NATIONAL RENEWABLE ENERGY LABORATORY

Field Monitoring Protocol: Heat Pump Water Heaters

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February 2013

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List of Acronyms

Btu	British thermal unit
COP	Coefficient of performance
CT	Current transformer
dB	Decibel
DHW	Domestic hot water
EE	Electrical energy
EES	Engineering Equation Solver
GE	General Electric
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air conditioning
NEEA	Northwest Energy Efficiency Alliance
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RH	Relative humidity
SHR	Sensible heat ratio
T&RH	Temperature and relative humidity
TC	Thermocouple
UA	Heat loss coefficient

Table of Contents

List of Figures

List of Tables

Introduction

An integrated heat pump water heater (HPWH) uses an air source heat pump as the main heat source and electric resistance elements as backup heaters. HPWH technology was first introduced in the 1950s and, unlike some earlier versions, integrated HPWHs combine the heat pump, water tank, and backup resistance elements in a single package. HPWHs are expected to have high system coefficients of performance (COPs), the ratio of useful energy transferred to the electrical energy (EE) consumed, relative to traditional electric water heaters that have a COP < 1. HPWHs have rated COP values > 2.

HPWHs are a good fit for water heater retrofits in existing homes, because they are about the same size as traditional electric water heaters, have the same plumbing and electrical connections, yet have the potential to save at least 50% of water heating energy relative to other electric water heaters (Sparn, Hudon, & Christensen, 2011). In homes and regions where natural gas is not available, this is the first technology with a typical water heater form factor that can provide an energy-efficient alternative to electric resistance water heaters. Solar thermal water heaters can also be an excellent alternative, but they are usually more expensive and require more infrastructure (Hudon, Merrigan, Burch, & Maguire, 2012).

Like other heat pumps used for space conditioning, those used in HPWHs absorb energy from the surrounding air. This heat is transferred to the water in the HPWH tank. The heat pump thus expels cooler and drier air into its surroundings. More than other types of water heaters, HPWHs are strongly influenced by—and have an effect on—their surroundings. Thus, the climate and installation location in the home can strongly impact HPWH performance. These effects are complex and different for virtually every house and climate region, so field tests will be used to improve modeling tools that are currently under development for HPWHs.

HPWHs have been tested in controlled laboratory environments, and their operation is well understood technically (Sparn, Hudon, & Christensen, 2011). However, several unique factors affect their performance, so monitoring installed performance of HPWHs in varied real-world settings will produce valuable data.

The scope of this work is to provide a standard field monitoring protocol for evaluating the installed performance of HPWHs in residential buildings. The report is organized to be consistent with the chronology of field test planning and execution. Research questions are identified first, followed by a discussion of analysis methods. The details of measuring the required information are then laid out. A field validation of the protocol at a house near the National Renewable Energy Laboratory (NREL) campus is included in the appendix.

Monitoring a Heat Pump Water Heater

HPWHs have enormous potential, but their performance is significantly affected by the installed conditions. Several factors affect their performance and energy consumption, beyond the amount of hot water used by the household.

- The installed location will influence the temperature and relative humidity (T&RH) of the ambient air the HPWH uses to heat the water. If the HPWH is installed in an unconditioned space that is too cold in the winter, the HPWH may not be able to use its compressor and so may use the backup electric resistance heaters to heat the water. If the installed location is inside conditioned space, the heat pump will always have warm air around it, so it is expected to increase the space heating load in the house during the winter and reduce the air conditioning load in the summer.
- The volume of hot water consumed, as well as the exact draw pattern, will also impact HPWH performance. If several large draws occur in close succession, the heat pump may not be able to keep up with demand and the resistance heaters will take over. However, the same volume of requested hot water, spaced out more evenly over a day, could be satisfied with the heat pump alone.
- Depending on where the unit is installed and how often the filter is cleaned, the cleanliness of the filter can affect overall performance. A very dirty filter can obstruct airflow and degrade performance.
- The tank volume will affect how often the resistance heaters are needed. A larger tank will be able to satisfy large hot water draws, and could avoid the use of the electric resistance heaters even in periods of high demand.
- Different manufacturers use different control logic that also affects when the heat pump is used and when the resistance heaters turn on.

Because so many variables affect HPWH performance, monitoring the performance of HPWHs installed in homes around the country is essential to understanding where they are best suited. Laboratory tests have guided installations, but there is still much to be learned.

