; however, the standby losses of these water heaters are considerably higher than those of ERWHs. Laboratory measurements of these units in resistance mode showed values about 10% lower than a comparably sized ERWH. Laboratory testing and analysis in this study also showed higher overall heat transfer coefficient values than those for ERWHs. Tank loss coefficients calculated in this study were about 25% higher than laboratory tests, which may reflect the real-life performance of these units better than the laboratory installations. A possible explanation for this difference is that thermal shorts were introduced by the wraparound heat exchanger. Improvements in tank insulation would need to be made to reduce the thermal heat loss for these tanks.

  Although the efficiency numbers of these units are impressive, this study did not completely address the interactions between the HPWHs and the space-conditioning systems. Because the HPWHs were placed in unconditioned basements, which act as buffer spaces, the total impact on the space-conditioning system cannot be measured without more information. However, the maximum potential impact of the HPWH on the conditioning loads of the houses was approximately 3 MBtu of increased heat load and 1.5 MBtu of decreased cooling load. In other climates, the overall effect may be quite different.

- Are homeowners satisfied with hot water delivery, efficiency, noise, and other characteristics?

  Ten of the 11 survey respondents said that they would recommend an HPWH to a friend or family member. The one dissenting homeowner had an issue with the noise of the HPWH, because a home office was located in the room adjoining the basement mechanical room.

Overall, this study provides considerable data about the performance of new HPWHs in unconditioned basements in the Northeast. The efficiencies were remarkable in these installations, and these units show considerable promise. However, more research is still necessary in several areas. Understanding the affects of HPWH installation in unconditioned basements is vital for quantifying HPWH impacts on the total building energy use. Calculating the interactions among the HPWH, conditioned space, buffer space, ground, and ambient air temperature is not a trivial task.

Furthermore, more information is needed to predict the effect of draw profiles on the efficiency of these HPWHs. Although the concentration of draws clearly affects the switching between the heat pump and the electric resistance elements, a direct connection between which draw profiles trigger resistance operating and which do not has not been drawn. Understanding this connection is particularly vital for developing test procedures that can accurately predict the field performance of HPWHs.

Although HPWHs are a promising technology that may finally be here to stay, installers must still address some installation hurdles. Successful installation requires careful consideration of clearance and weight, drain pans and condensate pumps, maintenance, and noise. Many of these details are discussed in more depth by Shapiro, Puttagunta, and Owens (2012) and SWA (2012).

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Appendix A: A History of Heat Pump Water Heaters in the United States

HPWHs are not new, despite their recent reintroduction into the mainstream residential marketplace. Since the first commercialization of HPWHs in the 1950s, HPWHs have followed a boom-bust cycle of product development and subsequent abandonment that closely follows retail electricity prices and demonstrates the reliability issues of past products. Even though HPWHs failed to gain significant market traction in the past, the current confluence of regulatory, economic, and market forces may be finally pushing HPWHs into the mainstream.

The Early Years: 1935–1970

The invention of HPWHs dates back at least to 1935, when the first HPWH was patented in the United States (Wilkes and Reed 1937).[12] The HPWH described in the patent (Figure 21) looks very similar to the current batch of HPWHs, with a supplemental electric resistance element, an integrated storage tank, a motor-driven compressor, and an immersed coil condenser. A unique feature of this HPWH, however, was the use of upper and lower chambers to prevent the electric resistance element from heating the entire storage volume.

