Heat Pump Water Heaters: Laboratory and Field Evaluation of New Residential Products

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ABSTRACT

The Electric Power Research Institute (EPRI) conducted laboratory evaluations of several heat pump water heaters to assess their performance and energy efficiency. Among U.S. heat pump water heaters evaluated were new products from A. O. Smith, General Electric (GE), and Rheem. These units are designed to be integral, drop-in replacements for standard electric water heaters.

EPRI conducted a series of "draw tests" and "24-hour tests" under conditions that were somewhat different from the prescribed bounds articulated in the U.S. Federal Code of Regulations water-heating test protocol. The lab tests were conducted using each water heater's default operating mode, a 120°F water temperature setting and other targeted testing conditions.

In addition to lab evaluations, EPRI recently launched a medium-scale energy efficiency technology demonstration project that includes installing and monitoring up to 200 new residential heat pump water heaters. Working with sponsoring utility companies, EPRI is providing heat pump water heaters, monitoring equipment, and data analysis for nationwide installations. This paper provides some highlights of the lab tests.

Background

Heat pump water heaters (HPWHs) are typically more than twice as efficient as standard electric water heaters, and can result in lower annual water heating bills for the consumer, as well as reductions in peak electric power demand. Heat pump water heating technology relies on using electricity to power a vapor-compression cycle to transfer heat from the surrounding air into a water storage tank.

All major U.S. water heater manufacturers are introducing heat pump water heater products in 2009 and 2010, marketed as energy-efficient alternatives to standard electric water heaters. With improved product designs and promises of 3–6 year payback periods, new heat pump water heaters have the potential to overcome previous barriers and a moribund U.S. heat pump water heater market. For the past two decades, less than 0.1% of about 9 million water heaters sold annually in the United States have been heat pump units, a legacy of early models that suffered from reliability problems, excessive noise levels, high initial costs, and lack of consumer awareness.

Heat pump water heaters differ from standard water heaters in that their performance and efficiency varies significantly under varying conditions, including inlet and outlet water temperature, ambient conditions, and user settings. Laboratory testing is required to characterize how varying conditions affect heat pump water heaters and to provide performance data beyond product nameplate ratings. Additionally, field demonstrations are necessary to provide insight into heat pump water heaters' energy use and performance over a wide range of diverse environments.

EPRI, through its End-Use Energy Efficiency and Demand Response Program, is assessing and demonstrating heat pump water heaters by conducting comprehensive lab and field tests of new products, extensively engaging water heater manufacturers and electric utilities in the process. Laboratory and field evaluations began in 2009 and are continuing through 2010 and 2011. Figure 1 shows the types of HPWHs tested at the EPRI lab in Knoxville, TN.

Figure 1. HPWHs Tested at the EPRI lab in Knoxville, TN

Laboratory Evaluation

Product Specifications

Electric power specifications are listed in Table 1 for three HPWH units from the following manufacturers (and rated storage volumes): A. O. Smith (80-gal), GE (50-gal), and Rheem (50-gal). Heat pump power values were obtained from EPRI's lab testing and were the observed power drawn by the heat pump system at two operating conditions: "high" at approximately 120°F water tank temperature and "low" at approximately 58°F water tank temperature. Generally, heat pump power will increase as the water tank temperature increases.

Table 1. Power Specifications

Manufacturer	A. O. Smith	GE	Rheem
Heat pump power, high (W)[1, 2]	970	540	1170
Heat pump power, low (W)[1, 3]	680	410	780
Upper element, rated power (W)	4500	4500	2000
Lower element, rated power (W)	2000	4500	2000

[1] Values obtained from 2009 EPRI lab tests
[2] Heat pump power, high, is at 120°F water tank temperature and 68°F air temperature
[3] Heat pump power, low, is at 58°F water tank temperature and 68°F air temperature

A. O. Smith and GE have included interlock mechanisms to prevent concurrent heat pump and resistive element operations. Rheem, however, allows both the heat pump and one 2,000W element to operate concurrently if needed. In Table 2 user-selectable operating modes are described for each water heater. All heat pump water heaters have a "vacation" mode that will essentially allow the water tank temperature to decrease to around 50-60°F so that standby losses are minimized during extended periods of non-use. Note that A. O. Smith and GE have "heat pump only" modes available, whereas Rheem does not provide a "heat pump only" mode.