The high level of interaction between a home's heating and cooling systems and the HPWH means that other systems will need to be monitored to fully understand its impact. The exact set of data required will vary for each house and the goals of that project. Data on basic house characteristics will also need to be collected to enable simulation of the HPWH for that house. By collecting data on the whole house and using a model to recreate the conditions in the house, the long-term effects of an HPWH can be fully quantified.

Before any field test is conducted, the project goals need to be defined. A monitoring plan will be devised based on the research questions and the specifics of a particular site. Researchers should collect information about the home and heating, ventilation, and air conditioning (HVAC) equipment when they arrive at the field test site. Then the monitoring equipment and data logger must be installed. Before leaving the field test site, the researchers should ensure that all sensors were installed correctly and are functional. The research plan may prescribe some short-term tests that should be performed after all the monitoring equipment has been verified. Long-term monitoring will collect data on HPWH performance over one or more seasons, depending on the research plan. Especially in places with a heating and a cooling season, the long-term monitoring should be planned to measure the HPWH performance in both. After the scheduled monitoring duration, the monitoring equipment will be removed from the field test site.

Potential Research Questions

1. What is the HPWH performance in the installed location—system COP as a function of ambient air T&RH, daily COP as a function of daily hot water use, and real-world variations in use patterns?
2. How does the daily average system COP vary over the course of the year? How does the annual system COP compare to rated efficiency? How do operational efficiency and energy consumption compare to simulation estimates based on conditions around the water heater and the hot water demands of the household? Rated efficiency and simulation performance estimates are used when choosing to install a HPWH, so it will be useful to see how well these performance metrics compare to actual installed performance.
3. Is the HPWH keeping up with hot water demand? Monitor outlet temperature to observe whether and how often it drops below 110°F. This minimum temperature threshold is taken from the Operating Conditions specified in the House Simulation Protocols (Hendron & Engebrecht, 2010). It may not be possible to determine the volume of hot water needs that are not met, but monitoring when and how often the hot water temperature drops below an acceptable level may indicate how well the HPWH is satisfying the home's domestic hot water (DHW) needs.
4. Do occupants change the operating mode or temperature set point to ensure they have enough hot water? Does this affect the actual energy savings relative to predicted savings?
5. Depending on the time of year and climate, an additional source of cold, dry air may be beneficial, because it could offset some of the cooling and dehumidifying loads. However, the HPWH will produce that same cold air in the winter. What is the overall impact of the HPWH on the other space conditioning equipment in the house?
6. An HPWH produces perpetual cooling, so installing or replacing a water heater with an HPWH in an unconditioned or semiconditioned area of the house, such as a basement or a garage, may be a good option. The ambient conditions in an unconditioned space will determine an HPWH's annual performance, but in new homes and retrofits, the temperature range in that unconditioned space is probably not well known. Are the monitored conditions in the unconditioned space favorable for the HPWH over a year? Can the heat pump operate during the entire year or are the electric resistance elements needed for long periods of time?
7. For installations in conditioned spaces, is noise a concern for homeowners? An HPWH sounds like an air conditioner and, depending on the location, the noise could be more or less amplified.
8. If the air inlet and outlet (or just the outlet) of the HPWH are ducted, the research questions will be more extensive. Where are the ducts pulling or depositing air? Are additional fans and dampers required for the duct system? How are they controlled? What

is the energy penalty or benefit? What is the first cost penalty? What energy gains are measured for the HPWH with the duct system, and for the HVAC system?

As with all field tests, the research questions dictate what must be measured. The measurements needed to answer these broad questions will be described in the following sections. The particular suite of sensors and controls used in any field test is tailored to each specific test.

Home Characteristics and Site Information

An HPWH field test could occur in virtually any area of the country, in a new home or a retrofit situation. As with any field test, some basic information about the home should be collected in the early planning stages to help frame the research questions and fine tune the monitoring plan. Also, the homeowner should be consulted at this point to clarify expectations and ensure that the long-term monitoring plan will not be an inconvenience. The following basic field test information should be collected to inform the monitoring plan.

Basic Field Test Information

- Geographical location
- Home heating and cooling type
- Original type (for retrofits) and location (conditioned/unconditioned) of water heater
- Homeowner approval for monitoring for at least one year, if long-term monitoring is needed for the research plan.
- Homeowner approval for release of historical utility bills (for retrofits)
- Reasonable expectation that an HPWH is an appropriate choice of water heating technology based on the climate, installed location, and family size. This assessment should be based on simulation results, if possible.

