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Field Performance of Heat Pump Water Heaters in the Northeast

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Consortium for Advanced Residential Buildings

August 2013

Building AMERICA SM
U.S. Department of Energy

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

Field Performance of Heat Pump Water Heaters in the Northeast

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

Golden, CO 80401

NREL Contract No. DE-AC36-08GO28308

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Prepared under Subcontract No. KNDJ-0-40342-03

August 2013

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Definitions

AERC	Annualized energy related cost
Btu	British thermal unit
CO_2	Carbon dioxide
COP	coefficient of performance
df	Degrees of freedom
DOE	U.S. Department of Energy
EF	Energy factor
EPRI	Electric Power Research Institute
ERWH	Electric resistance water heater
FHR	First hour rating
GE	General Electric
gpd	Gallons per day
gph	Gallons per hour
gpm	Gallons per minute
kW	Kilowatt
kWh	Kilowatt-hour
lbm	Pound mass
MMBtu	Million British thermal units
N	number of observances
NREL	National Renewable Energy Laboratory
NREMD	National Residential Efficiency Measures Database
HPWH	Heat pump water heater
ORNL	Oak Ridge National Laboratory
PG&E	Pacific Gas & Electric Company
quad	Quadrillion British thermal units
RE	Recovery efficiency
SEE	Source energy efficiency
SWA	Steven Winter Associates, Inc.
therm	100,000 British thermal units
UA	Overall heat loss coefficient
Wh	Watt hour

Executive Summary

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

Steven Winter Associates, Inc. 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 performance of HPWHs under various operating conditions, but publically available field studies have not been as available. This evaluation attempts to provide publically available field data on new HPWHs by monitoring the performance of three recently released products (General Electric GeoSpring, A.O. Smith Voltex, and Stiebel Eltron Accelera 300). Fourteen HPWHs were installed in Massachusetts and Rhode Island and monitored for more than one year. Of the 14 units, 10 were General Electric models (50-gal units), two were Stiebel Eltron models (80-gal units), and two were A.O. Smith models (one 60-gal and one 80-gal unit).

Although this study used a small sample size and all of the water heaters were in unconditioned basements in homes in the Northeast, the HPWHs studied show great promise. Excluding one site, the monitored units had coefficients of performance (COPs) of 1.5–2.6. The excluded site had ambient air temperatures < 50°F for much of the year resulting 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)	Rated Energy Factor	First Hour Rating (gph)	Measured Average COP	COP Range
General Electric	50	2.35	63.0	1.82	1.5–2.1
A.O. Smith	60/80	2.33	68.0/84.0	2.12	2.1
Stiebel Eltron	80	2.51	78.6	2.32	2.0–2.6

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 will reduce efficiency by increasing auxiliary electric resistance use. Higher ambient temperature will increase efficiency by increasing the efficiency of the heat pump and reducing standby losses. While the General Electric 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.

Despite the slower recovery rate of the heat pump compared to electric resistance elements, all three models delivered hot water at temperatures above a minimum acceptable temperature of 110°F during the vast majority of 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. Potential causes are the additional piping, wrap-around condensing unit, or inadequate insulation. Installation of HPWHs in confined spaces was also found to reduce 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 are considerably lower than those for propane- and fuel-oil fired systems. Natural gas storage water heaters, with the exception of condensing storage water heaters, have 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, are still the lowest cost storage water heater option on an annualized energy-related cost basis.

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 takes effect in 2015 that mandates energy factors (EFs) around 2.0 for all new electric storage water heaters with capacities > 55 gal (DOE 2010).[1] This regulation is a major driver of change in residential water heating technologies (Maynard 2011) because it effectively requires installation of HPWHs in applications with large hot water loads and where electricity will be used for water heating. In addition, for energy-conscious consumers looking 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 water heating 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, while HPWHs have higher first costs than traditional electric resistance water heaters (ERWHs), many utility companies are offering sizeable rebates for HPWH installations[3] in the hopes of making HPWHs 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 portion 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.

---

[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 1.92–1.99 for rated tank volumes between 55 and 119 gallons, 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).

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 (MMBtu)	U.S. Total (quads)	Per House-hold ($)	U.S. Total (billion $)
Electricity (kWh)	43.3	2,813	0.42	32.3	1.40	330	14.28
Natural Gas (therms)	59.8	241	1.44	26.3	1.57	265	15.80
Fuel Oil (gal)	4.3	226	0.14	36.6	0.16	887	3.81
Propane (gal)	5.8	277	0.15	29.2	0.17	790	4.58

Source: Adapted from EIA (2005).

Since all new HPWHs have a listed EF of 2.0 or higher, compared with EFs of 0.9–0.95 for resistance water heaters,[4] if all electric water heaters were replaced with HPWHs and these water heaters performed at their rated efficiencies, American consumers could save $7.8 billion annually (average of $182 per household) in water heating operating costs and cut annual residential source energy consumption for water heating by 0.70 quads. As HPWHs are not appropriate in all circumstances, and they may increase space-conditioning loads in some cases, these figures represent the upper limit of potential savings based on EF ratings associated with the move from ERWHs to HPWHs in the United States.

At the time this report was published, there were five major integrated[5] HPWH products in the American market. Key specifications for these HPWHs are shown in Table 3. These specifications include the two U.S. Department of Energy (DOE) 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-h 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 2.1 for more details regarding the EF and FHR test procedures.

[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 5.1 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. There are add-on HPWHs that are 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. Since electric resistance elements have an efficiency of 1, RE is not tested or reported.

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)
GE GeoSpring	50	2.35	63.0	Upper: 4.5 Lower: 4.5
A.O. Smith Voltex	60/80	2.33	68.0/84.0	Upper: 4.5 Lower: 2.0
Stiebel Eltron Accelera 300	80	2.51	78.6	Upper: 1.7
Rheem EcoSense	40/50	2.00	56.0/67.0	Upper: 2.0 Lower: 2.0
AirGenerate AirTap Integrated	50/66	2.39/2.40	60.0/75.0	Upper: 4.0

1.1 Background

While regulatory and economic factors may finally be 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 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.

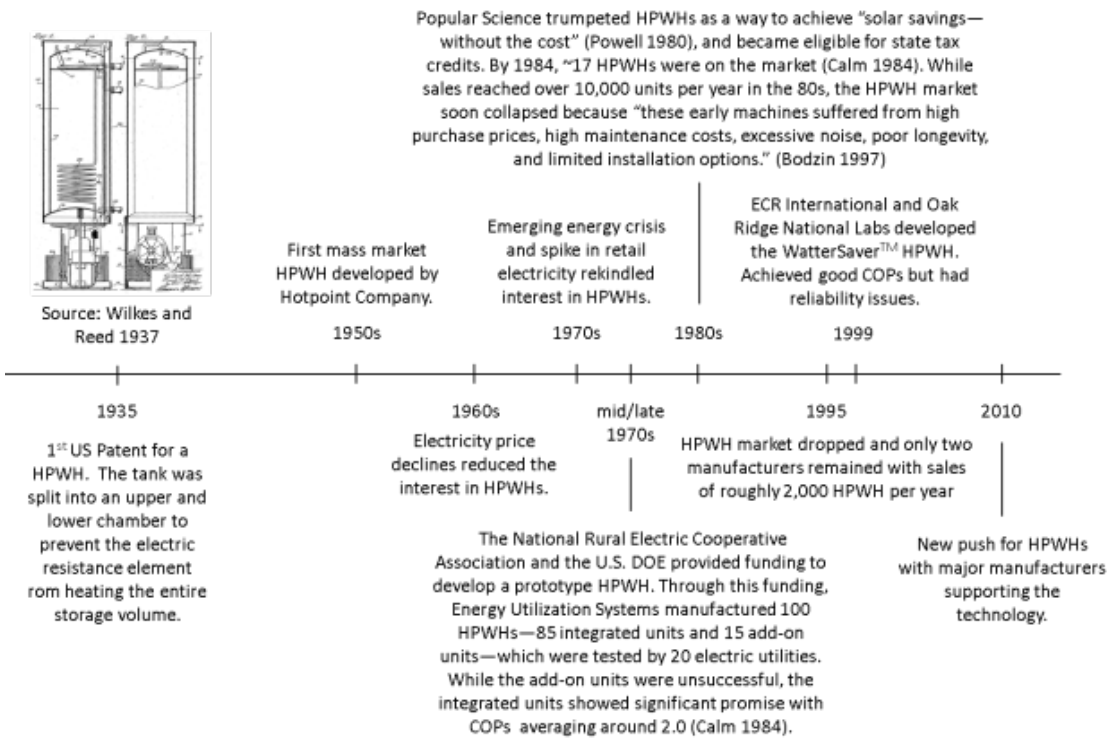

Figure 1. Timeline of HPWH development in the United States

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

As a result of the convergence of regulatory and financial forces that have pushed HPWHs into the mainstream residential market and the magnitude of the savings potential represented by this market, Steven Winter Associates, Inc. (SWA) 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 not been as forthcoming. This evaluation attempts to provide publically available field data on new HPWHs by quantifying the field 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 one 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), two were Stiebel Eltron models (80-gal units), and two were A.O. Smith models (one 60-gal and one 80-gal unit). The ten 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 are able to 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. While a refrigerator moves heat from the inside of the appliance into the kitchen, the heat pump inside a 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 operate at efficiencies > 200% in most cases.

Most HPWHs, however, are hybrid devices that combine a heat pump, backup electric resistance element(s), and a storage tank (Figure 2). While the heat pumps in these hybrid water heaters can heat water at high efficiencies, the recovery rate of these mechanisms is significantly slower than that of traditional electric resistance heating mechanisms. A typical 4.5-kW electric resistance element can reliably heat more than 20 gph of water. The heat pump has a lower heating rate; GE, for example, publishes a rate of 8 gph at 68°F air temperature (General Electric 2010). As a result, auxiliary electric resistance elements are 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 when there are large hot water needs.

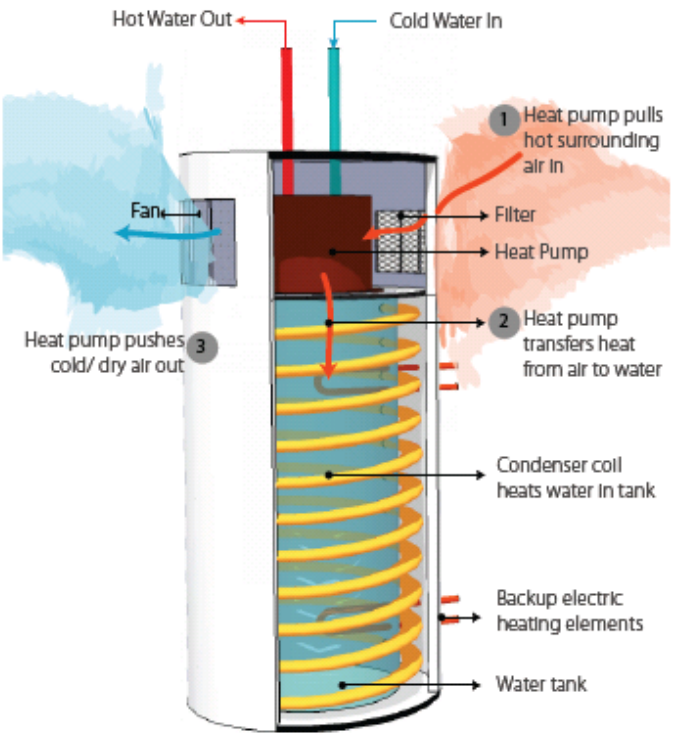

Figure 2. How HPWHs work

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 standalone heat pumps that are combined with traditional electric resistance tank water heaters. 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, however, can be used as retrofits to existing water heaters at a lower cost (Ashdown et al. 2004).

Integrated devices come in three different configurations of heat exchangers. The most common configuration in the United States is a wrap-around 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. Immersion coils, where the refrigerant coils are directly immersed in the potable water, are used in the Air Generate AirTap. Finally, coaxial heat exchangers can be used, as with the Rheem EcoSense, where 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 wrap-around 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. The Stiebel Eltron HPWH 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 will directly affect the space conditioning loads of the building. During the heating season, HPWHs increase loads on space heating systems. Conversely, HPWHs will 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. As most basements are thermally connected to conditioned space, HPWHs will 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.

Since these hybrid HPWHs are new to the mainstream market, installation will not be as straightforward for installers as for 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 substantially larger than typical ERWHs. Installers may not be familiar with these units or heat pump models in general, and it may be difficult to install these units in existing homes. Additional licensing considerations are also applicable to HPWHs. As with all systems connected to potable water, installers are typically required to be licensed plumbers. In some cases state or local regulations may be vague as to whether licensed plumbers may install HPWHs without also obtaining additional licensing for mechanical or electrical trades (Ashdown et al. 2004).

During installation the Consortium for Advanced Residential Buildings noted specific challenges faced by the installer at the various sites. Many of these details are discussed in more depth by Shapiro et al. (2012). Installation considerations are further discussed in SWA (2012), which SWA worked on with the sponsors of this evaluation for use in their rebate programs. In addition, a tri-fold brochure for consumers (Appendix F) was created for their rebate programs.