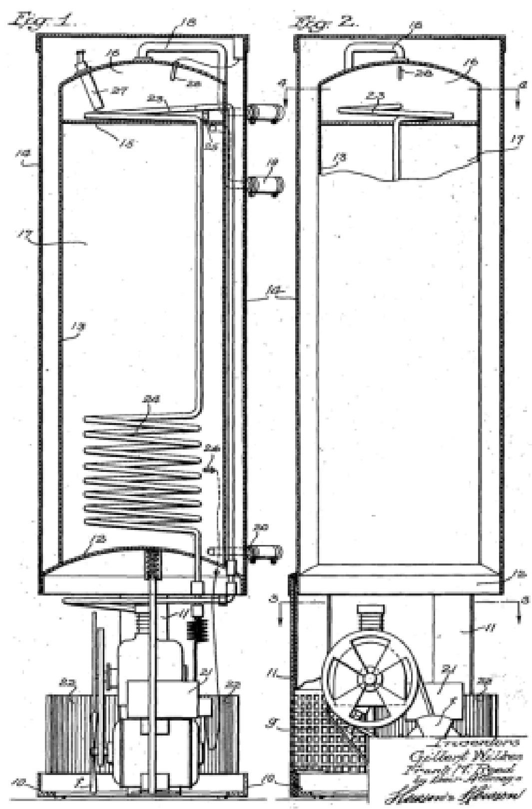


Figure 21. First patented HPWH. Image from Wilkes and Reed 1937.

[12] The search term *heat pump water heater* was used in Google's patent search, which has digitized every patent application in the United States since 1790.

Development of the first mass-market, commercialized HPWH, however, did not begin until the 1950s. A prototype developed by the Hotpoint Company—now a division of GE—performed well when monitored in collaboration with the Tampa Electric Company (Calm 1984). Throughout the 1940s and 1950s electricity prices declined considerably[13] (EIA 1996), which undoubtedly reduced the economic and commercial viability of the product. Development was discontinued, and HPWHs would not return to the mainstream market for more than 20 years (Calm 1984).

The Second Generation: 1970–1999

Interest in HPWHs subsided in the 1960s, during a period of low and falling electricity prices. By the 1970s, however, the emerging energy crisis and a spike in retail electricity prices rekindled interest in HPWHs as a mainstream, commercialized product. Retail electricity prices began to rise as fossil fuel prices spiked, utility companies overbuilt capacity based on inaccurate demand forecasts, and environmental regulation increased construction costs for capital improvements (EIA 1996).

During the mid- to late 1970s, the National Rural Electric Cooperative Association and the U.S. Department of Energy provided funding to develop a prototype HPWH. Through this funding, Energy Utilization Systems manufactured 100 HPWHs—85 integrated units and 15 add-on units—which were tested by 20 electric utilities. The add-on units were unsuccessful; however, the integrated units showed significant promise. Average COPs were around 2, operating savings approached 50%, the life span of the units matched similar natural gas water heaters and ERWHs, and consumer satisfaction was high (Calm 1984).

By the 1980s, the successful pilot program had driven HPWHs into the mainstream marketplace. *Popular Science* trumpeted HPWHs as a way to achieve "solar savings—without the cost" (Powell 1980), and HPWHs were soon eligible for state tax credits. Electric utilities, such as the Tennessee Valley Authority, pushed adoption through zero-interest loans and incentives (*Changing Times* 1982). By 1984, at least 17 commercialized HPWHs were in the marketplace under a multitude of trade names (Calm 1984).

These new units were met with enthusiasm during the early 1980s and sold more than 10,000 units per year. However, the HPWH market soon collapsed because "these early machines suffered from high purchase prices, high maintenance costs, excessive noise, poor longevity, and limited installation options." By 1995, only two manufacturers remained, and sales sat at approximately 2,000 units per year (Bodzin 1997). High first costs have been cited as a key reason for the collapse of the market (Ashdown et al. 2004), and declining electricity prices (EIA 1996, EIA 2012e) certainly played a role in the diminishing economic viability of these HPWHs.

The Third Generation: 1999–2010

Facing a collapse of the HPWH market, Arthur D. Little, Inc., ECR International, and Oak Ridge National Laboratory collaborated to develop a new integrated HPWH in the late 1990s to address the aforementioned issues with the previous generation of products. At that time, the only HPWHs on the market were add-on units to existing ERWHs. The first prototype was developed

[13] All references to electricity price changes are relative to inflation (i.e., electricity price fluctuations are stated in real terms).

in 1999, and within a year the final prototype was produced that had an EF of 2.47. The final product, which was branded as the WatterSaver, was tested for durability and field performance in subsequent years (Ashdown et al. 2004, Baxter and Linkous 2002, Tomlinson 2002).