Once the researchers visit the field test site to begin installing the monitoring equipment, additional information about the home and HPWH installation is needed for modeling and to determine expected performance. The following detailed information should be gathered while researchers are on site, as needed. Many of these questions will only be relevant for field tests with related research goals. In retrofit cases, the expectation is that the HPWH has already been installed before the field test begins. In new homes, the researchers may have the opportunity to install monitoring equipment before construction is finished. In that case, the researchers may have to follow up with the homeowners after they have moved in to complete the more detailed survey.

Detailed Site Information

- **Equipment specifications.** Make, model, and size of HPWH.
- **Building use.** Number of occupants, typical schedule.
- **Installation date and cost.** Include any known installation issues.
- **Installation site for HPWH.** Size and location of room, location within room.
    - For retrofit projects, is the HPWH installed in same location as the previous water heater?
    - Is the room part of conditioned space, unconditioned space, or semiconditioned space?
    - If in a smaller room, is the door properly louvered, per manufacturer instructions?

    - Where is the condensate drained to? Does it require a pump?
- **Does the installation comply with manufacturer recommendations?** Room size and clearance around the unit are important for HPWH performance.
    - Consult the Building America Measure Guideline for HPWHs for other installation considerations (Shapiro, Puttagunta, & Owens, 2012).
    - Should the manufacturer incorporate any additional installation recommendations into the user manual?
- **Maintenance requirements**, according to the installer and/or manufacturer. Most of this should come from the HPWH user manual.
    - Inspect the condition of the air filter and clean, if needed, prior to monitoring.
- **HPWH operating mode and set point.** In a retrofit case, what was the set point of the old water heater, if known?
    - Has the occupant had to adjust the set point or operating mode of the HPWH to improve comfort?
- **Is inlet and/or outlet air ducted?** If so, where to? Are there controls that can be used to change where ducting goes in summer and winter?
- **Determine the installer's experience and certifications.**
- **Detailed information about the home's heating and cooling equipment (make, model, age) and ducts (leakage, insulation level, location).** This information will be needed if assessing the impact of the HPWH on the space conditioning energy consumption.
- **System controls** for space conditioning: thermostat set points, deadband, zoning, and ventilation control settings (any that are applicable)
- **Home construction details**, including blower door results if applicable, for later use when modeling the home to predict energy use of the HPWH and space conditioning equipment.
- Complete list of **other retrofits** occurring with HPWH installation and during the monitoring period.

Data Analysis and Calculations

Once the research questions for a particular project have been identified, the data analysis plan should be reviewed to ensure that all the quantities needed for analysis will be measured. This also may help researchers avoid installing unnecessary sensors. The following calculations are commonly used when evaluating HPWHs, but other calculations may be needed depending on the research objectives of the field test.

System COP should be calculated each day for all field tests involving HPWH monitoring. All other calculations shown below are optional and may or may not be relevant to the research questions for a particular field test. Uncertainty analysis should be performed for all calculations, especially when the results will be presented in public reports. The appendix shows a few examples of uncertainty analysis.

System Coefficient of Performance

Daily system COP is a measure of the useful energy transferred to the water divided by the EE input to the system over the course of a day (ASHRAE, 2005).

$$COP = \frac{Q_{thermal}}{W_{input}} = \frac{Q_{draws}}{W_{input}} = \frac{\rho_{water} \cdot V_{draws} \cdot C_{p,water} \cdot \Delta T_{draws}}{W_{input} \cdot 3600 \frac{s}{hr}} \quad \textbf{(1)}$$

where

ρ_{water} is the density of water, 998 kg/m^3.

V_{draws} is the volume of the water drawn (m^3).

$C_{p,water}$ is the specific heat of water, 4.182 kJ/kg-C.

$\Delta T_{draws}=T_{out}-T_{in}$ is the difference between the outlet and inlet water temperature (°C).

W_{input} is the EE used by the water heater during the day (kWh)[1].

[1] To avoid the situation where the heat pump may still be running after draws on the previous day, it may be useful to define 4:00 a.m. as the start and end time for each day.

The heat removed during draws should be calculated at short intervals, such as every minute, to ensure that any changes in ΔT_{draws} over the course of the draw are taken into account. The total thermal energy removed from the tank in a day should be compared to the total EE needed during that day. That ratio will be the system COP for that day and a daily average should be calculated for the monitoring period.