1.4 Model Operation and Control Logic

While all three of the monitored HPWHs have similar components, the control logic differs substantially between 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, while 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 wrap-around 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, and Vacation (General Electric 2009). The control logic for these modes is described below:

- **Hybrid Mode** is the default operating mode. While the control logic for the GE unit is proprietary, the general operating principle behind the hybrid mode is to balance energy savings while providing hot water at rates similar to comparably sized ERWHs. As a result, the control logic tries to meet certain targets for availability of hot water. The unit will use 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. Since the unit does not measure average tank temperature or hot water flow rate directly and measures only the temperature at the top third of the tank, 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 will revert to standard resistance mode. If the water in the tank is significantly lower than the set point, then upper element will operate. The difference between the tank temperature and the set point depends on the circumstances, but is generally 25°–30°F. If the system senses that the water use is too high, then the lower element will operate. 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 will be 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 2.0-kW lower element. The A.O. Smith model has four operating modes, Hybrid, Efficiency, Electric, and Vacation (A.O. Smith 2010). The control logic of the A.O. Smith unit, however, is quite different than 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 upper and lower thermostats, where the upper thermostat gets 75% weighting (Sparn et al. 2011)—drops 9°F below the set point, the heat pump will be 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 will replace 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 will be used first to heat the top of the tank, and then the lower element will be used to heat the bottom of the tank (A.O. Smith 2010).
- **Vacation Mode** is identical to the 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 operation 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 below 112°F, the upper element is used as a backup heat source. The upper element will heat 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 heat pump water heating products, a growing body of literature has been devoted to measuring the performance, energy, and cost savings potential, and reliability of these new HPWHs. These reports can be broken down into four basic categories: (1) laboratory tests using variations on the approved DOE 10 CFR Part 430 testing procedures (DOE 1998); (2) laboratory tests using different draw profiles or analysis metrics that attempt to simulate real-world operating conditions; (3) field tests of in situ performance of HPWHs under real, random operating conditions; and (4) cost-benefit analyses that analyze the cost effectiveness of HPWHs as an energy reduction strategy. In order to compare the results of this field testing study to those of previous studies, all publically available prior research was aggregated.

2.1 Laboratory Testing: U.S. Department of Energy 10 CFR Part 430 and Related Testing

While EF and FHR are measured by qualified laboratories and advertised prominently for every HPWH, several laboratories have used variations on these tests to measure how various operating variables affect the rated EF and FHR. Furthermore, the tank heat loss coefficient (UA) and RE, which can be calculated from the standard test but are not reported, were calculated by many of these laboratories. The standard operating conditions for these tests are shown in Table 4.

Table 4. Standard DOE Test Procedure Conditions

Measurement	Required Testing Conditions
Ambient Temperature (°F)[a]	67.5 ± 1.0
Ambient RH (%)[b]	50 ± 12
Supply Water Temperature (°F)	58 ± 2
Set Point Temperature (°F)	135 ± 5
Flow Rate (gpm)	3.00 ± 0.25

[a] For HPWHs only; other systems may be 67.5°F ± 2.5°F
[b] For HPWHs only; other systems have no relative humidity requirements.

The EF represents the efficiency of the electric heating elements and tank losses under a consistent, 24-h test procedure. This procedure is known as the 24-h simulated use test and is meant to provide a consistent metric with which to measure residential water heating products. In this procedure, 64.3 ± 1 gal of water are drawn from the tank in six equal draws spaced 1 h apart. The EF is the ratio of energy output to energy input during the test procedure adjusted for the change in the stored energy of the tank during the test.

The RE is meant to represent the efficiency of the heating system (i.e. the conversion efficiency of a fossil fuel system or coefficient of performance [COP] of a heat pump system). The RE is measured using the recovery of the system following the first draw of the simulated use test. The RE is the ratio of the energy drawn from the tank over the energy use of the water heater, correcting for the change in the stored energy of the tank during the test. RE is not reported for HPWHs, although it could be directly measured from the rating procedure.

The FHR is meant to represent the amount of hot water that can be delivered by a residential water heater during a 1-h period if the tank begins fully heated. During the test, water is drawn at 3.0 ± 0.25 gpm until the outlet temperature of the water drops 25°F below the maximum delivered

temperature. A new draw is initiated once the heating element(s) have stopped operation. The FHR is the amount of water removed from the tank during the test, corrected for the elapsed time of the test, which can vary depending on the recovery time of the heating elements and storage volume of the tank.

Recent studies have measured the performance of HPWHs using the standard DOE rating procedures specified under 10 CFR Part 430. In addition to reporting the EF and FHR, many of these studies also report the RE and UA, which are both defined in 10 CFR Part 430, but not reported. Furthermore, many of these studies perform the standard tests under conditions that are slightly different from those specified in 10 CFR Part 430. These different testing conditions allow comparisons between the field performance of water heaters and the laboratory testing ratings at varying operating conditions. In order to facilitate these comparisons, laboratory ratings from these studies (Table 5) are aggregated in the tables in Appendix E for the five major HPWH products currently on the market. The tables in Appendix E compare the laboratory values that were determined for EF, FHR, UA, and RE.

Table 5. Aggregated Laboratory Studies

Reference Study	Source	Units Studied
A	Norhwest Energy Efficiency Alliance (Larson and Logsdon 2012)	GE
B	Bonneville Power Administration (Larson et al. 2011)	Rheem and GE
C	Electric Power Research Institute (EPRI) (Amarnath and Trueblood 2010)	A.O. Smith, Rheem, and GE
D	Pacific Gas and Electric (PG&E) (PG&E 2010)	Rheem and GE
E	National Renewable Energy Laboratory (NREL) (Sparn et al. 2011)	Air Generate, A.O. Smith, Rheem, GE, and Stiebel Eltron
F	Advanced Energy (Fitzpatrick and Murray 2011)	GE
G	Florida Solar Energy Center[a] (Colon 2012)	GE

[a] Only measured system COP[8] and not included in 10 CFR Part 430 tables

The results in the tables in Appendix E show EF values and FHRs that are all over the map. The variation in tested EF is unsurprising, considering the large error in the tested values implicitly allowed in the EF test (Healy et al. 2003) and the fact that many of these laboratories are not certified under 10 CFR Part 430 to test water heaters. For example, the EF measurements for the laboratory tests summarized in Appendix E are plotted against the set point temperature in Figure 3. The values are considerably different from each other and consistently higher than the rated value.

[8] COP is a fraction that represents the efficiency of a system. In the case of HPWHs, COP may represent the efficiency of the heat pump or the overall system. In this paper, the COP represents the COP of the overall system. COP is in the same units as EF, except it does not have to be calculated under the operating conditions specified by the test procedure.

The results, however, do show the expected inverse relationship between set point temperature and efficiency. The best fit equation shown in Figure 3 can be used to determine the effect of using a lower set point temperature than the set point used under the DOE test.

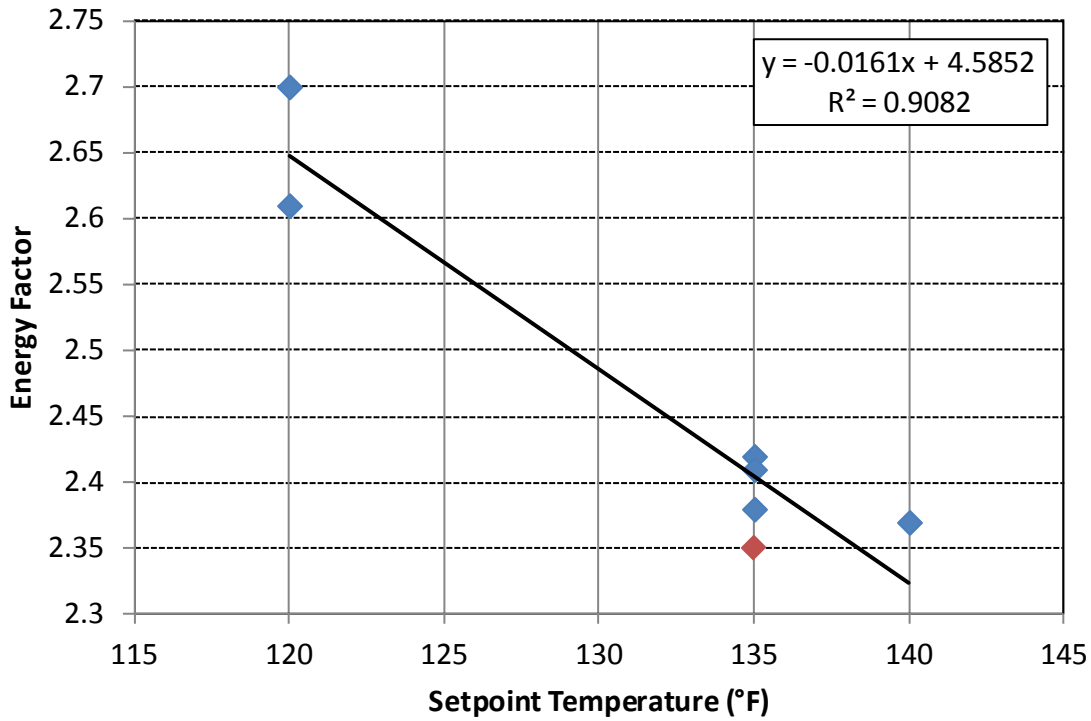

Figure 3. EF for GE GeoSpring by set point temperature. Blue represents laboratory measurements. Red indicates the rated EF.

The EF measurements of the GE and Rheem units operating in electric resistance mode offer some interesting insights into the performance of these water heaters. Surprisingly, the measured EF in electric resistance mode for these units was 0.84 and 0.82, respectively, which is considerably lower than a comparably sized ERWH. As a result, the thermal insulation of these units must be lower than comparable ERWHs. A possible explanation for this difference is the existence of thermal shorts introduced by the wrap-around heat exchanger in the GE unit or the piping for the heat pump in the Rheem unit. Improvements could be made to reduce the thermal heat loss for these tanks.

2.2 Laboratory Testing: System Coefficient of Performance

COP values that were generated in laboratory studies are displayed in Table 6. The difference between COP values can be explained by difference in testing methods used by each lab. Data from these tables were compiled through many of the research labs listed in Table 5. Table 7 gives details of the methods used and the conditions which were present for each test. The reference study and test condition column is a matrix combination of reference study letters (A, B, C, etc.) and individual test conditions for each reference study (1, 2, 3, etc.) that is used to categorize each individual test. The test description column provides information on the individual conditions and test methods.

Table 6. COP Values of Lab Studies

Brand and Model	Reference Study and Test Condition					
	B1	C1	E1	E2	E3	G1
Air Generate AirTap	–	–	1.68	2.77	–	–
A.O. Smith Voltex	2.3	2.2	3.55	3.42	2.62	–
GE GeoSpring	1.7	2.1	1.21	1.81	3.46	2.27
Rheem EconSense	1.1	2.0	1.44	2.61	2.53	–
Stiebel Eltron Accelera 300	–	–	3.85	5.37	3.09	–

Table 7. System COP Reference Studies and Test Conditions

Reference Study and Test Condition	Test Description
B1	Total daily water use of 49 gal, and the average COP is based on heating water from 90°F to 120°F
C1	Performed at DOE 24-h EF test conditions with set point at 120°F Single continuous water draw Average 3-gpm flow rate Draw is stopped when hot water outlet decreases by 25°F
E1	Draw profile to represent high demand situation in morning. Consists of 4 showers (64 gal) over the course of 1 h and 8 mins. Test begins with tank full of 120°F water
E2	Draw profile to represent medium demand situation in evening. Consists of range of flow rates and duration to simulate food preparation and dishwashing and draws 40 gal in 4 h. Test begins with tank full of 120°F water
E3	Draw profile to represent low demand situation (consists of many short, uninterrupted draws). Draws 20 gal in 5.75 h Test begins with tank full of 120°F water
G1	Alternating Building America and ASHRAE draw profiles in uncontrolled conditions in Cocoa, Florida.

2.3 Field Testing Studies

Unfortunately, robust and publically available field test results for the new HPWHs have not been as readily available as laboratory testing results. PG&E 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, 62.0% relative humidity, 70.5°F inlet water temperature, 1.3 gpm flow rate, 18.6 draw events per day, and 18.3 gpd (Hu and Davis 2011).

Working with four electric utility companies—Bonnevile Power Administration, Kansas City Power & Light, Tennessee Valley Authority, and Southern Company—EPRI has been testing 160 water heaters across the U.S. The vast majority of these water heaters are GE, A.O. Smith, and Rheem HPWHs, but several ERWHs were installed as control units. EPRI has provided preliminary

results from the study, but unfortunately the results are identified only as Model A, Model B, and Model C. The COPs of these units were 0.7–2.7, with a large variation in performance. Model B was generally the best performer, while Model C was the worst performer. Reliability has been high so far for these units, but EPRI saw only minimal peak demand savings (Amarnath and Bush 2012).

2.4 Cost-Benefit Studies

A 2009 PG&E HPWH study (PG&E 2009) concluded that, in terms of source energy[9] efficiency (SEE), a HPWH was more efficient (67% SEE) than a standard natural gas (57% SEE) or electric (29% SEE) tank water heater when the heating, ventilation, and air conditioning interaction of the HPWH is ignored. If the heating, ventilation, and air conditioning interaction is included, then HPWHs are significantly more efficient (104% SEE) than both standard systems in the cooling season and less efficient (44% SEE) than natural gas tank water heaters in the heating season.

According to a 2010 life cycle cost analysis paper (Franco et al. 2010) by Lawrence Berkeley National Laboratory, 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 would need venting for successful HPWH installation, and as a result, many older homes could not install HPWHs cost effectively. Furthermore, there was a greater cost benefit of HPWHs in new, single-family homes.

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

[9] 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 on efficient methods to provide electric water heating. In addition, this information can be used as validation by utilities and other program implementers throughout the United States attempting to develop incentive programs for this technology. While this study is primarily applicable to colder climates, the measured performance of the HPWH units themselves is relevant in many climate zones. Even though the sample for this evaluation was relatively small, there were some clear results consistent with other ongoing field testing across the country.