During field testing of units across the United States, the average COP was 2, which is more than double the efficiency of a comparable ERWH (Ashdown et al. 2004). In-house durability testing at Oak Ridge National Laboratory uncovered no major durability issues (Baxter and Linkous 2002). Outside studies, however, had more mixed results from these products. A study in California found an average COP of 1.27 for sites in California (Zogg, Murphy, and Hoyt 2004). SWA performed field-testing of 20 WatterSaver HPWHs in 2002 in the northeast for Connecticut Light & Power, which is a division of Northeast Utilities. With an average COP of 1.67, the efficiency of the unit was slightly lower for these field sites, and operational and reliability issues with the units were uncovered (SWA 2004).

During the course of SWA's monitoring, customer satisfaction was fairly high, and many participants noted 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 monitoring showed that water temperatures near the tops of the tanks often exceeded 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). These issues were communicated to the manufacturer (SWA 2004). Ultimately, the WatterSaver was removed from the market because of the identified problems with installed performance and a nonexistent service infrastructure (*Environmental Building News* 2005).

Current Products: 2010–Present

A variety of economic and regulatory factors are pushing HPWHs back into the mainstream marketplace, as discussed in Section 1. Five major HPWH products are currently available in the water heater market. Key specifications for these HPWHs are shown in Table 17. These specifications include the two U.S. Department of Energy performance metrics: EF and FHR.[14]

The EF represents the efficiency of the electric heating elements and tank losses under a consistent, 24-hour test procedure. The FHR represents the amount of hot water that can be supplied by a fully heated storage water heater during an hour of operation. Storage tank volume is often used as a proxy for water-heating capacity, but FHR is the preferred metric. See Section 4.2 for more details about the EF and FHR test procedures.

[14] RE is also used to quantify the efficiency of natural gas, fuel oil, and propane water heaters. RE is an approximate metric of the burn efficiency of the heating device. Because electric resistance elements have an efficiency of 1, RE is not tested or reported.

Table 17. Key Specifications of Integrated HPWHs Currently Available in the U.S. Market[15]

Model	Capacity (gal)	EF	FHR (gal)	Electric Resistance Elements (kW)
GE GeoSpring	50	2.35	63	Upper: 4.5 Lower: 4.5
A.O. Smith Voltex	60/80	2.33	68/84	Upper: 4.5 Lower: 2
Stiebel Eltron Accelera 300	80	2.51	78.6	Upper: 1.7 Lower: None
Rheem EcoSense	40/50	2	56/67	Upper: 2 Lower: 2
AirGenerate AirTap Integrated	50/66	2.39/2.4	60/75	Upper: 4

Outlook for the Future

While HPWH development in the United States focused on traditional refrigerants, Japanese manufacturers, in conjunction with the Tokyo Electric Power Company, focused on developing an HPWH based on the carbon dioxide (CO_2) cycle. At the same time the WatterSaver was being developed, a Japanese consortium started developing the CO_2 HPWH, which had a COP of 3.4 when subjected to an ambient air temperature of 46.4°F and average tank temperature of 149°F. Marketed under the EcoCute brand, this CO_2 HPWH was released in 2001. The EcoCute is a split system, meaning that it does not affect space-conditioning loads. Furthermore, the units can be connected to a smart grid to try to move reheating periods to off-peak electricity periods. COPs have increased to higher than 4 in more recent models, and sales of the EcoCute have increased dramatically since its introduction (Hashimoto 2006).

The development of CO_2 HPWHs in the United States is just beginning. Market, technological, regulatory, and structural hurdles still remain for this technology, but CO_2 HPWHs have been actively pushed in recent years. Oak Ridge National Laboratory and GE have collaborated to develop a prototype integrated HPWH based on the CO_2 cycle for the residential U.S. market. Although this prototype is still in its early phases of development, future products may take advantage of CO_2 as a more environmentally benign refrigerant (Abdelaziz et al. 2012).

[15] Any omission of a manufacturer or product is unintentional, and no endorsement of any commercial product or manufacturer is implied.

Appendix B: Alternative Water-Heating Calculations

Alternative water-heating products were evaluated using the equations underlying the WATSMPL simulation program (EPRI 2000, 1995). For electric tanks the assumed recovery efficiency is 1, and the pilot load is 0. The net water-heating load is computed using the hot water load, inlet temperature, and outlet temperature:

$$Q_{net} = Vc_p\gamma\left(T_{out} - T_{in}\right), \tag{9}$$

where

Q_{net}	=	net water-heating load (Btu)
V	=	hot water use (gal)
c_p	=	specific heat of water (Btu/lb°F)
γ	=	specific weight of water (lb/gal)
T_{out}	=	outlet temperature (°F)
T_{in}	=	inlet temperature (°F).