Table 2. Operating Modes and Airflow Pattern

Manufacturer	A. O. Smith	GE	Rheem
User-selectable operating modes	**Maximum Efficiency** (heat pump only) **Hybrid** (either heat pump or upper element; algorithm favors heat pump, based on water temp) **Conventional Electric** (either upper or lower element)	**eHeat** (heat pump only) **Hybrid** (either heat pump or upper element; algorithm favors heat pump, based on water temp) **High Demand** (either heat pump or upper element; algorithm favors element, based on water temp) **Standard Electric** (either upper or lower element)	**Energy Saver** (heat pump; time-based algorithm adds upper element after 45 minutes) **Normal** (heat pump; time-based algorithm adds upper element after 30 minutes)[4] **Electric Heat** (both upper and lower elements)
Airflow pattern	Into the left side, out of the right side	Into both sides, out of the back	Into the top, out of the sides and back

Because the Rheem unit requires the user to select a mode upon powering the unit, it does not have a default operating mode. In this case, the "Energy Saver" mode was chosen to represent the default operating mode because this mode provides the closest resemblance to both the A. O. Smith and GE factory default "Hybrid" modes.

Test Design and Procedure

EPRI has established a set of lab test procedures loosely based on the U.S. Code of Federal Regulations water heating test protocol.[5] EPRI used the HPWHs factory default setting conditions; these are not necessarily held within the prescribed bounds articulated in the federal standard. By doing this, EPRI could characterize a water heater's performance and efficiency under other test conditions by performing a series of "draw tests" and "24-hour tests." For example, EPRI has tested water heaters using a 120°F water temperature setting (typically default settings provided by manufacturers) instead of enforcing the standard 135°F water temperature setting.

[4] Rheem has considered renaming "Normal" mode to "High Demand" mode for clarity

[5] "Uniform Test Method for Measuring the Energy Consumption of Water Heaters." Title 10 *Code of Federal Regulations,* Pt. 430, Subpt. B, App. E. 2009 ed., 176-194. Print.

The electrical supply for these tests was provided by single-phase 240Vac 60Hz service. The test voltage was targeted to be 240Vac; however, voltage regulation and tolerance was not maintained during these tests.

Test area. EPRI's water heater lab test area consists of an indoor water retention barrier located within a semi-controlled environment. Domestic water supply is implemented with a 125-gallon storage tank with a jet pump and pressure tank to provide approximately 40-psi water pressure. The water system is capable of delivering up to 10 gallons per minute (gpm) of water flow. Supply water temperature is regulated manually, by adding multiple bags of ice or warm tap water to the storage tank as needed. The indoor ambient conditions are regulated by two unitary heating and cooling systems. One system is set to cooling mode while the other system is set to heating mode, and both thermostats are set such that a desired ambient temperature can be maintained. Ambient humidity control was not available for these laboratory tests.

Sensors and meters. The following sensors and meters were used to obtain measurement data collected in the heat pump water heater tests. Each measurement point is polled at 5-second intervals:

- **Water flow rate and totalization** is measured using a turbine-based, high-frequency pulse output water meter (Omega, FTB4607). The water meters are installed in the supply water piping. Accuracy, from 1.1 to 20.0 gpm, is ±1.5% of the measured flow rate.
- **Water temperatures**, both inlet and outlet, are both measured using a T-type thermocouple insertion probe assembly (Omega, TTIN-18U-12). Both temperature probes are inserted into the water piping near the hot and cold ports on the water heater, but they do not penetrate into the water heater tank or pass through the heat trap (if present). Measurement accuracy was calibrated to within ±1.0°F, as reported by the data acquisition's thermocouple input module (Advantech, ADAM-4118).
- **Electric power and energy** is measured using an ac power meter (Continental Control Systems, WattNode WNC-3D-240-MB) with two 30A solid-core current transformers (Continental Control Systems, CTT-0300-030). The power meters and current transformers are installed adjacent to a nearby circuit breaker panel, approximately 10-20 feet away from the water heater test locations. Accuracy, at nominal line voltages and current draws between 3.0A and 39.0A, is ±1.5% of the reading.
- **Ambient temperature** is measured using a T-type thermocouple (Omega, 5SRTC-TT-T-24-36), and **ambient relative humidity** is measured using a humidity transmitter (Vaisala, HMP233). These ambient sensors are placed such that they are not in the direct path of a heat pump water heater's exhaust air stream.