3.1 Research Questions

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

- What is the measured efficiency of a 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 was collected at 14 sites in Massachusetts and Rhode Island in the service districts of National Grid, NSTAR, and Cape Light Compact. Measurements were taken for a minimum of 12 months at all sites to establish the efficiency and performance of each unit on an annual basis. These measurements included water temperatures, flow rates, and electricity consumption. Sensors were sampled at 5-s intervals and output at 15-min intervals in the form 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 of the sites, the following HPWH parameters were measured every 5 s:

- 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 resistance heating element (Wh)
- Entire system energy consumption (Wh).

At each 5-s 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-min 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).

In addition, the start time, volume, and duration of each hot water draw were recorded.

3.3 Equipment

As shown in Figure 4, a Campbell-Scientific CR-1000 data logger and various sensors (Table 8) were used at each site to take measurements. A wireless modem was used for the remote downloading of data for evaluation throughout the monitoring period. Thermistors were used for all temperature measurements. Cold water inlet and hot water outlet water temperature were measured using an Omega tubular immersion sensor with a 4.5-in. probe length and national pipe threads. These were installed directly in the water flow by the HPWH installer. To measure domestic hot water flow, Omega FTB4607 low flow (0.22–20 gpm), turbine-type flow meters were used. All flow meters were installed by the HPWH installer and located on the cold water inlet side.

Figure 4. Example of a HPWH monitoring system installation

Table 8. Installed Monitoring Equipment

Measurement	Equipment
Record and Output Measurements	Campbell-Scientific CR-1000 datalogger
Inlet and Outlet Water Temperatures	Omega ON-910-44006 NPT 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

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, Wh transducers with pulse outputs.

3.4 Analysis

The COP has been defined differently in numerous studies (AIL Research 2001, 2002; Murphy and Tomlinson 2002; 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

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

where

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

The water heating energy Q_{DHW} was calculated by the datalogger every 5 s using measured data. These energy values were summed and logged at 15-min 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), and
ρ	=	density of water (lbm/ft^3).

4 Performance Results

Measured performance as well as the rated capacity, EF, and FHR, for each of the monitored models are shown in Table 9. All systems were set to hybrid mode, but there were differences in set point temperature. The electric resistance percentage represents the fraction of electricity consumed by the electric resistance elements (rather than heat pump, controls, or peripherals). While this is a small sample and many variables affect water heater performance, the values do provide insight into some differences between the units.

Table 9. Summary Statics of Performance by Model.

Model	Capacity (gal)	Rated EF[a]	FHR[b]	Measured Average COP	COP Range	% Electric Resistance
GE	50	2.35	63.0	1.82[c]/1.61	1.0–2.1	32.7%[c]/44.0%
A.O. Smith	60/80	2.33	68.0/84.0	2.12	2.1–2.1	5.6%
Stiebel Eltron	**80**	**2.51**	**78.6**	**2.32**	**2.0–2.6**	**5.5%**

[a] COP and EF are similar, except the EF is the ratio of heat output to energy input as measured *during a specific 24-h test procedure*.
[b] FHR is measured in gph.
[c] 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 lower than the rated EF for all three models. The A.O. Smith and Stiebel Eltron models were only slightly lower than the rated EF, while the GE model showed a more pronounced difference between measured COP and rated EF. These results are 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 preventing electric resistance use.

More detailed summary statistics for each site are shown in Table 10. These statistics include operational conditions as well as efficiency values. While 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, while the residents at Site 10 used an average of 41 gpd with a COP of 2.0. Larger hot water draw volumes will dilute the impact of tank thermal losses and elevate the COP of the unit—as long as larger draws do not increase the use of resistance heating. As a result, Site 2 has a COP slightly higher than the rated EF. 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, it seems the GE model requires more electric resistance heating to meet the demands.

Table 10. Summary Table of Performance by Site

Site	HPWH Model	Adults + Children	Water Heater Set Point Temp (°F)	Days Moni-tored	Avg. Daily Hot Water Use (gal)	Average Cold Water Temp. (°F)	Avg. Hot Water Temp. (°F)	% of Electric Consumption From Electric Resistance[b]	Avg. Air Temp. (°F)[a]	Avg. RH (%)[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	1.0
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	2.0
10	Stiebel Eltron	2 + 0	140	424	41	57	138	2%	68	55%	58	2.0
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 electric kWh that was used by resistance, NOT thermal energy fraction provided by electric resistance.

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 can have a different impact on different HPWH models, particularly when looking at the effects of hot water use and electric resistance element operation.

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 5 shows 7 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 relatively small. As a result, the heat pump was able to meet recovery needs for those days. During days 2 and 7, the water draws were more concentrated, and the electric resistance element was needed to provide additional hot water.

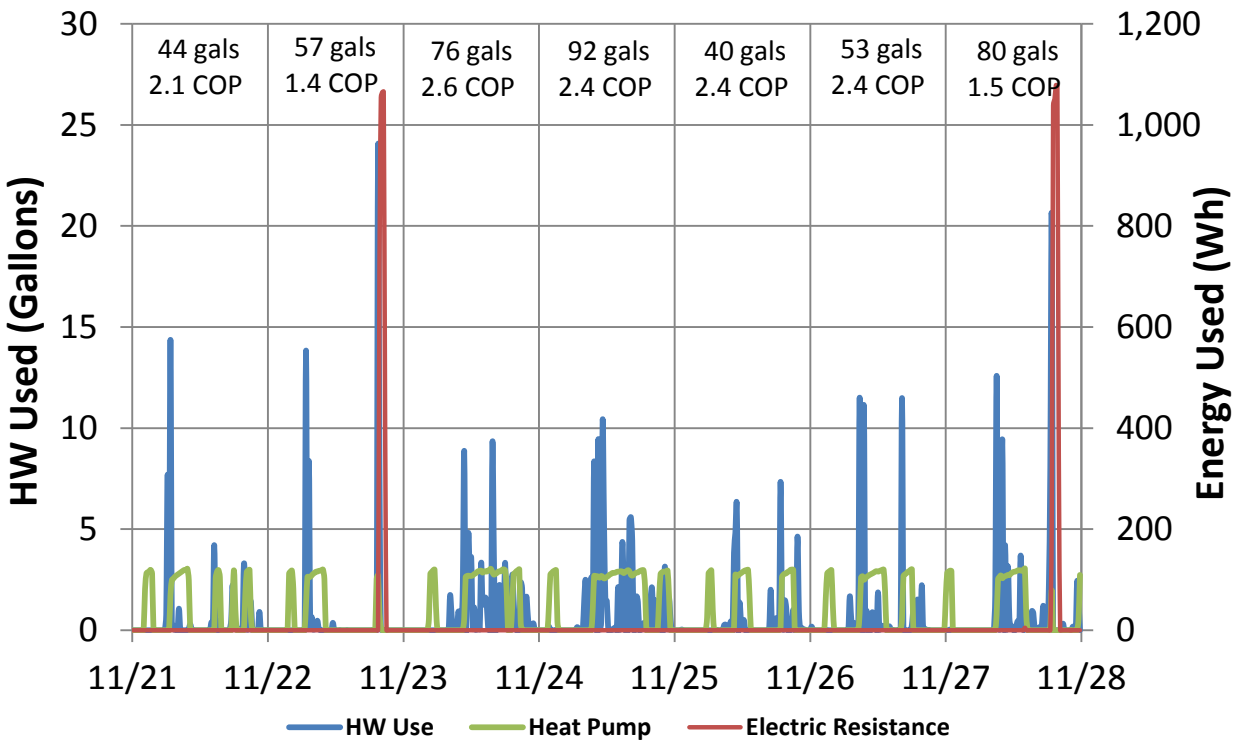

Figure 5. Ideal operation of the GE HPWH in hybrid mode (Site 9)[10]

While Figure 5 shows how large and concentrated draws can reduce the efficiency of the unit, low water use can also result in low COPs, as shown in Figure 6. 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.

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

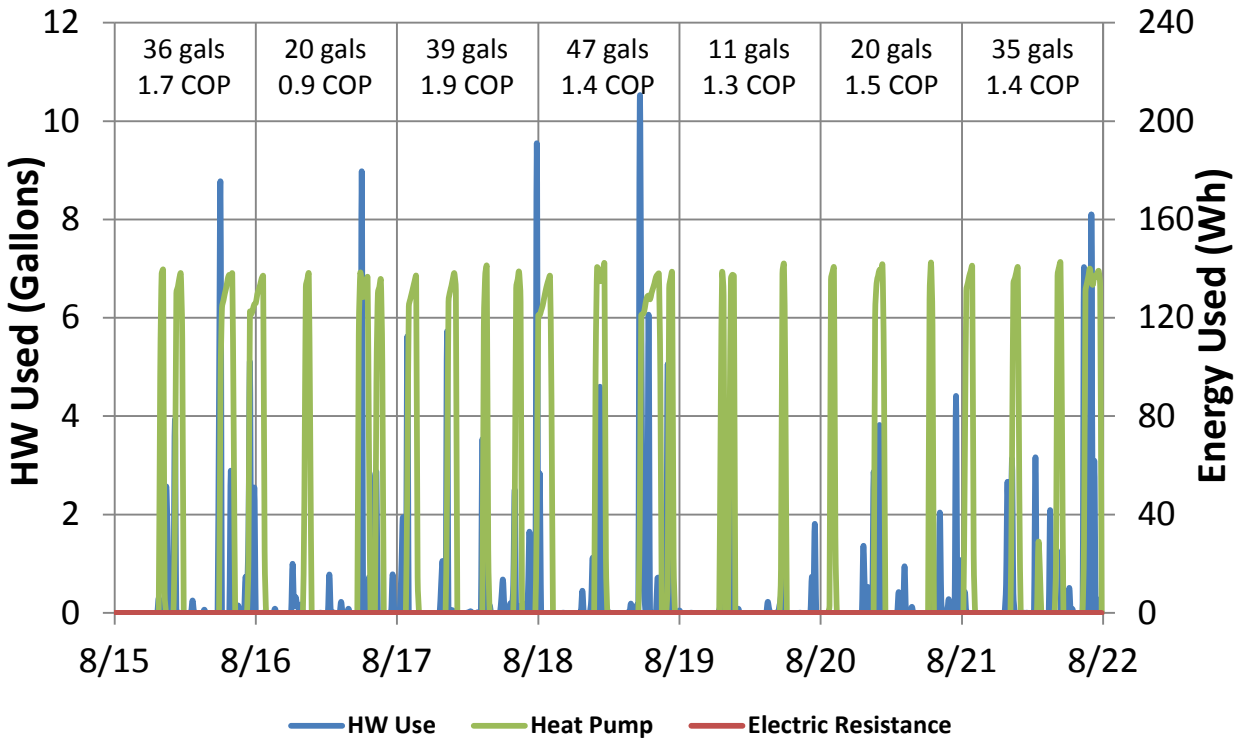

Figure 6. Low water use can reduce the overall benefit of a HPWH when assessing cost benefit

Scatter plots of the daily hot water use[11] versus the daily COP are shown in Figure 7. Each daily observation is also color coded by the electric resistance fraction, where blue is zero electric resistance use, and red is when the electric elements are used to reheat the entirety of the recovery load. The GE unit has the most observations, and 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 less apparent trends because there were fewer monitored sites, the scatter plots appear to agree with the trend observed for the GE units, with one primary distinction. While 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

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

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.

4.2 Impact of Air Temperature on Efficiency

Although hot water demand is a primary driver of efficiency, other factors are still playing a prominent role, as shown in the large scatter in the data in Figure 7. The efficiency of the heat pump is primarily a function of the ambient temperature in the space. To give a sense of how ambient temperature affects overall efficiency, two sites with cold and hot operating environments are compared. At Site 5, the HPWH was installed in a cold basement with ambient air temperatures dropping below 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 8, but with an added parasitic of the heat pump cycling on and off at the cutoff temperature of the unit.

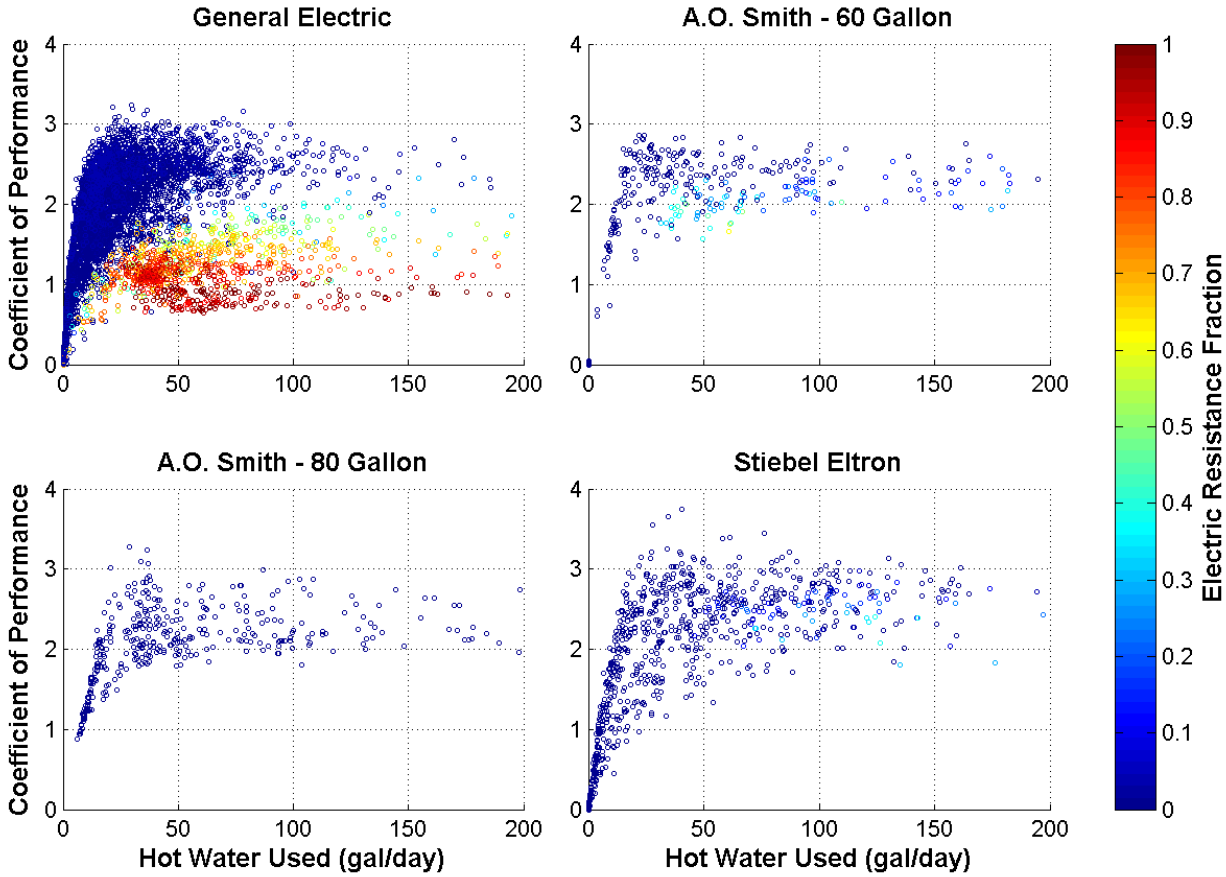

Figure 7. Scatter plots of daily hot water use versus COP color coded by electric resistance fraction