The energy lost from the tank during the EF test $Q_{tank,EF}$ (Btu) is

$$Q_{\mathrm{tank,EF}} = Q_{water} \times \left(\frac{RE}{EF} - 1\right), \tag{10}$$

where

Q_{water}	=	thermal energy drawn during EF test (41,063 Btu/day)
RE	=	recovery efficiency
EF	=	energy factor.

The energy lost from the tank during operation minus the lost energy from the pilot load Q_{tank} (Btu) is

$$Q_{\mathrm{tank}} = Q_{\mathrm{tank,EF}} \times \left(\frac{T_{out} - T_{amb}}{135 - 67.5}\right) - RE \times Q_{pilot}, \tag{11}$$

where

Q_{pilot}	=	pilot load (Btu)
T_{amb}	=	ambient temperature (°F).

The tank combustion losses $Q_{\mathrm{combustionloss}}$ (Btu) is

$$Q_{\mathrm{combustion\ loss}} = \left(Q_{net} + Q_{\mathrm{tank}}\right) \times \left(\frac{1}{RE} - 1\right). \tag{12}$$

The gross water-heating load Q_{net} (Btu) is

$$Q_{gross} = Q_{net} + Q_{\mathrm{tank}} + Q_{\mathrm{combustion\ loss}} + Q_{pilot}. \tag{13}$$

Appendix C: Monitored and Modeled Energy Use and Costs by Site

Using the equations listed in Appendix B and the operating characteristics discussed in Section 5, the following site energy, source energy, and annual operating costs are listed in Table 18 through Table 21. HPWH numbers are annualized based on monitored data, and all other systems are modeled using the operating conditions measured for each HPWH site.

Table 18. Annual Site Energy Consumption by Site

Site	HPWH (kWh)	ERWH (kWh)	Standard Gas (therms)	Premium Gas (therms)	Condensing Gas (therms)	Standard Oil (gal)	Premium Oil (gal)	Standard Propane (gal)	Premium Propane (gal)
1	1,155	3,045	173	149	117	124	106	189	163
2	1,969	5,899	304	271	221	217	193	331	295
3	1,838	4,152	222	195	157	158	139	242	213
4	1,186	2,981	169	145	115	120	104	184	159
5	3,612	4,739	258	225	180	184	161	281	246
6	892	2,502	149	126	98	106	90	162	137
7	714	1,756	116	95	71	83	68	126	103
8	909	2,403	144	122	94	103	87	157	133
9	1,169	2,665	154	132	103	110	94	168	144
10	1,475	3,434	198	169	133	141	121	216	185
11	3,080	5,927	303	271	222	216	193	330	296
12	1,380	3,114	176	151	120	125	108	192	165
13	1,317	2,393	145	122	94	104	87	158	133
14	922	2,235	136	114	88	97	82	148	125

Table 19. Annual Source Energy (MMBtu) Consumption by Site

Site	HPWH	ERWH	Standard Gas	Premium Gas	Condensing Gas	Standard Oil	Premium Oil	Standard Propane	Premium Propane
1	13.3	35.0	18.9	16.3	13.5	20.1	17.2	19.9	17.1
2	22.6	67.7	33.1	29.6	25.4	35.2	31.3	34.9	31.2
3	21.1	47.7	24.2	21.3	18.1	25.7	22.6	25.5	22.4
4	13.6	34.2	18.4	15.9	13.2	19.5	16.8	19.4	16.7
5	41.5	54.4	28.1	24.6	20.8	29.8	26.1	29.6	25.9
6	10.2	28.7	16.3	13.8	11.3	17.2	14.6	17.1	14.5
7	8.2	20.2	12.6	10.3	8.2	13.4	11.0	13.3	10.9
8	10.4	27.6	15.7	13.3	10.8	16.7	14.1	16.6	14.0
9	13.4	30.6	16.8	14.4	11.9	17.8	15.3	17.7	15.2
10	16.9	39.4	21.6	18.5	15.3	22.9	19.6	22.8	19.5
11	35.4	68.1	33.1	29.6	25.5	35.1	31.3	34.8	31.2
12	15.8	35.8	19.2	16.5	13.8	20.3	17.5	20.2	17.4
13	15.1	27.5	15.8	13.3	10.8	16.8	14.1	16.7	14.0
14	10.6	25.7	14.8	12.5	10.1	15.7	13.2	15.6	13.1