Test procedure summary. Each HPWH is subjected to an initial reheat cycle to ensure that a full tank of hot water is available just prior to testing. Additionally, the domestic water supply tank and ambient conditions are established and maintained to within EPRI's lab capabilities throughout the duration of each test.

The draw test consists of a single, continuous water draw event that is terminated when the tank is nearly depleted of hot water (i.e. water outlet temperature decreases by 25°F). The HPWH is then allowed to fully reheat undisturbed. A flow rate of 3.0 gpm is maintained during the draw, and the cutoff temperature is obtained by subtracting 25°F from the maximum recorded water outlet temperature.

The 24-hour test subjects the HPWH to a simulated usage pattern. During the first six hours of the 24-hour test, a standard volume of water (10.7 gallons) is drawn from the tank at hourly intervals for a total of 64.3 gallons drawn. The remaining 18 hours are then allowed to elapse with no water draw events.

Draw Test Results

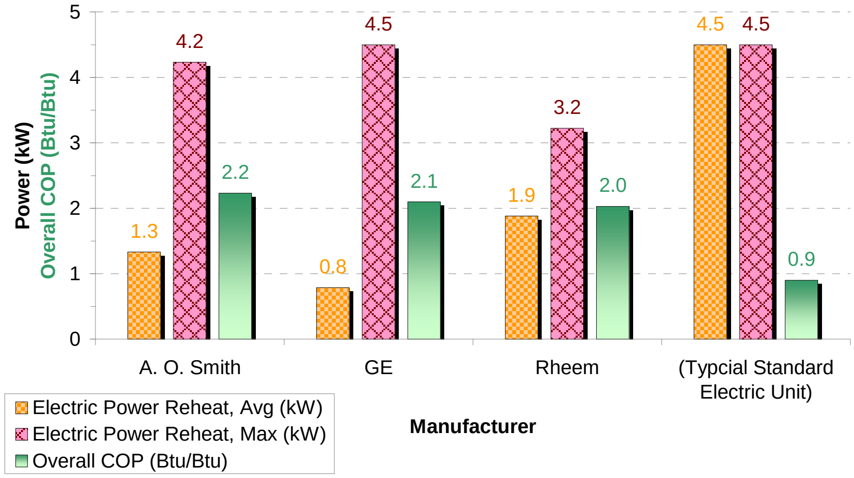
A summary of the draw test results are shown in Table 3 for the A. O. Smith, GE, and Rheem heat pump water heaters. Draw tests were performed at target conditions of 67.5±2.0°F ambient temperature, 50% ambient relative humidity, 58.0±2.0°F supply water temperature, and a 120°F water temperature setting. The summary includes each water heater's settings, measured conditions, calculated process variables, and overall efficiency (coefficient of performance).

Table 3. Summary of the Draw Test Results

Test Condition or Measurement	A. O. Smith	GE	Rheem
Operating Mode	Hybrid	Hybrid	Energy Saver
Water Temp Setting (°F)	120	120	120
Test Duration & [Recovery Time] (hours)	3.4 [3.3]	3.1 [2.8]	1.4 [1.4]
Ambient Temp, Avg (°F)	68.6	68.8	69.0
Ambient Humidity, Avg (%RH)	52.4	48.5	34.4
Water Draw Flow Rate, Avg (gpm)	3.0	3.0	2.9
Water Draw Inlet Temp, Weighted Avg (°F)	58.9	58.1	59.2
Water Draw Outlet Temp, Weighted Avg (°F)	119.6	113.6	114.6
Water Draw Volume & [Actual Tank Volume] (gal)	64.9 [80]	36.4 [45]	39.7 [50]
Water Draw Energy (ton-h)	2.7	1.4	1.5
Electric Power Reheat, Avg (kW)	1.3	0.8	1.9
Electric Power Reheat, Max (kW)	4.2	4.5	3.2
Electric Energy Reheat (kWh)	4.3	2.3	2.6
Overall COP (Btu/Btu)	2.2	2.1	2.0