Heat Loss Coefficient

The heat loss coefficient (UA) of the HPWH can be measured in a short-term test or during the long-term monitoring phase when there are long periods of time without hot water draws. Even if there are no hot water draws for a day or more, the heat pump will need to come on periodically to compensate for standby heat loss. The rate at which heat is lost through the tank walls is described by the UA of the water heater. The higher the UA value, the faster heat is lost and the more energy is required to keep the tank hot.

It is important that the tank be heated with the heat pump prior to the standby period evaluated for the tank UA measurement. When the tank is heated with the heat pump, it is expected to be more uniformly heated than if the resistance elements are used, which will affect UA.

Whether the UA is measured during a short-term test or during the long-term monitoring period, the tank needs to be conditioned so that the entire tank is at the same temperature. During a short-term test, this can be induced by drawing enough water to force the heat pump to come on. Once the heating cycle is finished, the tank's temperature will be nearly uniform. As the tank cools, laboratory measurements indicate that the average tank temperature is well approximated by the average of temperatures in its upper and lower thirds. This is where the surface-mounted thermocouples (TCs) will be installed when there are upper and lower resistance heaters. If the HPWH under test does not have two resistance heaters, it may not be possible to measure average tank temperature and by extension, UA. The geometry for five of the integrated HPWHs currently on the market is discussed below.

Once the tank is conditioned and the heat pump turns off, the standby period will begin. Ideally, this test should be done when the ambient temperature is relatively steady, such as at night. The standby period is defined as the amount of time between the end of one heating cycle and the beginning of the next. All measurements and calculations should begin about 10 min after the heat pump turns off, because the condenser coil will be hotter than the water in the tank for several minutes after the heat pump stops running. The following equation will be used to calculate UA after the standby period is finished (DOE, 1998).

$$UA = \frac{V_{st} \cdot \rho_{water} \cdot C_{p,water} \cdot \left(\bar{T}_i - \bar{T}_f\right)}{\tau_{stdby} \cdot (\bar{T}_{tank} - \bar{T}_{amb})} \qquad \textbf{(2)}$$

where

V_{st} is the volume of the storage tank (m^3) [1],

$\bar{T}_i$ is the average tank temperature, $(T_{tank,upper}+T_{tank,lower})/2$, at the beginning at the end of the standby period (°C) [2],

$\bar{T}_f$ is the average tank temperature, $(T_{tank,upper}+T_{tank,lower})/2$, at the end of the standby period (°C),

τ_{stdby} is the total standby time (h),

$\bar{T}_{tank}$ is the average tank temperature during the entire standby period (°C),

$\bar{T}_{amb}$ is the average ambient temperature during the entire standby period (°C).

[1] The actual tank capacity is usually lower than the rated capacity. If the manufacturer does not prove the actual tank volume, approximate the tank volume as 10% less than the rated value. For example, the actual volume of a 50-gal tank is usually closer to 45 gal.

[2] Right after the heat pump turns off, the surface of the tank will be hotter than the water, because the condenser coils are still hot. The average tank temperature at the beginning of the standby period should be calculated a few minutes after the heat pump turns off to avoid an artificially high temperature reading.

Cooling Capacity

A heat pump removes heat from the air with a vapor compression cycle similar to an air conditioner. The total cooling capacity can be calculated to quantify the cooling effect of the HPWH on its surroundings. This calculation requires the airflow of the heat pump to be measured using a duct blaster. The cooling effect can be separated into sensible and latent cooling effect, and the ratio of sensible cooling capacity, q_s, to the total cooling capacity, q_t, is called the sensible heat ratio (SHR) (ASHRAE, 2005).

$$q_t = \rho_{air} \cdot \dot{V} \cdot (h_{inlet} - h_{outlet}) \tag{3}$$

$$q_s = \rho_{air} \cdot \dot{V} \cdot C_{p,air} \cdot (T_{in} - T_{out}) \tag{4}$$

$$q_t = q_s + q_l \tag{5}$$

$$SHR = q_s / q_t \tag{6}$$

where

q_t is the total cooling capacity of the heat pump (W),
q_s is the sensible cooling capacity of the heat pump (W),
q_l is the latent cooling capacity of the heat pump (W),
SHR is the sensible heat ratio for the heat pump (unitless),
ρ_{air} is the density of air at the average air temperature, expression given in Equation (7),
$\dot{V}$ is the volumetric flow rate of the air through the heat pump (m^3/s),
h_{inlet} and h_{outlet} are the enthalpies of the air entering and leaving the heat pump, respectively, (J/kg). Air enthalpy can be calculated based on air temperature and humidity, expression given in Equation (8).
$C_{p,air}$ is the specific heat of air at the average air temperature, expression given in Equation (9), and
T_{in} and T_{out} are the temperatures of the air at the inlet and outlet of the heat pump, respectively (°C).