Table 20. Annual Operating Costs ($) by Site

Site	HPWH	ERWH	Standard Gas	Premium Gas	Condensing Gas	Standard Oil	Premium Oil	Standard Propane	Premium Propane
1	135	357	191	164	129	486	418	539	463
2	231	691	334	298	243	852	760	944	842
3	215	487	244	214	173	622	547	690	607
4	139	349	185	160	126	473	408	525	452
5	423	555	283	248	198	723	632	801	700
6	105	293	164	139	108	418	353	463	392
7	84	206	127	104	78	325	266	360	295
8	107	282	158	134	104	404	341	448	378
9	137	312	170	145	114	433	370	480	410
10	173	403	218	186	146	556	476	616	527
11	361	695	333	298	244	850	760	942	842
12	162	365	193	167	132	493	425	546	471
13	154	280	159	134	103	407	342	451	379
14	108	262	150	126	97	382	320	423	355

Table 21. Annualized Energy-Related Costs ($) by Site

Site	HPWH	ERWH	Standard Gas	Premium Gas	Condensing Gas	Standard Oil	Premium Oil	Standard Propane	Premium Propane
1	471	417	262	253	437	577	560	622	561
2	567	751	405	387	551	943	902	1,028	940
3	429	547	315	304	481	713	690	773	704
4	353	410	257	249	434	564	550	608	550
5	637	616	355	337	506	814	774	885	798
6	318	353	235	228	415	508	496	547	490
7	298	266	199	194	386	416	408	444	392
8	320	342	230	223	411	495	484	532	476
9	351	372	241	234	421	523	512	563	508
10	509	463	289	276	454	647	618	700	625
11	575	755	404	387	551	940	902	1,025	940
12	376	425	264	256	439	584	568	630	569
13	368	341	231	224	411	498	485	535	477
14	322	322	221	215	404	472	463	507	453

Appendix D: Identifying Heating Events

Choosing an appropriate analysis period to investigate the trends in the collected data is vital for untangling the various input variables that can affect performance. Looking at the data on a yearly site-by-site basis is inappropriate, because the sample size for this project is not large enough and seasonal swings in operating conditions cannot be considered. Conversely, looking at the 15-minute data is also inappropriate, because knowing the internal state of the tank, which was not monitored in this study, would be necessary to understand the transient response of the water heater to the operating conditions. Using daily data would be more appropriate, because the system can be assumed to be in a steady state—i.e., the system operating variables do not change considerably, but a larger sample size needs to be investigated.

Daily data, however, are not quite perfect, because the response rate of the heat pump system is considerably slower than other heating mechanisms. A large draw at the end of one day can be recovered entirely during the following day (Figure 22); the red ellipse highlights an incidence of such a draw. As a result of this issue, the COP trends in relation to the draw volume are reversed. One would expect the first day to have a lower COP than the second day because the draw volume is smaller, which means that the standby losses account for a larger percentage of the recovery load. The trend from using the daily data, however, is reversed, which confuses the analysis.