Draw test results observations. When studying the draw test results presented in Table 3, several observations can be made. First, the testing conditions for each water heater were maintained within the specified desired ranges except for the ambient relative humidity, which was not controllable in the lab test area. Second, one of the most significant differences in the results is the volume of water drawn from each water heater. As expected, a larger water draw volume occurs with a larger tank size and necessitates more electrical energy to recover. In an effort to normalize the draw test results for varying water draw volumes, one may study the average power, maximum power, and overall coefficient of performance (COP) for each water heater, as charted in Figure 2.

Figure 2. Draw Test Average and Maximum Power, and Overall COP



The overall COPs (quotient when dividing "energy output" by "energy input") for each water heater are within about 10% of each other (2.0 to 2.2), even though the average and maximum power values vary quite largely. The Rheem unit has the highest average power (1.9kW), but it recovers in less than half of the time required by the A. O. Smith and GE units. While the A. O. Smith unit achieves the highest overall COP from this draw test, it took the longest time to recover. As expected, a trade-off must be made between average power consumption and recovery time for heat pump water heaters. The Rheem unit maximum power is the lowest of the three water heaters because Rheem utilizes a 2.0kW resistive element, whereas A. O. Smith and GE utilize a 4.5kW resistive element during a portion of the recovery period. As listed in

Table 3, the A. O. Smith unit maximum power was 4.2kW instead of 4.5kW. The maximum power was observed when the supplied ac voltage was 235Vac.

Heat pump water heaters twice as efficient. The estimated results from a standard electric water heater (without heat pump technology) are also shown in Figure 2 to serve as baseline data. Typical standard electric units would likely utilize 4.5kW upper and lower resistive elements, which would draw relatively constant power during the reheat period. The overall COP for a standard electric water heater must be less than 1.0 (the theoretical efficiency of a resistive electric heating element is 100%), and in general such water heaters are typically at least 90% efficient in recovering from a water draw event. Based on the results from this draw test, the U.S. heat pump water heaters are more than twice as efficient as a typical standard electric water heater.

24-Hour Test Results

The summary of the 24-hour test results is provided in Table 4 for A. O. Smith, GE, and Rheem heat pump water heaters. These tests were performed at target conditions of 67.5±2.0°F ambient temperature, 50% ambient relative humidity, 58.0±2.0°F supply water temperature, and a 120°F water temperature setting.

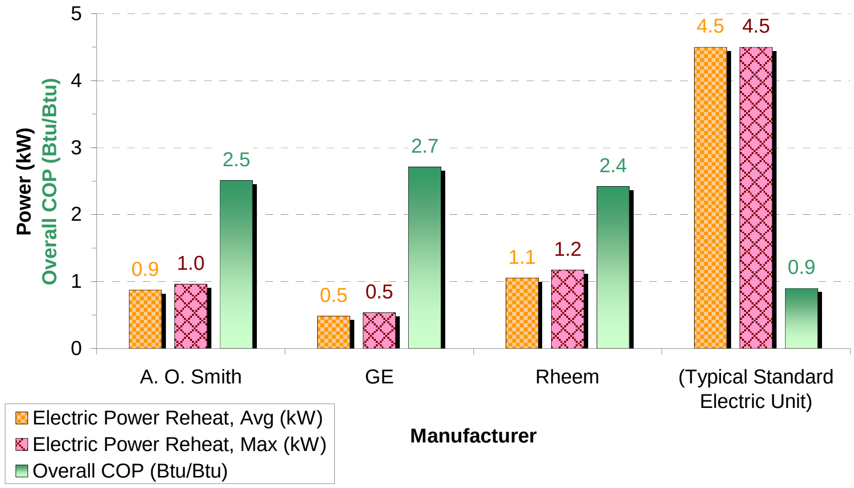
Table 4. Summary of the 24-Hour Test Results