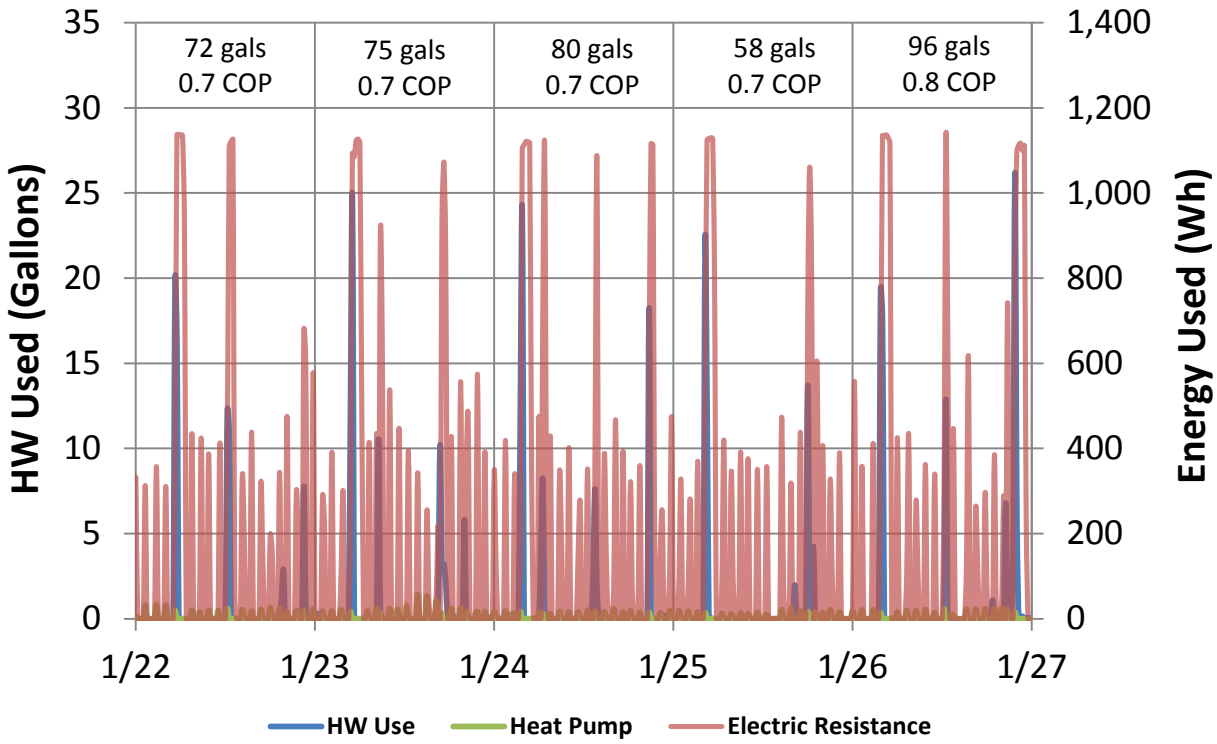

Figure 8. Due to the Site 5 basement being too cold, this GE HPWH switched primarily to electric resistance mode during the winter months.

At the other end of the spectrum, Site 11 experienced higher COPs during the winter months because the HPWH was placed in a boiler room (Figure 10) with ambient temperatures around 80°F (Figure 9). At the beginning of January, the unit was able to supply hot water in large quantities with COPs greater than the rated EF of 2.35, as shown in Figure 11. There were 2 days over this week of data in which high water use concentrations resulted in electric resistance operation to meet demand. Furthermore, there are periods with draw quantities lower than the EF test conditions of 64.3 gal with COPs higher than the rated EF. As we saw in the previous section, lower draw quantities can decrease overall COP because standby losses account for a larger percentage of the recovery load. The high ambient temperatures are boosting the efficiency of the heat pump and increasing the corresponding overall COP of the unit during these periods.

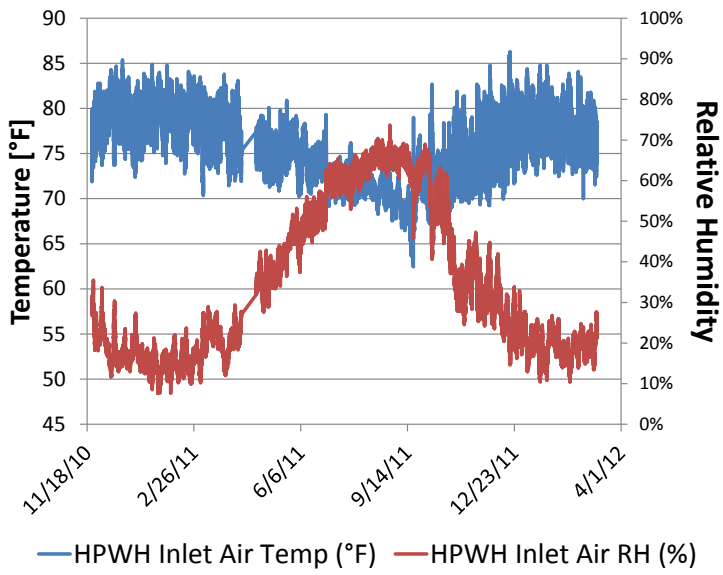

Figure 9. Ambient temperature at Site 11

Figure 10. This HPWH benefited from the waste heat of the boiler used for space heating

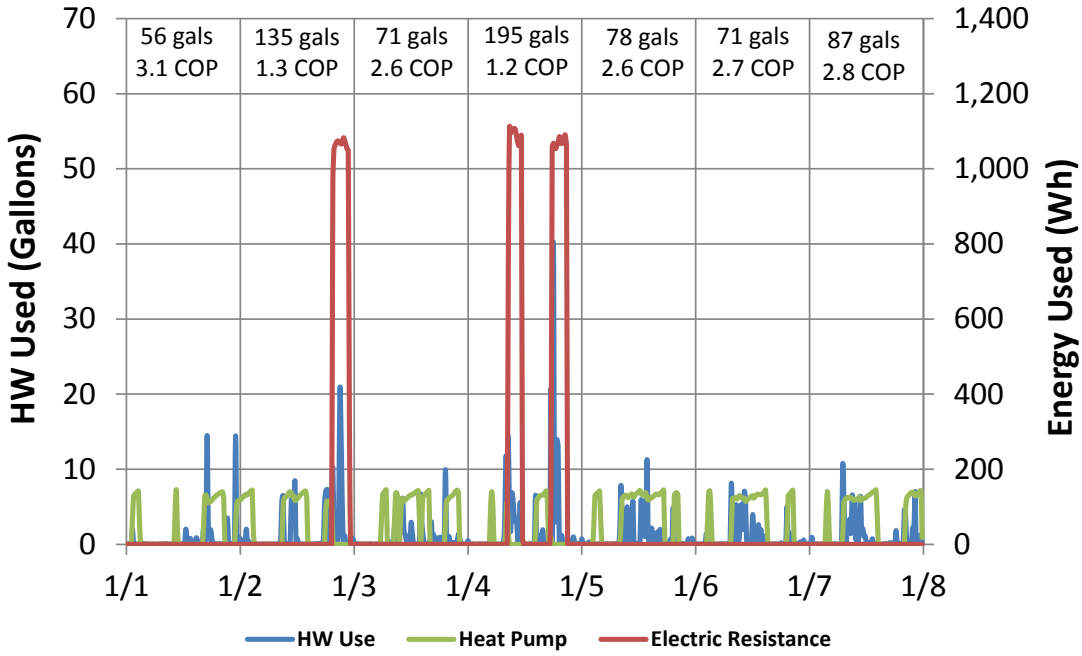

Figure 11. Typical winter performance of the GE HPWH in the Site 11 warm mechanical room

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 12. Periods with electric resistance fractions > 0.04 were excluded, as well as 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 2.0 to nearly 3.0.

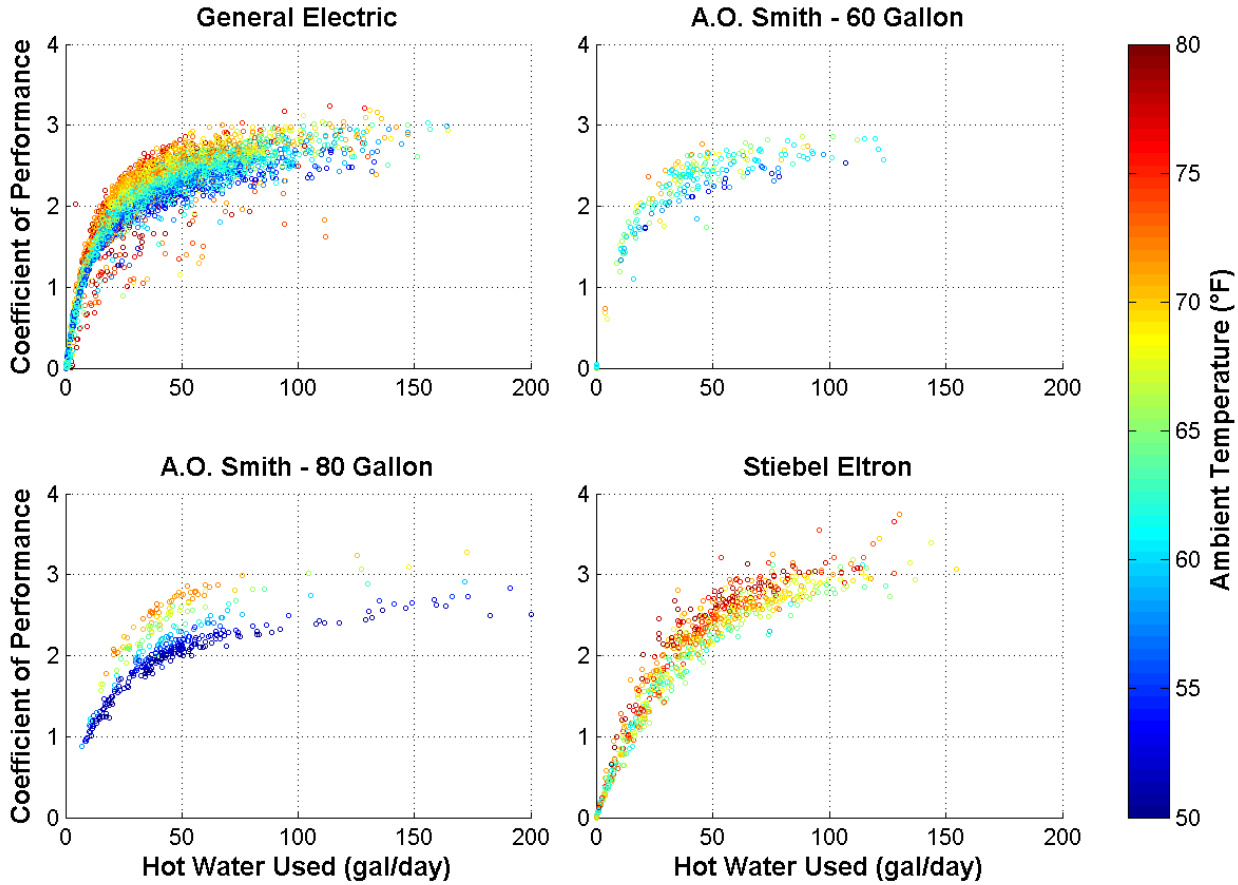

Figure 12. Scatter plots of COP versus daily hot water use color coded by ambient temperature. Periods with electric resistance fractions > 0.04 and Sites 5 and 13 were excluded.

4.3 Delivered Water Temperature

While the efficiency of water heating is important from a performance standpoint, 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 13. While the electric resistance element was needed to supply additional heating, the unit performed with COPs > 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, as shown in Figure 14. 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.