Air Density (ASHRAE, 2005)

$$\rho_{air} = \frac{P_{amb}}{R_{da} \cdot (273.15 + T_{avg}) \cdot (1 + 1.6078 \cdot \omega)} \tag{7}$$

where

ρ_{air} has units of kg/m^3,
P_{amb} is the ambient pressure (Pa),
R_{da} is the universal gas constant for dry air, 287.055 J/kg-C,
T_{avg} is the average air temperature (°C), $T_{avg} = (T_{in}+T_{out})/2$, and
ω is the humidity ratio of the air, expression given in Equation (10).

Air Enthalpy (ASHRAE, 2005)

$$h = C_{p,air} \cdot T + \omega \cdot (2501 + 1.86 \cdot T) \quad \textbf{(8)}$$

where

T is the temperature of the air (°C), and

ω is the humidity ratio of the air (kg/kg).

Specific Heat of Air (ASHRAE, 2005)

$$C_{p,air} = \frac{1005.625 + 0.023881 \cdot T_{avg} + 3.79x10^{-4} \cdot {T_{avg}}^2 - 8.3x10^{-8} \cdot {T_{avg}}^3}{1000} \quad \textbf{(9)}$$

where

$C_{p,air}$ has units of kJ/kg-C, and

T_{avg} is the average air temperature (°C), $T_{avg} = (T_{in}+T_{out})/2$.

Humidity Ratio of Air (ASHRAE, 2005)

$$\omega = 0.62198 \frac{RH \cdot P_{ws}}{P_{amb} - RH \cdot P_{ws}} \quad \textbf{(10)}$$

where

ω has units of kg/kg,

RH is the relative humidity of the air (unitless fraction),

P_{ws} is the saturation vapor pressure of the air (Pa), expression given in Equation (11), and

P_{amb} is the ambient pressure (Pa).

Saturation Vapor Pressure (ASHRAE, 2005)

$$P_{ws} = \exp\left(\frac{C_1}{T_K} + C_2 + C_3 T_K + C_4 {T_K}^2 + C_5 {T_K}^3 + C_6 {T_K}^4 + C_7 \, ln(T_k)\right) \quad \textbf{(11)}$$

where

P_{ws} has units of Pa, and

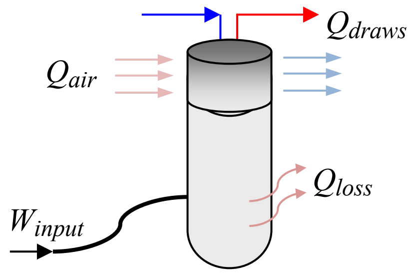
T_K is the absolute air temperature ($T_k=T+273.15$) (K).

C_n coefficients given below.

For $T_K \leq 273.15K$:	**For $T_K > 273.15K$:**
$C_1 = -5.6745 \times 10^3$	$C_1 = -5.8002 \times 10^3$
$C_2 = 6.3925$	$C_2 = 1.3915$
$C_3 = -9.6778 \times 10^{-3}$	$C_3 = -4.8640 \times 10^{-2}$
$C_4 = 6.2216 \times 10^{-7}$	$C_4 = 4.1765 \times 10^{-5}$
$C_5 = 2.0748 \times 10^{-9}$	$C_5 = -1.4452 \times 10^{-8}$
$C_6 = -9.4840 \times 10^{-13}$	$C_6 = 0$
$C_7 = 4.1635$	$C_7 = 6.5460$