Test Condition or Measurement	A. O. Smith	GE	Rheem
Operating Mode	Hybrid	Hybrid	Energy Saver
Water Temp Setting (°F)	120	120	120
Ambient Temp, Avg (°F)	69.2	68.4	68.0
Ambient Humidity, Avg (%RH)	40.7	39.6	38.6
Water Draw Flow Rate, Avg (gpm)	3.0	3.0	3.0
Water Draw Inlet Temp, Weighted Avg (°F)	58.1	58.2	58.7
Water Draw Outlet Temp, Weighted Avg (°F)	121.2	117.5	121.6
Water Draw Volume (gal)	64.3	64.4	64.2
Water Draw Energy (ton-h)	2.7	2.6	2.7
Electric Power Reheat, Avg (kW)	0.9	0.5	1.1
Electric Power Reheat, Max (kW)	1.0	0.5	1.2
Electric Energy Reheat (kWh)	3.8	3.4	4.0
Overall COP (Btu/Btu)	2.5	2.7	2.4

24-hour test results observations. When studying the 24-hour test results presented in Table 4, several observations can be made. The conditions in which each water heater is tested were maintained within the specified desired ranges except for ambient relative humidity, which cannot be controlled in the lab test area. The total water draw volume for each water heater is within 0.1 gallons of the required 64.3 gallons water draw. One noticeable difference on the water measurements is that the GE unit's average water outlet temperature is approximately 4°F lower than the other units' average water outlet temperatures. This difference occurs because the GE unit does not fully reheat its water tank between any of the hourly water draw periods.

The most significant differences in the results are seen in comparing the reheat power levels and overall COPs for the 24-hour test (COP is the quotient when dividing "energy output" by "energy input"). The average power, maximum power, and overall COP for each water heater are charted in Figure 3. In all cases, the heat pump water heaters did not engage any resistive elements during the 24-hour test period. If a similar 24-hour test was to be conducted using another operating mode that favors faster reheat times (such as "High Demand" or "Normal" modes) then the resistive elements are expected to be engaged during a portion of the reheat period.

Figure 3. 24-Hour Test Average and Maximum Power, and Overall COP



As depicted in Figure 3, the GE unit's average and maximum power levels (measured during the reheat periods) are about 50% lower than the comparable power levels for the A. O. Smith and Rheem units. This difference should be expected because the GE unit's heat pump power ratings are roughly half of the power ratings shown for the A. O. Smith and Rheem units (see Table 1). All three U.S. water heaters exhibited relatively stable power profiles, where the maximum power was observed to be within 10% of the average power during each water heater's reheat period.

Heat pump water heaters more than twice as efficient and draw a quarter of the power. The estimated results from a standard electric water heater (without heat pump technology) are also shown in Figure 3 to serve as baseline data. Typical standard electric units would likely utilize 4.5kW upper and lower resistive elements, which would draw relatively constant power during the reheat periods. The overall COP for a standard electric water heater must be less than 1.0 (the theoretical efficiency of a resistive electric heating element is 100%), and in general such water heaters are typically about 90% efficient after subjected to a 24-hour test. Based on the results from this 24-hour test (at 120°F water temperature setting), these heat pump water heaters are at least 2.5-times more efficient than a typical standard electric water heater. Additionally, these heat pump water heaters draw less than 25% of the power drawn by a typical standard electric water heater (1.1kW or lower, compared to 4.5kW).

Performance Characterization

As heat pump technologies involve moving heat from one medium to another, the primary drivers that affect a heat pump's performance and efficiency are source and sink temperatures over which the heat transfer takes place. In the case of heat pump water heaters, the ambient air temperature acts as the source, and the water tank temperature acts as the sink.