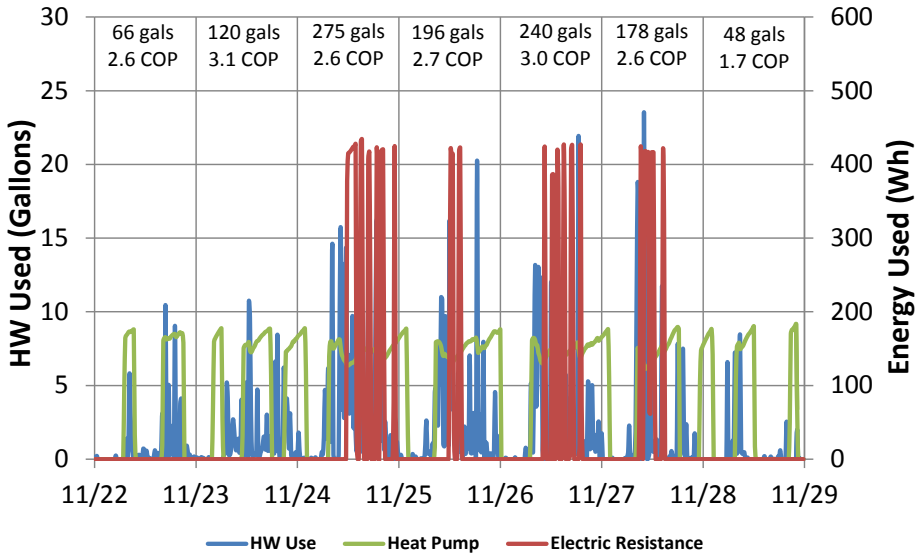

Figure 13. This Stiebel Eltron HPWH was able to maintain high COPs during high water demand

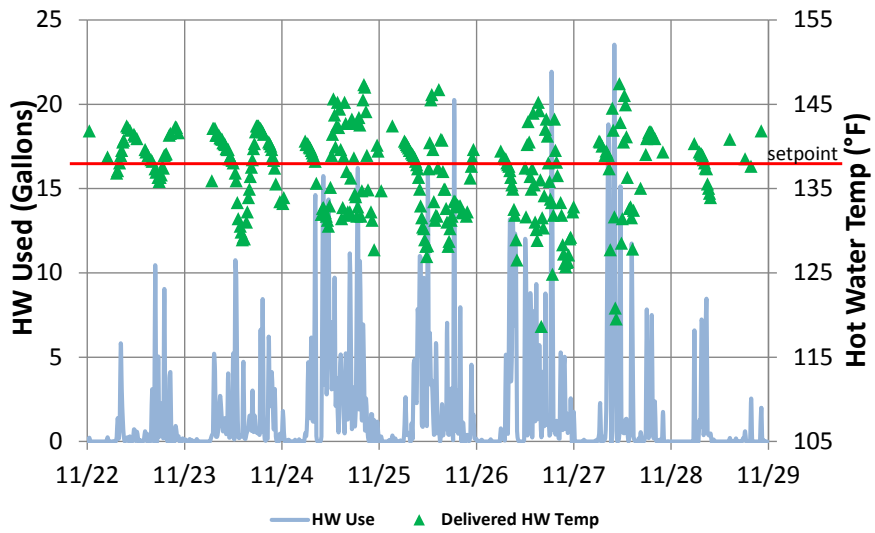

Figure 14. Even with high water demand, the hot water temperature only dropped as low as 118°F

In order to determine the ability of the HPWHs to deliver water at an acceptable delivery temperature, normalized histograms of maximum delivered water temperature for 15-min periods with draws > 1 gal were plotted for each site in Figure 15. 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 below the minimum acceptable delivery temperature is listed in the upper left corner of each plot. The normalized histograms show that all three units perform well at delivering hot water above 110°F at a variety of set point temperatures. However, many of the units did not maintain set point for all draw occurrences, and temperatures dropped more than 10°F below set point for a significant fraction of the 15-min periods.

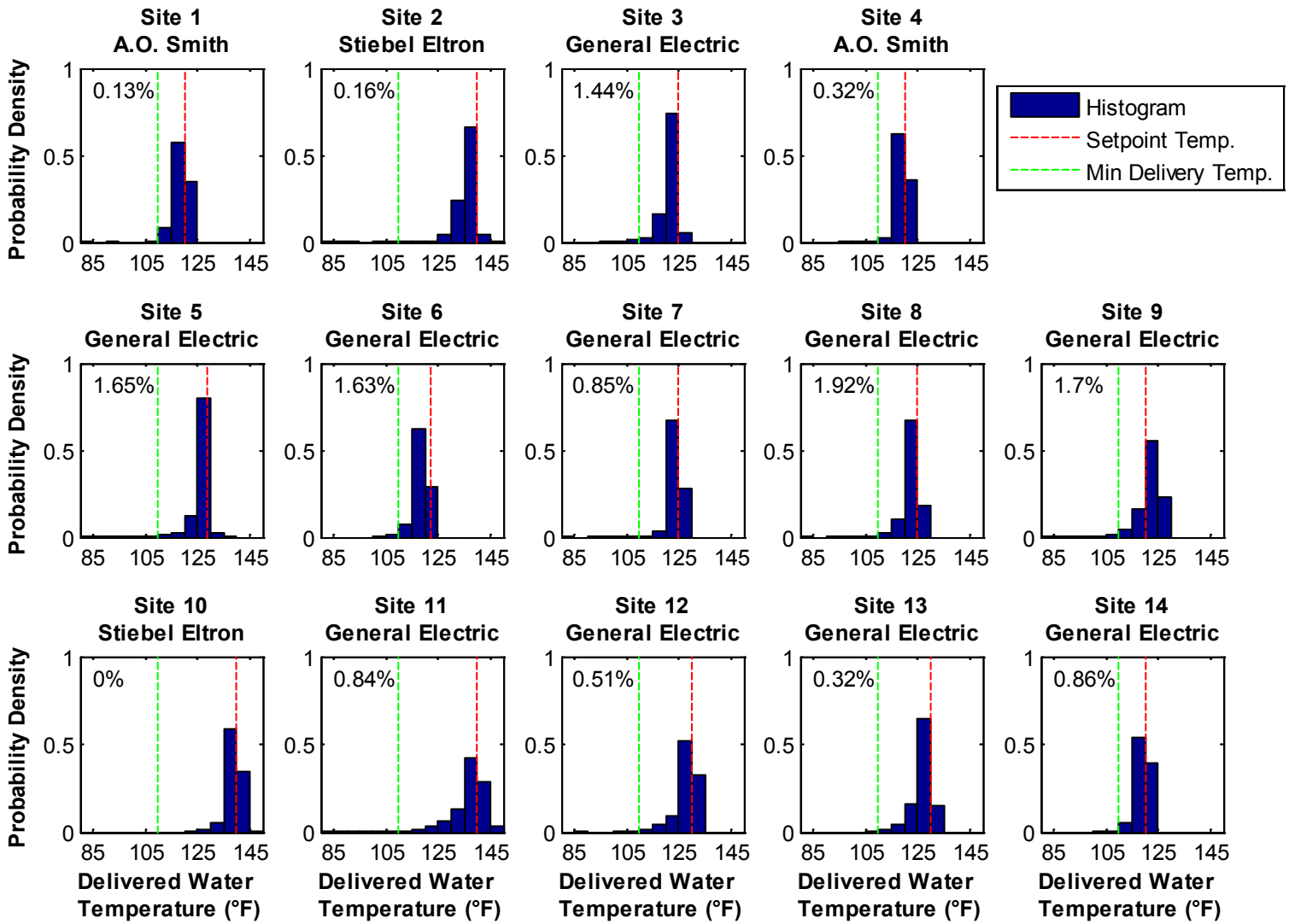

Figure 15. Normalized histograms of delivered water temperature. Red lines indicate set point temperatures. Green lines indicate minimum delivery temperature (110°F). The percentage of occurrences with water temperatures below 110°F is listed.

Unfortunately, the aforementioned method of determining whether the HPWHs are able to maintain the delivered water at a minimum acceptable temperature has flaws related to the 15-min recording interval used in this study. Because the average delivered water temperature will include water inside the pipe before the draw, the maximum delivered water temperature for the interval must be used. As a result, this analysis is only looking at the delivery temperature at the beginning of the draw or at the beginning of a 15-min 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 below usable temperatures.

4.4 Calculating Standby Losses

Tank losses to the ambient are an important contributor 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 UA. 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 DOE test procedure (DOE 1998) and NREL's field testing protocol (NREL 2012c). These methods measure the change in the average tank temperature during a period of no draws. NREL specifies that this period should begin 10 min after the heat pump has shut off because the condensing coil will still be giving off heat directly after the reheat period.

Since internal tank temperatures were not measured in this study, a different procedure was used to measure standby losses. The basic procedure used was to identify 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), and
Δt	=	time elapsed since the last reheat (hr).

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 be assumed to 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.

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

- No draw over the period
- Period begins and end with the termination of heat pump operation to ensure similar stratification
- The overall period must be longer than 3 h.

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. As a result, laboratory performance maps discussed in 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

$$COP_{hp} = COP_{hp,rated}\left(C_1 + C_2 T_{wb} + C_3 T_{wb}^{\ 2} + C4 T_{tank} + C_5 T_{tank}^{\ 2} + C_6 T_{wb} T_{tank}\right), \qquad (4)$$

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, and
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), and
C	=	conversion factor for kWh to Btu (3.412 Btu/kWh).

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

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

Robust regression[12] analysis was used to estimate the UA

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

Regressions using Equation (7) were performed with and without a constant (i.e., nonzero intercept). While 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 11 and Table 12, respectively, and Figure 16 shows the two regression lines plotted against the observed data. While the intercept estimate is significant at the 95% confidence level and the tank loss coefficient is similar to that of other studies (Table 29), there are reasons to argue that the model without the constant is preferable.

Table 11. Tank Heat Loss Robust Regression Results With Constant (N = 113, df = 111)

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

Table 12. Tank Heat Loss Robust Regression Results Without Constant (N = 113, df = 112)

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

[12] 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 16), 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.

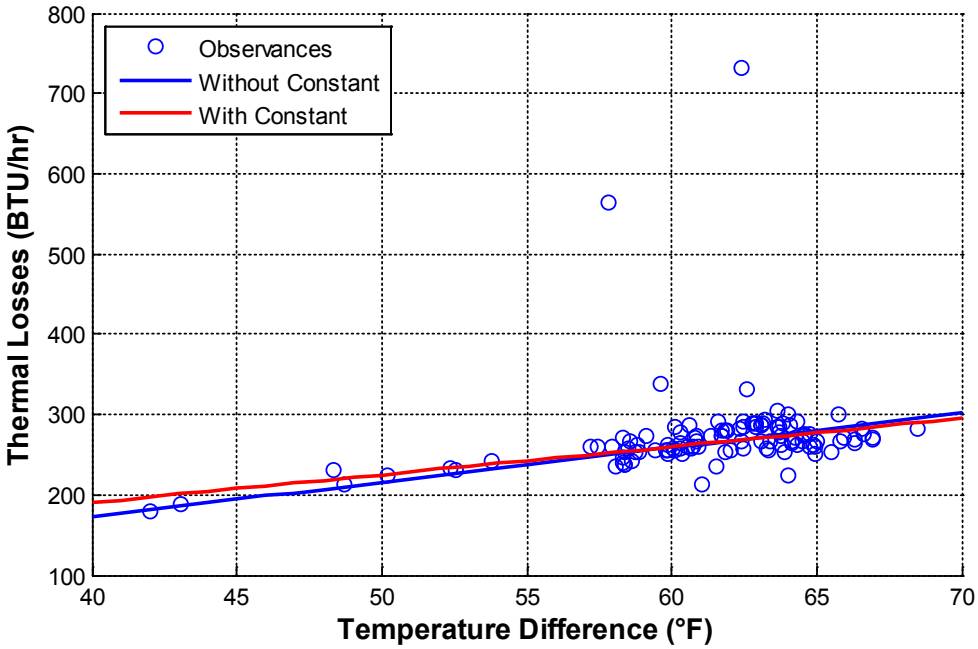

Figure 16. Regression results and data points for GE standby losses. Temperature difference is between the tank average temperature and ambient air.

Since the estimate of the UA 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 whose response is well known and should follow a well-described deterministic phenomenon.

The UA for the model without the constant is 4.312 Btu/h-°F, which is significantly higher than the consensus *UA* of 3.7 Btu/h-°F found by the laboratory results shown in Table 29. Several factors may have contributed to this discrepancy. The laboratory setups would have included significantly shorter pipe runs than the field sites; this would have reduced the effects of thermosiphoning and thermal shorts on the heat transfer coefficients measured in the lab. Furthermore, the EF test measures the UA of the tank over a period where there may be a change in net energy of the tank. While the equation governing this calculation in 10 CFR Part 430 accounts for this change in energy (DOE 1998), the difference in measurement methodology between the DOE test and this study could play an important part in the difference in results. By starting and ending the analysis period just after a reheat cycle, our method includes the net change in energy of the refrigeration loop, while the EF test does not. As a result, the cause of the higher UA of this study compared to laboratory tests is hard to determine. The field installations could have a higher UA than the laboratory installations, but the difference could be attributable to differences in the setup of the calculation.

4.5 Impact of Confined Spaces

Because an HPWH removes 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 of these tests were performed on the GE GeoSpring. Advanced Energy compared two HPWHs subjected to the EF test, one placed in a 220.5-ft^3 uninsulated space and another subjected to the default DOE test operating conditions. GE recommends a volume of 750 ft^3 (General Electric 2010). The efficiency of the unit in the confined space was 10% lower than that of 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). NREL'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.

Site 13 in this study was installed in a confined space with approximately 400 ft^3 of available air. The heating event shown in Figure 17 has operating conditions similar to that of an EF test conducted at a set point temperature of 130°F. The duration of the heating event and the amount of water drawn during the heating event are approximately half that of the EF test; the resulting draw rate is within 5% of the EF test draw rate of 2.68 gph. With a COP of 2.02, the resulting performance drop was approximately 15.8% below an approximate expected EF 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).