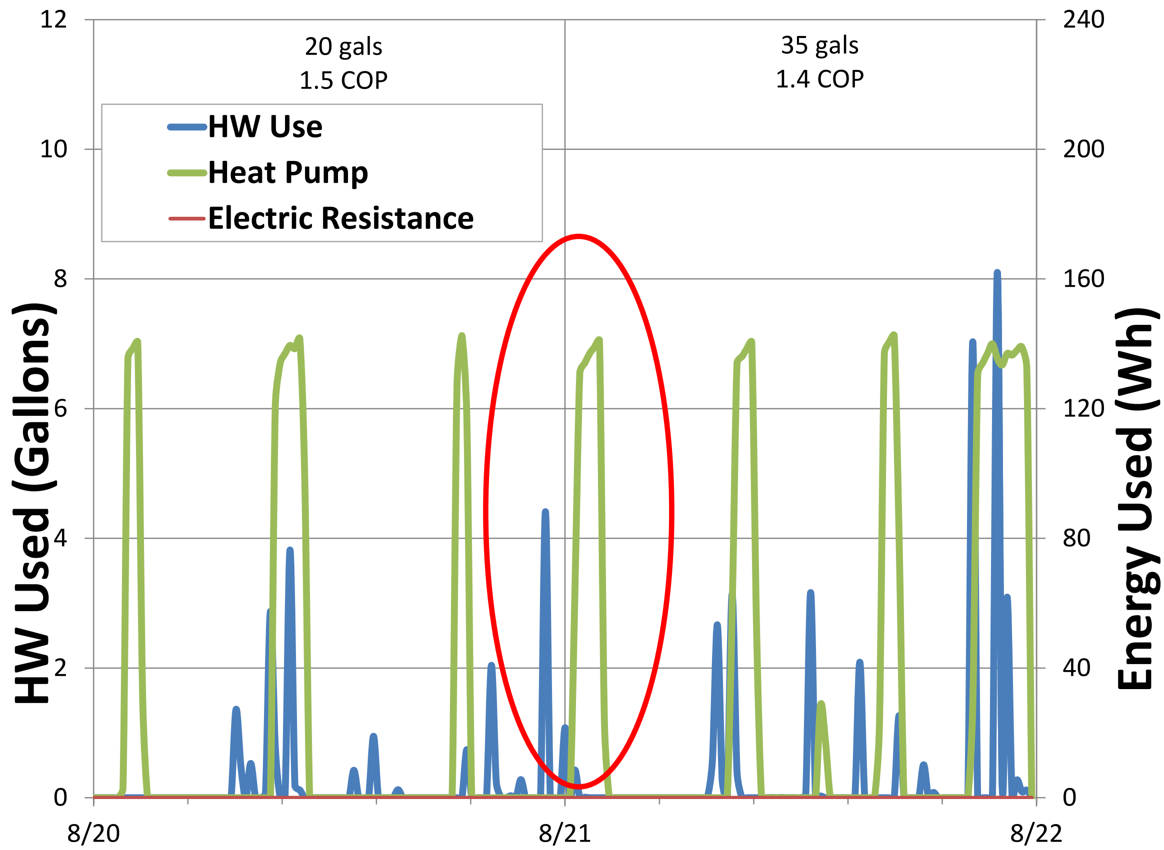


Figure 22. Results from using daily data for analysis

A solution to this problem is to find periods of time when the water-heating tank starts fully heated and ends fully heated. The criteria for finding such periods, which are defined as heating events in this study, are: (1) the heating event must be at least 4 hours long, and (2) the heating event must begin and end after a reheat cycle that has a duration one of at least 1 hour during which no draws occurred. There are some tolerances to allow for noise in the measurements.

To demonstrate how this works in practice, consider Figure 23. Five heating events are displayed in this graph, four of which have no electric resistance use. Each heating event begins and ends at the end of a reheat cycle. As shown in the figure above, the COPs are related to the draw volumes, as expected. Furthermore, the heating events have the advantage of operating near steady state, the same as the daily values but without the limitations of the daily values.