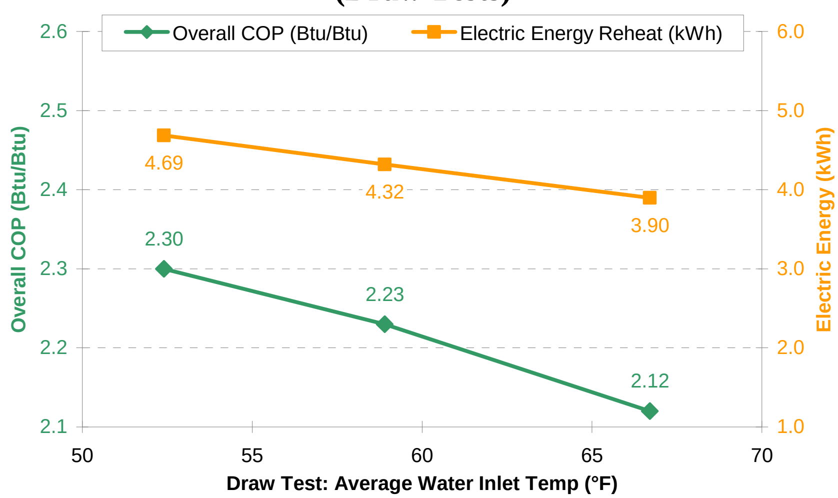
Effects of water inlet temperature. Assuming a constant ambient air temperature and a constant water outlet temperature, the theoretical maximum COP will be higher for lower water tank temperatures. While lower supply water temperatures may yield higher system efficiencies, more electrical energy input is required to reheat the water tank. This may appear contradictory, but it is indeed a phenomenon of heat pump water heating technology. The matrix shown in Table 5 provides a general representation of how a heat pump water heater's efficiency and energy use will change based on varying water inlet temperatures, assuming all other conditions are held constant.

Table 5. General Effects of Water Inlet Temperature on Efficiency and Energy Use

Water Inlet Temperature	Cooler	Warmer
Heat Pump Efficiency	Higher	Lower
Electrical Energy Used	More	Less

To demonstrate how lower water temperatures affect efficiency and energy use, the A. O. Smith heat pump water heater was subjected to three different draw tests. For each draw test, the average water inlet temperature was changed, but all other conditions and settings were held constant (to within EPRI's lab testing capabilities). The graph shown in Figure 4 contains a plot of overall COP and electrical energy for the set of draw tests conducted at these average water inlet temperatures: 52°F, 59°F, and 67°F.

Figure 4. Overall COP and Electrical Energy for Varying Water Inlet Temperatures (Draw Tests)



As shown in Figure 4, a 15°F decrease in water inlet temperature (67°F to 52°F) results in an 8% increase in overall COP (2.1 to 2.3) but requires 20% more electrical energy (3.9kWh to 4.7kWh) to reheat the water tank.

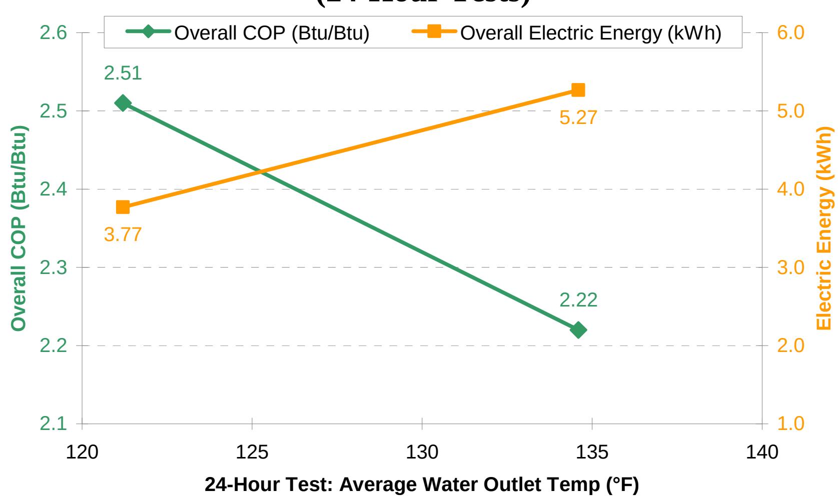
Effects of water outlet temperature. Assuming a constant ambient air temperature and a constant water inlet temperature, the theoretical maximum COP will be higher for lower water outlet temperatures. When lower water outlet temperature yields higher system efficiencies, less electrical energy input is required to reheat the water tank. The matrix shown in Table 6 provides a general representation of how a heat pump water heater's efficiency and energy use will change based on varying water outlet temperatures, assuming all other conditions are held constant. Please note that the effect of varying water outlet temperature results in the electrical energy *decreasing* with *increasing* efficiency, which is inverse from the effect caused by varying water *inlet* temperature as explained in the previous section.