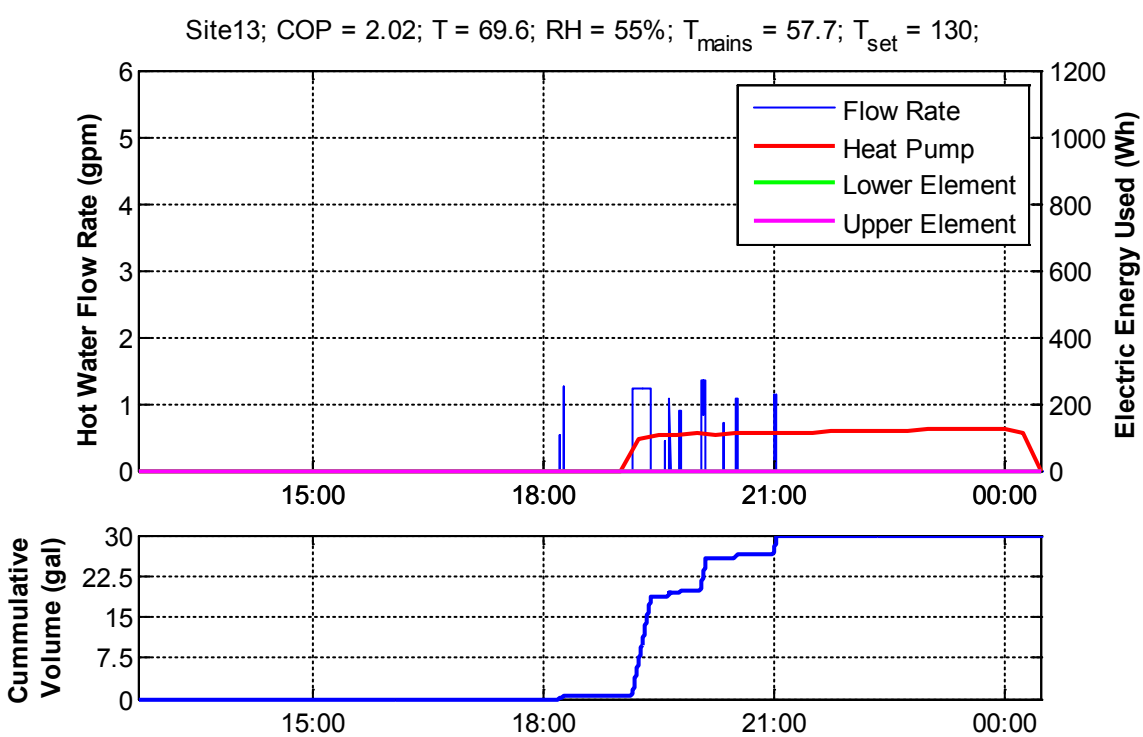

Figure 17. Performance of Site 13 in confined space

4.6 Impact on Space Conditioning Systems

Since an HPWH moves heat from the air surrounding the water heater into the storage tank, an HPWH will have an impact on the space conditioning loads of the building in which it is located. When an HPWH is located in conditioned space, there is a very direct effect on space conditioning loads. In the summer, the HPWH will reduce the cooling load of the building; conversely, the heating load will be increased 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 on these impacts, see the modeling results described by Hudon et al. (2012). A less complex analysis was also presentedby Shapiro et al. (2012).

For HPWHs installed in unconditioned or "semi-conditioned" spaces such as basements, the space conditioning impacts are harder to determine. These spaces act as buffer spaces, 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 means that the HPWH space conditioning impacts are potentially reduced.

Since these transient heat transfer interactions cannot be directly addressed for the HPWHs installed in unconditioned basements in this study, the space conditioning impacts will be 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), and
Q_{dhw}	=	thermal energy removed from storage tank (Btu).

The maximum potential thermal impact of 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, $Q_{net,space}$ will be positive, but for HPWHs the net energy to the space is negative.

While the HPWHs will remove energy from the space, the impact on the space conditioning loads depends on the season. For the purposes of this analysis, the cooling season for these sites was considered to be June through September, and all other periods are considered the heating season. Box plots of the space conditioning impacts on an hourly load basis and a seasonal basis are shown in Figure 18, which shows negative values reducing the space conditioning loads and positive values increasing 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 1.5 inner quartile range. Outliers are represented by a red plus, and the mean is represented by a black plus.

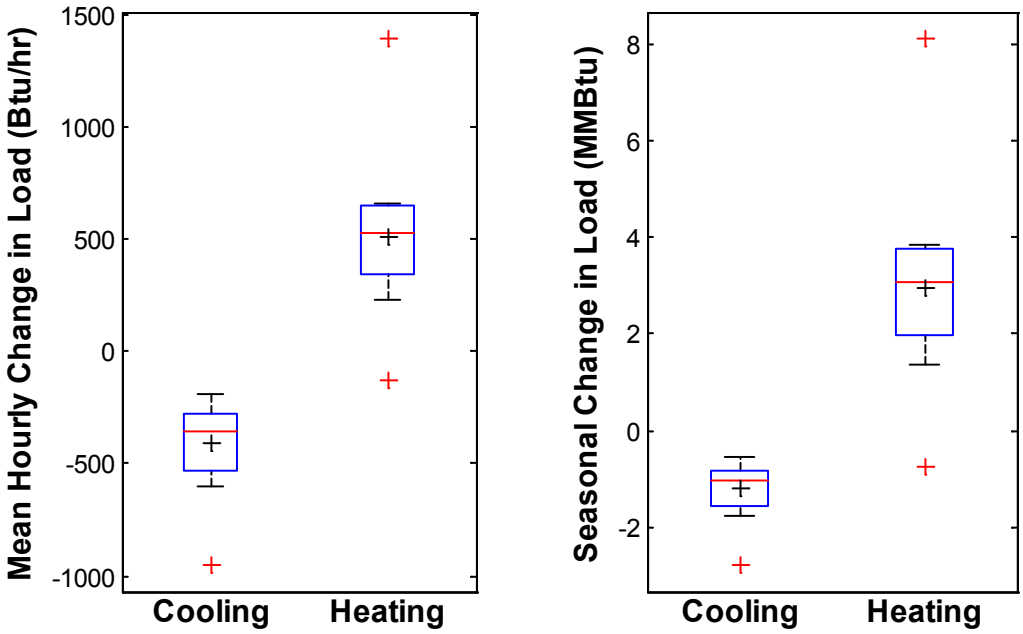

Figure 18. Box plots of maximum potential space conditioning impacts for monitored HPWHs

As shown in the box plots, the magnitude of the mean hourly heating impact is slightly higher than the magnitude of the mean hourly cooling impact. Similarly, the magnitude of total heating seasonal impact is nearly twice the magnitude of the total cooling seasonal. 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 MMBtu and heating load increases of approximately 3 MMBtu.

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, and 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, REs, and pilot light energy are listed in Table 13, 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 13. Alternative Water Heaters

Water Heater	Fuel Types	EF	RE	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). For each of the alternative water heaters, the daily operating conditions at each site—set point temperature, mains temperature, volume of water drawn, and ambient temperature—were simulated 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, of each water heater was normalized to yearly energy consumption. The normalization procedure accounts for the fact that the monitoring period at each site was different and that there was some overlap in the days that were monitored.

While 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 units of 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 easily is converted to source energy using site-to-source ratios (Deru and Torcellini 2007), which are defined to the fuels studied in Table 14. As a result, energy use will be 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 14.

Table 14. 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 19 and Figure 20. Figure 19 shows that HPWHs have operating costs significantly lower than electric resistance, oil, and propane, and operating costs comparable 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 20 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 are able to 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.

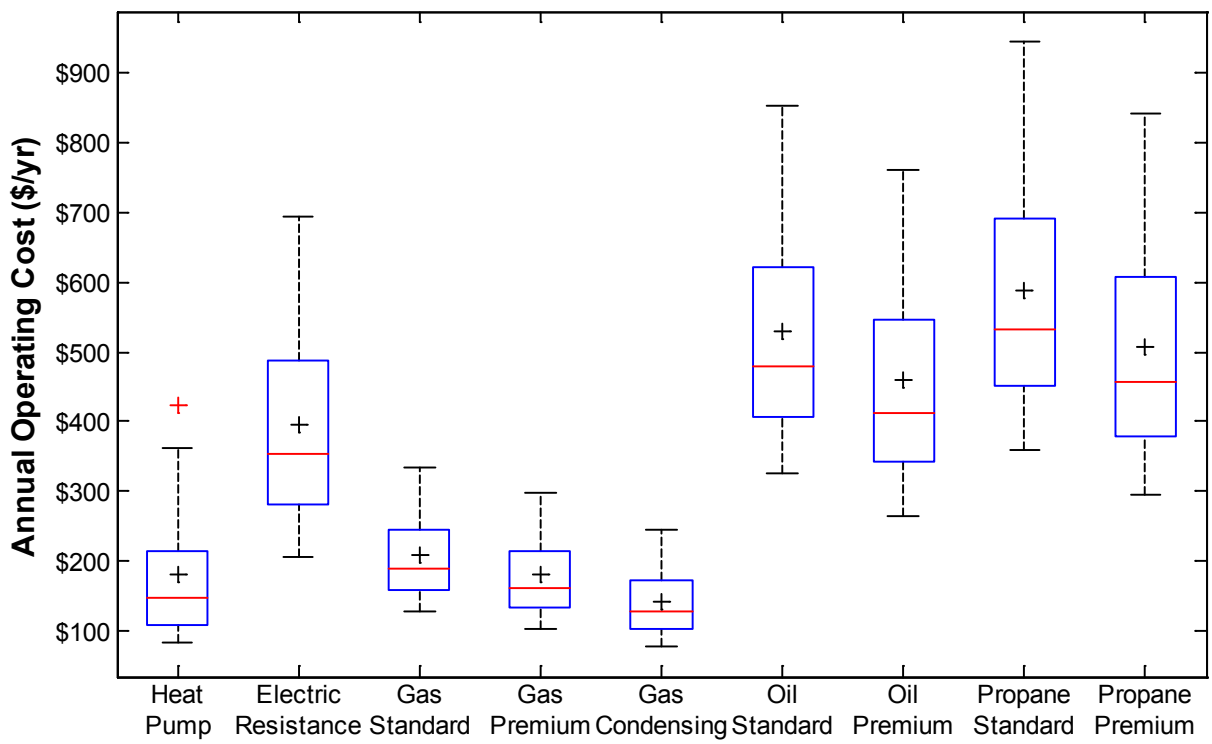

Figure 19. Annual operating cost of monitored HPWHs and alternative water heaters

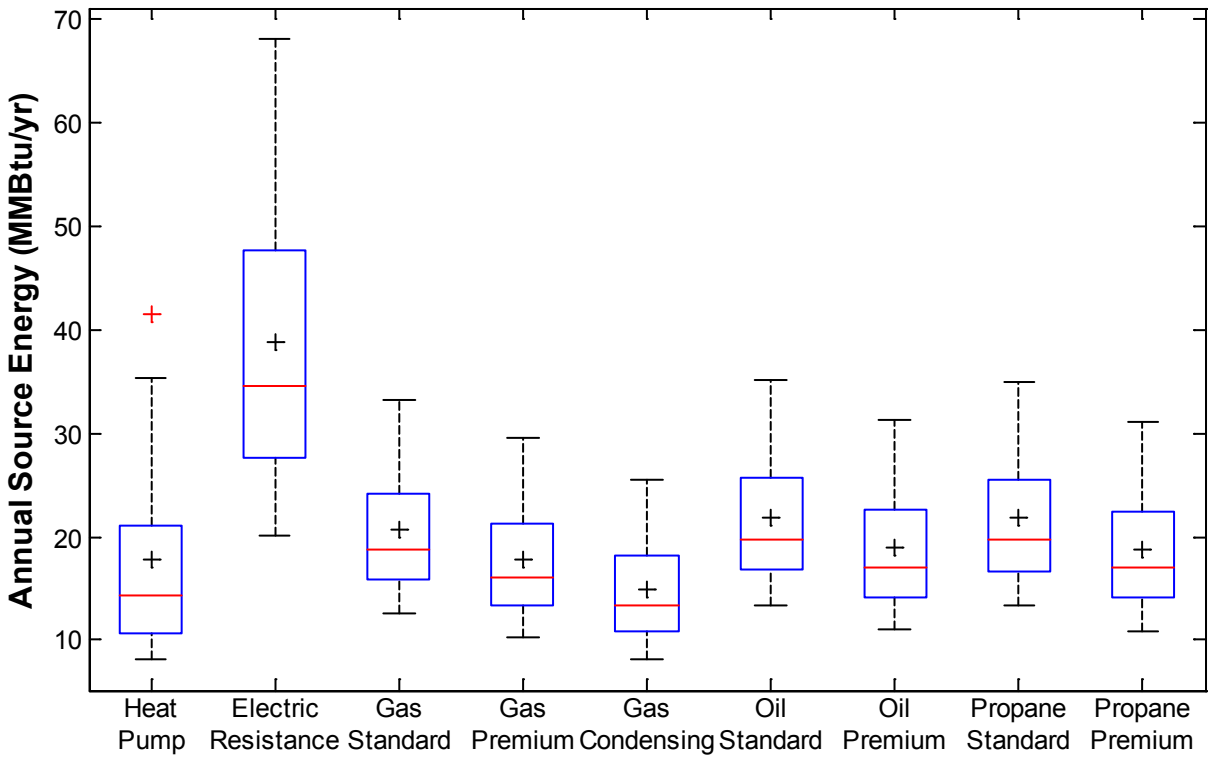

Figure 20. Annual source energy of monitored HPWHs and alternative water heaters

While HPWHs have the second lowest operating costs and source energy use of the water heating products considered in this study, installation costs will 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 15. 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 16 lists the installation costs and typical lifetimes of the various water heating products considered. Using these values, the annualized energy related cost (AERC) of each of the water heating units was calculated. AERC 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 15. 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] BEopt defaults (NREL 2012b)
[b] Average rate for 2011 (Freddie Mac 2012)

Table 16. Installation Costs and Lifetimes of Water Heating Products

Water Heater	Installation Cost[a]	Typical Lifetime (years)[a]
Heat Pump (80 gallons)	$3,300	10
Heat Pump (50-60 gallons)	$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 (2009)
[c] Estimated lifetime based on National Residential Efficiency Measures Database (NREMD) values for gas storage and condensing tankless heaters.