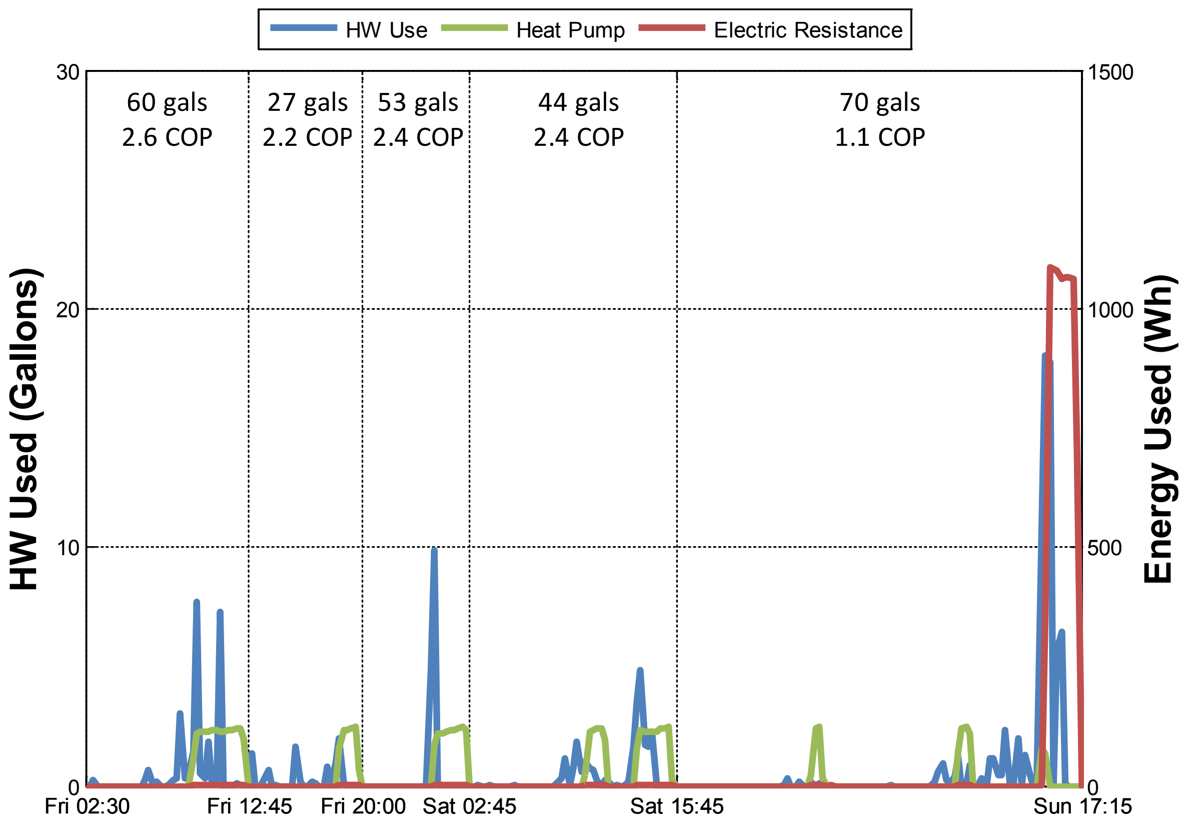
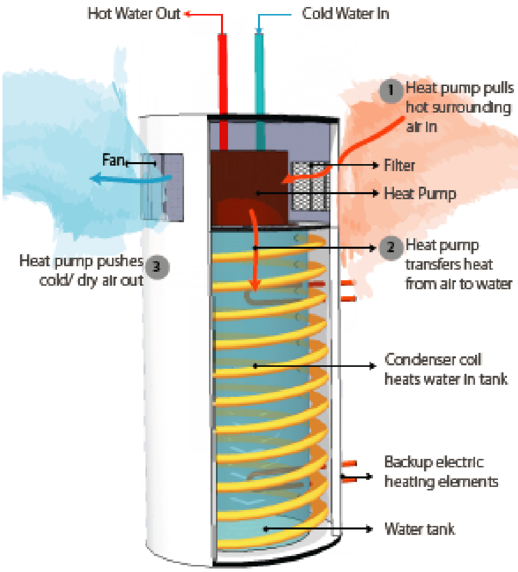


Figure 23. Example of five heating events as defined in this study

Appendix E: Trifold Brochure for Consumers

How a Heat Pump Water Heater Works



Installation

While not rocket science, installing a HPWH is more involved than installing a standard electric water heater. Make sure your contractor has the know-how to install HPWHs.

Resources

- Utility QI Guide
- Building America HPWH Measure Guideline
- EPA Energy Star Products - Water Heater, Heat Pump
- DOE Energy Savers - Heat Pump Water Heaters

Sponsored By

Cape Light Compact

nationalgrid

NSTAR

Western Massachusetts Electric
A Northeast Utilities Company

Unitil

HEAT PUMP WATER HEATERS 101

Brochure Prepared By:

Steven Winter Associates, Inc.
Improving the Built Environment Since 1972

How Much Do I Save?