Table 6. General Effects of Water Outlet Temperature on Efficiency and Energy Use

Water Outlet Temperature	Hot	Hotter
Heat Pump Efficiency	Higher	Lower
Electrical Energy Used	Less	More

To demonstrate this effect, the A. O. Smith heat pump water heater was subjected to two different 24-hour tests. For each 24-hour test, the water temperature setting was changed, but all other conditions and settings were held constant (to within EPRI's lab testing capabilities). The graph shown in Figure 5 contains a plot of overall COP and electrical energy for the pair of 24-hour tests conducted when the average water outlet temperatures were measured at 121°F and 135°F.

Figure 5. Overall COP and Electrical Energy for Varying Water Outlet Temperatures (24-Hour Tests)



As shown in Figure 5, a 14°F decrease in average water outlet temperature (135°F to 121°F) results in a 13% increase in overall COP (2.2 to 2.5) and results in 28% less electrical energy required (5.3kWh to 3.8kWh) to reheat the water tank over the 24-hour test period.

Implications/Conclusions from Lab Evaluation

The lab evaluations show that heat pump water heaters could be more than twice as efficient as standard electric water heaters. Additionally, the heat pump component of the water heaters can operate while drawing less than 25% of the average power required of standard electric water heaters.

While the energy efficiency and power consumption figures are favorable for heat pump water heating technologies tested by EPRI, longer reheat periods are required to recover a tank of hot water. The recovery time could last over 3 hours for reheating a cold tank, but this will vary based on the water heater model, operating mode, and usage characteristics.

Technical application issues. Technically, each water heater tested at EPRI exhibited reliable performance during its relatively short time undergoing laboratory tests. Practical application issues may arise with the adoption of heat pump water heating technology. For example, the following issues must be addressed when installing a heat pump water heater in a residence:

- **Adequate physical space:** Heat pump water heaters are generally larger (height, width, and/or depth) compared to standard water heaters. Having limited physical space may prevent the water heater from being installed in a desired location within a residence.
- **Adequate air volume and circulation:** Heat pump water heaters have specific air volume and circulation requirements that can degrade a heat pump water heater's performance if installed in a confined sealed space, such as a closet or a small room.
- **Condensate removal:** Access to a drain or to the outdoors is required for removing the heat pump water heater's condensate. Typically, existing water heaters will have a drain pan, but additional piping may be required for handling condensate removal.
- **Noise:** Heat pump water heaters generate a humming or whirring noise when the heat pump system operates. Depending on the heat pump water heater model and location within a residence, occupants may take notice of potentially undesirable noise levels.
- **Exhaust air:** Heat pump water heaters exhaust cool, dehumidified air into their surroundings, which may or may not be desirable to the occupants. The U.S. heat pump water heaters reviewed in this report each have a means to disable the heat pump operation to stop the exhaust air.