The installation costs for the cost analysis were derived from the NREMD, but HPWH installation costs reported for this study, as shown in Table 17, were generally in line with the costs reported in the NREMD. The NREMD reports 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 17. 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 AERCs for the nine water heating technologies is shown in Figure 21. The HPWHs have lower AERCs than the electric resistance, fuel oil, and propane water heaters, although the AERC 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, will 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. Other issues are related to tankless units, so a direct comparison may not be appropriate.

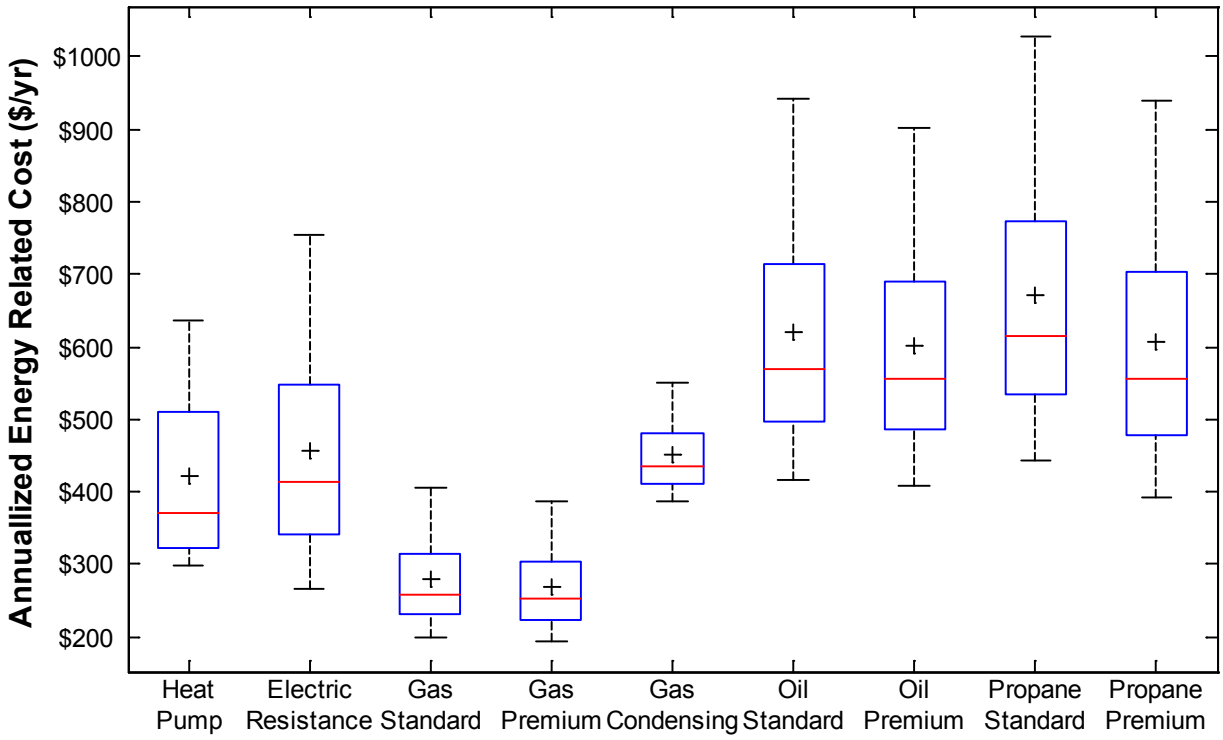

Figure 21. Annualized energy related cost of monitored HPWHs and alternative water heaters

6 Homeowner Surveys

After complete monitoring of the HPWHs, residents at the 14 sites were surveyed about their satisfaction with the HPWHs. All of the homeowners were satisfied with the HPWHs. The majority (70%) noticed cooling and/or dehumidification. Some noted that noise was an issue (18%). Some homeowners experienced running out of water (36%), though these were isolated incidences and weren't a significant concern to the homeowners. The vast majority (73%) noticed lower utility bills. One "No" response 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 electric rate (the savings were indeed due to the HPWH). Detailed survey results are shown in Table 18 and Table 19.

Table 18. 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 non-ideal 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 19. 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, non-ideal 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 the way hot water is used. When large quantities of hot water are used in clusters, HPWHs will revert to electric resistance mode, reducing the efficiency of the unit. A homeowner can reduce this effect by purchasing a larger HPWH, increasing the set point temperature, or changing behavior. By increasing the size and temperature of a 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 installation location of a HPWH is also an important factor to consider when installing an HPWH. 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 > 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 a HPWH in a buffer space such as an unconditioned basement can temper the space conditioning affects. In hot climates, the removal of 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, there are some installation hurdles that installers must address. Successful installation requires careful consideration of clearance and weight. By adding an additional heating mechanism, 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 the HPWH 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 et al. (2012), SWA (2012), which SWA worked on with the sponsors of this evaluation for use in their rebate programs, and a tri-fold brochure for consumers (Appendix F) that was created for their rebate programs.

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, there has only been one instance in which a compressor for a HPWH unit had to be replaced. It is unclear as to the cause of this failure. No other major issues have been identified regarding durability and reliability of these units, but this is something that will need to be followed up as these systems age. This evaluation was successful in answering the following research questions:

What is the measured efficiency of a 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 electric water heaters. With the exception of one unit that was placed in a basement with very low ambient temperatures, the monitored units had COPs > 1.5, which represents more than a 50% reduction in energy consumption compared to an ERWH. The highest COP was 2.6.

Table 20. Summary of Test Results by Model

Model	Units Monitored	Capacity (gal)	Rated EF	Measured Average COP	COP Range
GE	10	50	2.35	1.82	1.5–2.1
A.O. Smith	2	60/80	2.33	2.12	2.1
Stiebel Eltron	2	80	2.51	2.32	2.0–2.6

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

The key variables that affect performance were studied based on the data from this study. 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 will reduce the overall efficiency of the water heater by increasing the fraction of the recovery load that is standby losses. High water demand will also reduce efficiency by requiring more electric resistance use. Higher ambient temperatures will increase the efficiency of the heat pump and reduce standby losses.

While 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 large 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?

While HPWHs are significantly more efficient than ERWHs, the standby losses of these water heaters are considerably higher than ERWHs. Laboratory measurements of the EF of these units in resistance mode show rated values about 10% lower than a comparably sized ERWH. Laboratory testing and analysis in this study also show higher UA values than for ERWHs. UAs 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 the existence of thermal shorts introduced by the wrap-around 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 is 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 MMBtu of increased heat load and 1.5 MMBtu 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 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 interaction between the HPWH, conditioned space, buffer space, ground, and ambient is not a trivial task.

Furthermore, more information is needed to predict the effect of draw profiles on the efficiency of these HPWHs. While 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, there are some installation hurdles that installers must address. Successful installation requires careful consideration of clearance and weight, drain pans and condensate pumps filer maintenance and noise. Many of these details are discussed in more depth by Shapiro et al. (2012), Selection and Quality Installation Guide for HPWHs, by SWA (2012), which SWA worked on with the sponsors of this evaluation for use in their rebate programs, and in a tri-fold brochure for consumers (Appendix F) that was created for their rebate programs.

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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. While HPWHs failed to gain significant market traction in the past, the current confluence of regulatory, economic, and market forces may finally be 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).[13] The HPWH described in the patent (Figure 22) 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 an upper and lower chamber to prevent the electric resistance element from heating the entire storage volume.

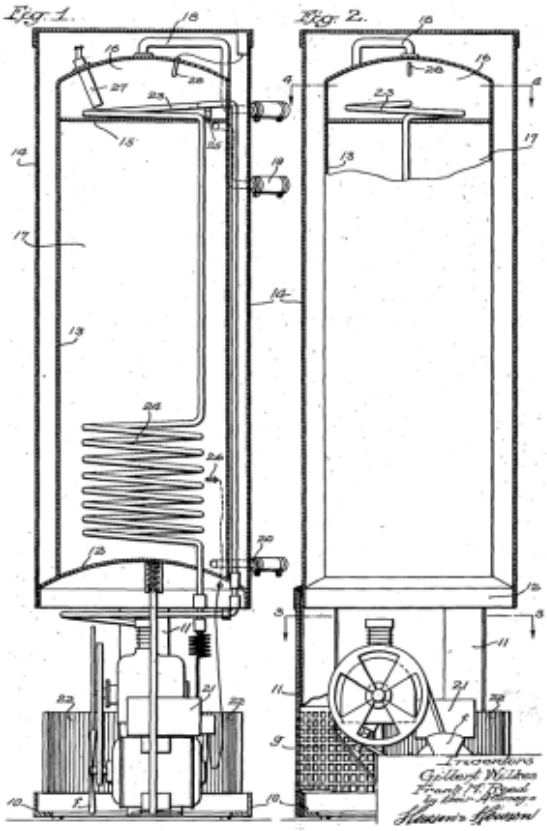


Figure 22. First patented HPWH (Source: Wilkes and Reed 1937)

[13] 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[14] (EIA 1996), which undoubtedly reduced the economic and commercial viability of the product. As a result, 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 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 DOE 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. While the add-on units were unsuccessful, the integrated units showed significant promise. Average COPs were around 2.0, operating savings approached 50%, the lifespan of the units matched similar natural gas 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 different commercialized HPWHs were in the marketplace under a multitude of trade names (Calm 1984).

While these new units were met with enthusiasm during the early 1980s, with sales sitting at more than 10,000 units per year, 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, 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, a collaboration effort between Arthur D. Little, Inc., ECR International, and Oak Ridge National Laboratory (ORNL) began development of 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 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

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

and field performance in subsequent years (Ashdown et al. 2004; Baxter and Linkous 2004; Tomlinson 2002).

During field-testing of units across the United States, the average COP was 2.0, which is more than double the efficiency of a comparable ERWH (Ashdown et al. 2004). In-house durability testing at ORNL uncovered no major durability issues (Baxter and Linkous 2004). 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 et al. 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 water temperatures near the tops of the tanks often exceeding 150°F. These high temperatures were partly due to excessive tank stratification—water temperatures near the top could be 50°F higher than temperatures near the bottom—and in many systems the high-temperature safety switches shut down the water heaters completely (these were designed to shut down the system when temperatures reached 170°F). 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. There are currently five major HPWH products in the water heater market. Key specifications for these HPWHs are shown in Table 21. These specifications include the two DOE performance metrics—EF and FHR.[15]

The EF represents the efficiency of the electric heating elements and tank losses under a consistent, 24-h 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 2.1 for more details regarding the EF and FHR test procedures.

[15] 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. Since electric resistance elements have an efficiency of 1, RE is not tested or reported.

Table 21. Key Specifications of Integrated HPWHs Currently Available in the U.S. Market[16]

Model	Capacity (gal)	EF	FHR (gal)	Electric Resistance Elements (kW)
GE GeoSpring	50	2.35	63.0	Upper: 4.5 Lower: 4.5
A.O. Smith Voltex	60/80	2.33	68.0/84.0	Upper: 4.5 Lower: 2.0
Stiebel Eltron Accelera 300	80	2.51	78.6	Upper: 1.7 Lower: None
Rheem EcoSense	40/50	2.00	56.0/67.0	Upper: 2.0 Lower: 2.0
AirGenerate AirTap Integrated	50/66	2.39/2.40	60.0/75.0	Upper: 4.0

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 a HPWH based on the carbon dioxide (CO_2) cycle. At the same time the WatterSaver was being developed, a Japanese consortium started development of 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 of149°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 > 4.0 in more recent models, and sales of the EcoCute have increased dramatically since its introduction (Hashimoto 2006).

Development of CO_2 HPWHs in the United States is just beginning. While market, technological, regulatory, and structural hurdles still remain for this technology, there has been active engagement in pushing CO_2 HPWHs in recent years. A collaboration between ORNL and GE has developed a prototype integrated HPWH based on the CO_2 cycle for the residential U.S. market. While 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).

[16] 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 RE is 1 and pilot load is 0. The net water heating load is computed using the hot water load, inlet temperature, and outlet temperature

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

where

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

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

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

where

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

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

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

where

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

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

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

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

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

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, yearly operating costs are listed in the following tables. HPWH numbers are annualized based on monitored data, and all other systems are modeled using the operating conditions measured for each HPWH site.

Table 22. 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 23. 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 24. 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 25. 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-min 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 steady state; i.e.. the system operating variables do not change considerably, but there is a larger sample size to investigate.

Daily data, however, are not quite perfect because the response rate of the heat pump system is considerably slower than other heating mechanisms. As a result, a large draw at the end of one day can be recovered entirely during the following day, as shown in Figure 23, where 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.