No. of People	Avg. Hot Water Use (Gal/Day)	Annual Hot Water Cost ($)	HPWH Savings ($)
2	40	470 / 160 - 300	$170 - $310
4	70	820 / 290-530	$290 - $530
6	100	1,180 / 410-760	$420 - $770

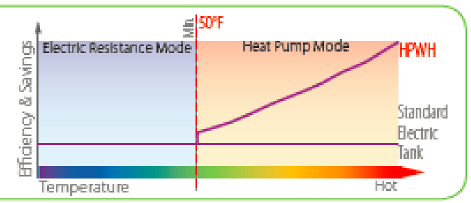
Standard Tank (EF 0.9)
HPWH*

* HPWH cost is based on performance range observed in New England Homes. Read *When Does it Work Best* for details.

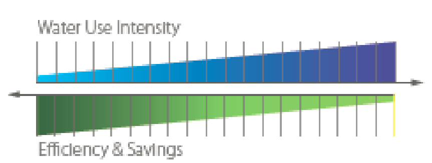
Savings depend primarily on hot water use.

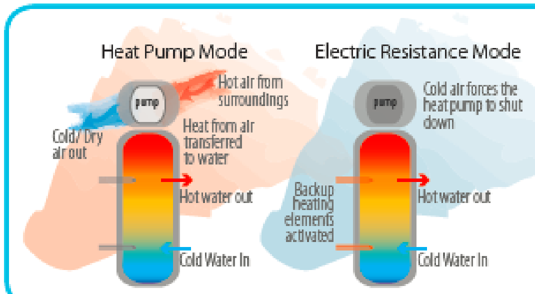
There will always be overall savings when compared to a standard electric water heater. Even if the HPWH runs in electric resistance mode all winter, during the warmer months you will benefit from the increased efficiency (along with some free cooling and dehumidification).

When Does it Work Best?



HPWHs are more efficient when the surrounding air is warmer. Intense water use may result in lower efficiencies.





What is a Heat Pump Water Heater?

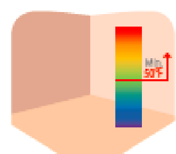
A 'heat pump' is a device that moves heat from one place to another; it works much like an air conditioner or a refrigerator. While a refrigerator moves heat from your fridge to your kitchen, a heat pump water heater (HPWH) moves heat from your home into the hot water tank. Most HPWHs include an integrated hot water tank and a 'hybrid' mode (i.e. they can also run as standard electric water heaters if necessary).

Is It Right For You?

While HPWHs can certainly provide savings over standard electric water heaters, there are several other factors to consider before buying and installing.

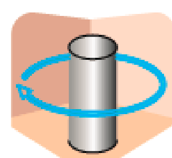
Location

For the HPWH to run efficiently, the space should generally stay above 50°F.

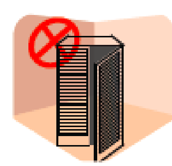


Space

A heat pump removes heat from ambient air. Hence there must be a considerable volume of air available; most manufacturers recommend about 750 ft³. HPWHs often require larger clearances from walls so that air can circulate properly, and they are often taller and heavier than standard water heaters.

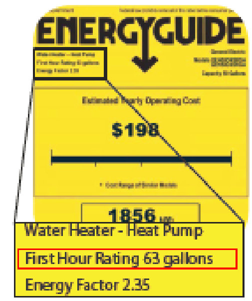


Most closets – even closets with louvered doors – are not appropriate for HPWHs.



Size

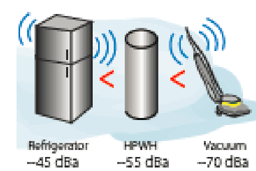
When selecting the proper water heater size and model, look at the ***First Hour Rating (FHR)*** on the yellow Energy Guide labels. Talk to your contractor or refer to manufacturers to determine what FHR is appropriate for you.



Look at the FIRST HOUR RATING NOT the tank size

Noise

Make sure the HPWH is located where this noise will not be disruptive.



Condensate Drain

Because HPWHs remove moisture from the air, the condensed water must be channeled to a drain or a condensate pump must be installed.

Maintenance

Maintenance requirements are not onerous, but they are important. Many HPWHs have air filters which should be cleaned regularly for best performance. Refer to product manuals for more information.

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