Field Evaluation

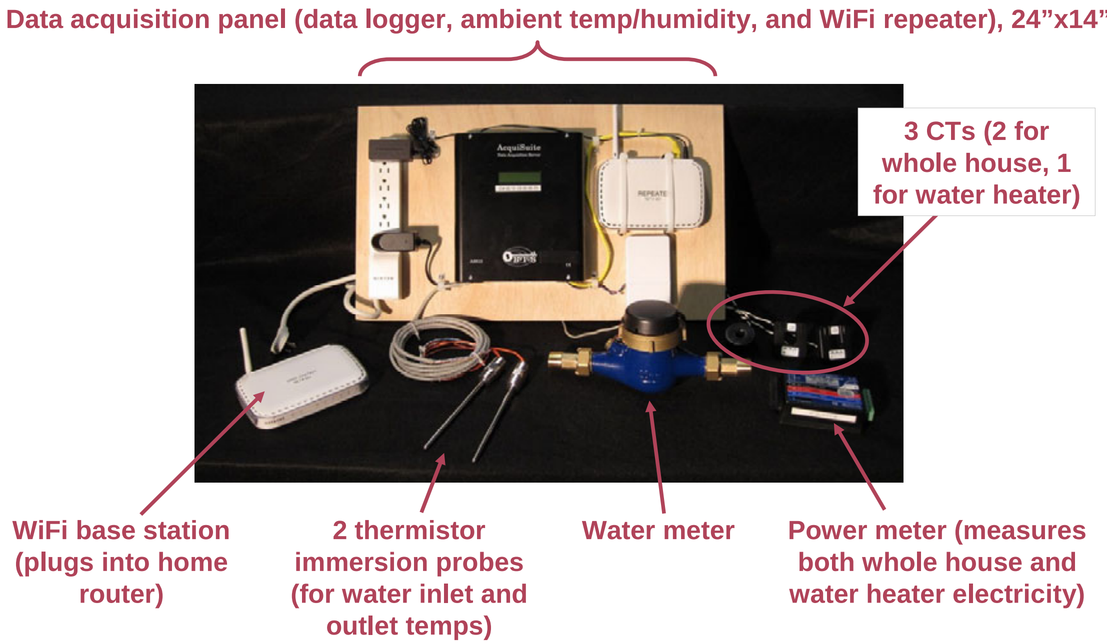
Overview

In 2009, EPRI launched a medium-scale energy efficiency technology demonstration project that includes installing and monitoring up to 200 new residential heat pump water heaters. Working with sponsoring utility companies, EPRI is providing heat pump water heaters, monitoring equipment, and data analysis for nationwide installations. The objectives of the demonstration are to assess heat pump water heater technology by measuring efficiency, to provide credible data on the performance and reliability of heat pump water heaters, and to assess user satisfaction in a residential setting.

The heat pump water heaters slated for field installations include the latest Underwriters Laboratories (UL) approved models from A. O. Smith, GE, Rheem, Stiebel-Eltron, and Daikin (Note: The last two will be evaluated at field sites only). Demonstrations sites must be owned by the occupants, have standard utility rates, and be served by no more than l water heater. Treatment sites (those receiving a new HPWH) require adequate physical space and air circulation for proper installation, as well as access to a condensate drain line and electrical service. Control sites will have existing water heaters (standard electric or natural gas) monitored in parallel with treatment sites over the 2-year demonstration period. Occupants are requested to operate the water heaters normally, year-round, and are allowed to adjust the water temperature setting and operating modes as desired.

Instrumentation. Both treatment and control sites will be provided with appropriate instrumentation for collecting usage data. The data collection efforts allow multiple sensors and meters to capture the performance and operational characteristics of a field-installed HPWH. EPRI offers two types of instrumentation packages for field installations: a Full package and a Lite package. Both packages provide water heater and whole house energy and power consumption plus hot water usage volume. A photograph showing of the contents of a Full package is provided in Figure 6.

Figure 6. Instrumentation for Field Data Collection (Full Package)



The Full package adds measurements of basic power quality data (voltage, current, reactive power, and frequency), ambient temperature and relative humidity, water inlet and outlet temperatures. Data is recorded every minute for the Full package and every 5 minutes for the Lite package. Both packages have on-board memory for data storage and will periodically upload data logs to EPRI via the internet.

Initial findings. As of this writing, field data are just being collected and analyzed. Interim data will be made available (first to the funders, and subsequently to the public), as and when analyses are being completed.

References

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