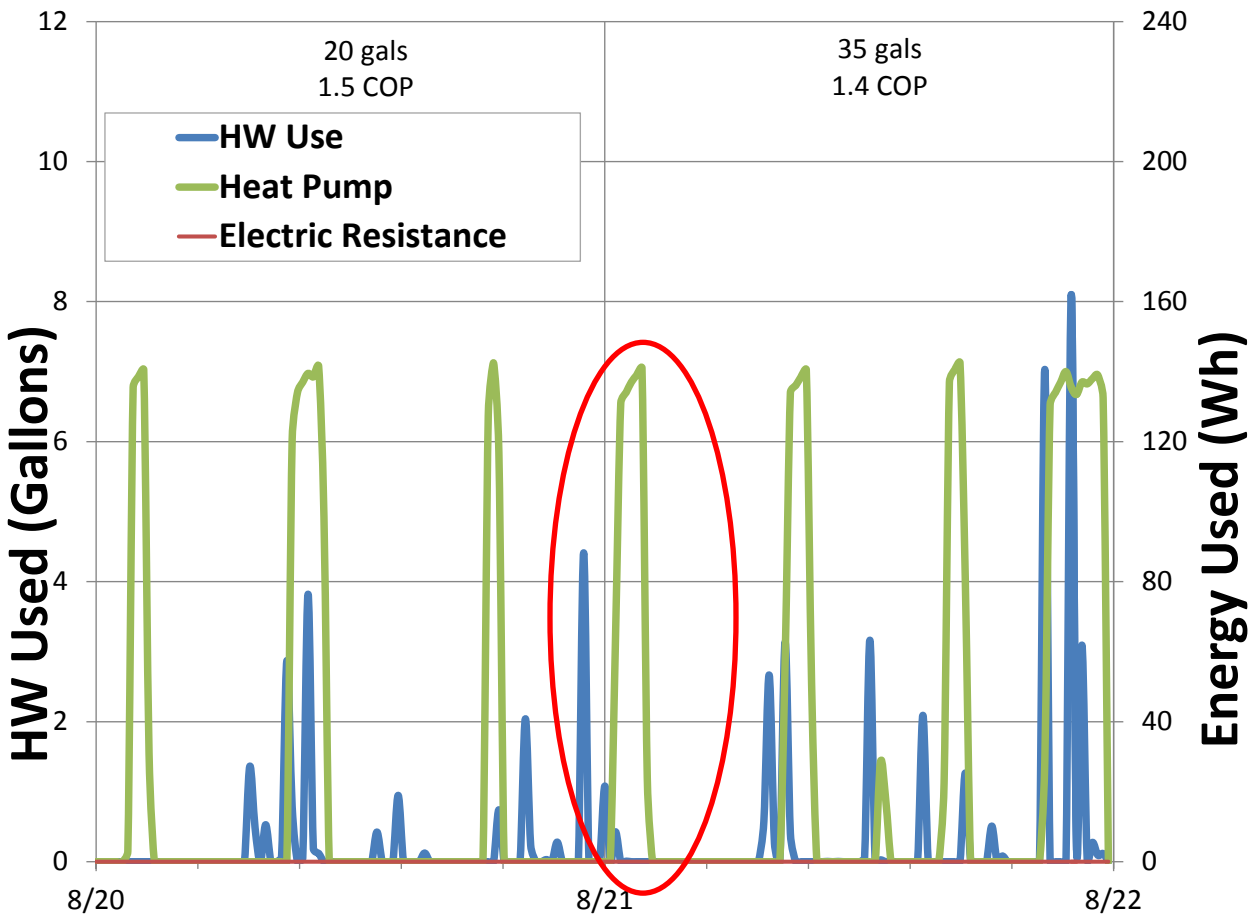


Figure 23. Results from using daily data for analysis

A solution to this problem is to find periods of time where 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 ≥ 4 h in length; and (2) the heating event must begin and end after a reheat cycle that has a duration ≥ 1 h 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 24. 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 in near steady state, just as daily values, but without the limitations of daily values.

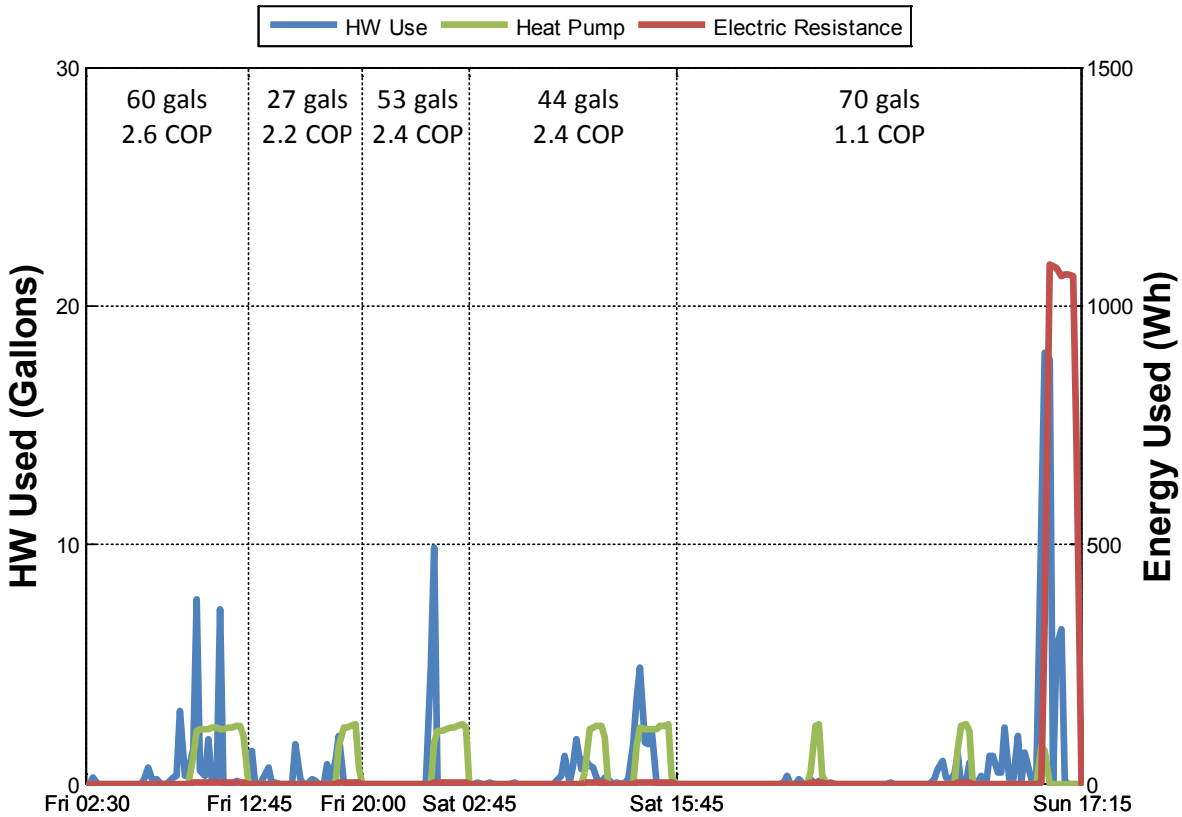


Figure 24. Example of five heating events as defined in this study

Appendix E: Laboratory Tests of Heat Pump Water Heaters Under 10 CFR Part 430

Table 26 through Table 30 display information that corresponds to laboratory study test results and manufacturer ratings for various HPWHs. All laboratory study test were performed at DOE laboratory rating standards. Deviations from DOE specifications are denoted by footnotes.

Table 26. Air Generate AirTap

Laboratory Study Results							Rated
Reference Study	A	B	C	D[17]	E	F	
EF	–	–	–	–	2.25	–	2.39/2.40
FHR (gal)	–	–	–	–	65.0, 64.7[S129], 74.0 [S126]	–	60.0/75.0
UA (Btu/h-°F)	–	–	–	–	3.30	–	–
RE	–	–	–	–	2.64	–	–

Table 27. A.O. Smith Voltex Integrated

Laboratory Study Results							Rated
Reference Study	A	B	C	D[17]	E	F	
EF	–	2.29	2.50 [S120]	–	2.24 [S129]	–	2.33/2.33
FHR (gal)	–	87.0	–	–	89.0 [S129], 89.0, 88.5[S140]	–	68.0/84.0
UA (Btu/h-°F)	–	3.9	–	–	3.9 [S129]	–	–
RE	–	–	–	–	2.46 [S129]	–	–

[17] Ambient conditions not maintained to DOE specifications for lab study
[S120] 120°F set point
[S126] 126°F set point
[S129] 129°F set point
[S136] 136°F set point
[S140] 140°F set point
[†] Thermostat set point reduced to between normal and hot (~129°F) from hot (~133°F)
[A50] Ambient air temperature at 50°F
[N] Normal mode
[ES] Energy saver mode
[HP] Heat pump only mode
[H] Hybrid mode
[EH] eHeat mode
[HD] High Demand Mode
[R] Resistance mode
* Standard DOE procedure was not followed

Table 28. Rheem EcoSense

Laboratory Study Results							Rated
Reference Study	A	B	C	D[17]	E	F	
EF	–	1.69	2.40[S120]	1.33[N],1.61[ES], 1.98[†ES],0.82[R]	1.68[S136], 1.19[S129],	–	2.00/2.00
FHR (gal)	–	37.5	–	60.0[ES],59.0[ES], 61.0[N]	39.4[S136], 52.6[S129], 36.2[S126]	–	56.0/67.0
UA (Btu/h-°F)	–	5.1	–	–	5.1[S136], 5.2[S129]	–	–
RE	–	–	–	–	2.04[S136], 1.55[S129],	–	–

Table 29. GE GeoSpring

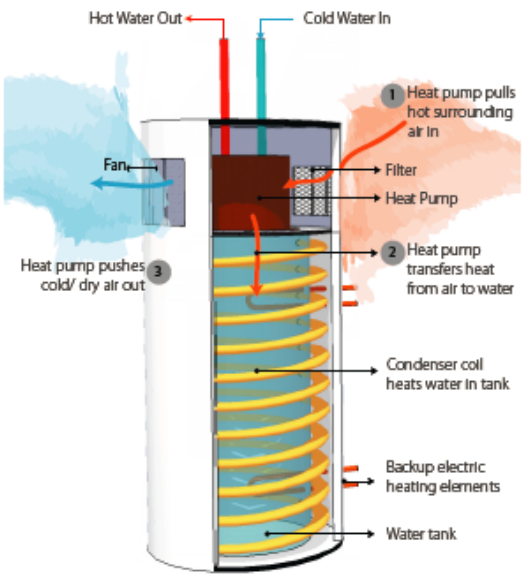
Laboratory Study Results							Rated
Reference Study	A	B	C	D[17]	E	F	
EF	2.42, 1.92[A50]	2.41	2.70[S120]	2.44[H], 0.84[R]	2.37[S140]	2.38,2.36[EH], 1.08[HD],0.83[R], 2.61[S120], 1.83[EH,S120], 1.63[HD,S120], 0.92 [R,S120],	2.35
FHR (gal)	66.0	57.0	–	59.0, 34.0[EH], 62.0[R]	57.3[S140]	–	63.0
UA (Btu/h-°F)	3.6	3.8	–	–	3.7[S140]	–	–
RE	–	–	–	–	2.78[S140]	–	–

Table 30. Stiebel Eltron Accelera 300

Laboratory Study Results							Rated
Reference Study	A	B	C	D[17]	E	F	
EF	–	–	–	–	2.48[S129]	–	2.51
FHR (gal)	–	–	–	–	77.1[S129],74.0,75.3[S140]	–	78.6
UA (Btu/h-°F)	–	–	–	–	4.6[S129]	–	–
RE	–	–	–	–	3.08[S129]	–	–

Appendix F: HPWH Informational Tri-Fold

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

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HEAT PUMP WATER HEATERS 101

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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

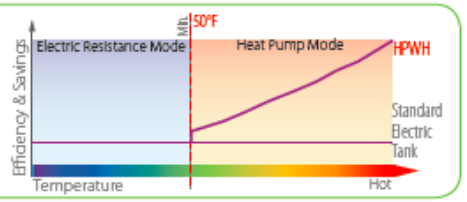
Standard Tank (EF 0.9)
HPWH*

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

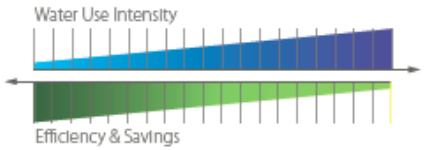
Savings depend primarily on hot water use.

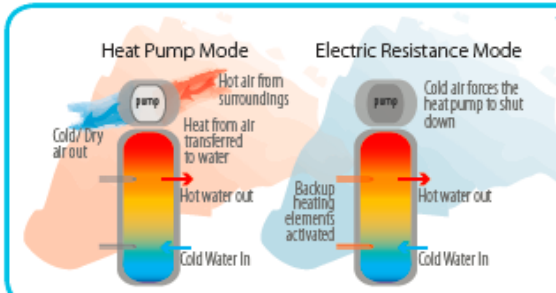
There will always be overall savings when compared to a standard electric water heater. Even if the HPWH runs in electric resistance mode all winter, during the warmer months you will benefit from the increased efficiency (along with some free cooling and dehumidification).

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?

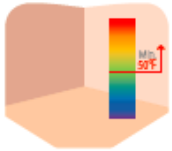
A 'heat pump' is a device that moves heat from one place to another; it works much like an air conditioner or a refrigerator. While a refrigerator moves heat from your fridge to your kitchen, a heat pump water heater (HPWH) moves heat from your home into the hot water tank. Most HPWHs include an integrated 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.

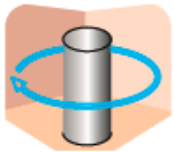
Location

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



Space

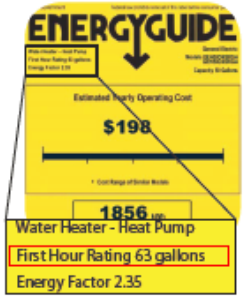
A heat pump removes heat from ambient air. Hence there must be a considerable volume of air available; most manufacturers recommend about 750 ft³. HPWHs often require larger clearances from walls so that air can circulate properly, and they are often taller and heavier than standard water heaters.



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

Size

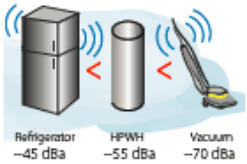
When selecting the proper water heater size and model, look at the ***First Hour Rating (FHR)*** on the yellow Energy Guide labels. Talk to your contractor or refer to manufacturers to determine what FHR is appropriate for you.



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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