Effect of Heat Pump Water Heater on Heating and Cooling Loads

Calculate the effect of the HPWH on the space conditioning load by looking at the energy balance. The net effect on the space, $Q_{net,space}$, includes the heat loss and the cooling load from the heat pump. The energy balance is shown below:



$$W_{input} + Q_{air} = Q_{draws} + Q_{loss} \tag{12}$$

$$\Rightarrow Q_{net,space} = Q_{loss} - Q_{air} = W_{input} - Q_{draws} \tag{13}$$

$$\Rightarrow Q_{net,space} = W_{input} - \rho_{water} \cdot V_{draws} \cdot C_{p,water} \cdot \Delta T_{draws} \tag{14}$$

where

Q_{air} is the energy from the air that is added to the tank (kJ),
Q_{draws} is the hot water energy removed from the tank during draws (kJ),
Q_{loss} is the energy lost from the tank via convection (kJ),
$Q_{net,space}$ is the net energy added to the space (kJ),
W_{input} is the EE used by the water heater to reheat the tank (kJ),
ρ_{water} is the density of water, 998 kg/m^3,
V_{draws} is the volume of the water drawn (m^3),
$C_{p,water}$ is the specific heat of water, 4.182 kJ/kg-K, and
$\Delta T_{draws}=T_{out}-T_{in}$ is the difference between the outlet and inlet water temperature (°C).

The result of this energy balance will calculate the net effect of the HPWH on the space around it. If the heat pump is being used to heat the water, the heat added to space, $Q_{net,space}$, should be a negative number, indicating that heat is removed from the space. If only the resistance heaters are used, $Q_{net,space}$ will be a positive number, indicating that heat is added to space by heat loss from the tank. As with the COP calculation, the Q_{draws} term is calculated on shorter time steps and totaled over an entire day. W_{input} is equal to the total EE used on the same day.

If the heat pump is primarily used, this will create a net cooling effect on the space. If the HPWH is located in conditioned space, it could help offset some of the cooling load in the summer, but it could also add to the heating load in the winter. That impact should be compared to the heating or cooling energy used in the house. If those systems are being monitored, a daily comparison can be employed to provide a frame of reference. For instance, it would be important to know if the amount of heat being removed from the air by the HPWH is equivalent to 1% or 20% of the daily heating load. If the other HVAC equipment is not being monitored, monthly bills can be used and compared to the month-long effect of the HPWH on the space. It is unlikely that the entire cooling effect would need to be made up by the heating system during the heating season, or that the exhaust air would provide all the building's cooling needs during the cooling season.

$Q_{net,space}$ calculates the net cooling effect on the space from the HPWH, but includes both sensible and latent cooling, where thermostats respond to sensible heat only. To extract the sensible cooling effect, multiply the SHR by $Q_{net,space}$, if SHR has been calculated. However, SHR is close to 1 for the HPWHs tested at NREL in 2011 (Sparn, Hudon, & Christensen, 2011).

Monitoring Package

The following measurements should be tailored for the specific field test, based on the research questions for that project. All are optional, except those needed for system COP.

The sampling rate required for the data depends on the goals of the field test. If HPWH energy consumption is the paramount concern, making measurements once every minute may be sufficient. If more detailed information about hot water use at the fixture level is desired, higher frequency data acquisition, on the order of 1 Hz, may be required. Increasing the rate of data logging increases the size of the resulting data files and may require more frequent upload depending on the data logger's onboard storage capacity. Also, unnecessarily high (temporal) resolution data will increase the time required for data processing.

It is also possible to take higher frequency data for a subset of channels for a short time. If high-resolution data are needed at the fixtures only when hot water is being used, some data loggers can save high-resolution data only during the times when a draw is occurring.

Electrical Energy Measurements

CAUTION! Working on a high-voltage system is extremely hazardous. Work inside of a circuit breaker panel must be performed by a qualified electrician.

1. Whole-house EE (if applicable)
2. Photovoltaic (PV) EE production (if applicable; needed for whole-house measurement)
3. HPWH EE
4. EE for HPWH fan (optional, if HPWH is ducted)
5. EE for HPWH circulation pump (optional, if applicable)
6. EE for DHW recirculation pump (if applicable)
7. EE for space conditioning electric heaters (if applicable)
8. EE for air conditioning or heat pump (if applicable)
9. EE for dehumidifier (if applicable)
10. EE for furnace fan or air handler (if applicable)

Temperature and Humidity Measurements

1. HPWH inlet air temperature and humidity
2. HPWH outlet air temperature and humidity (placed very near the air outlet)
3. Same room air temperature and humidity (placed away from the HPWH, in a well-mixed location—this measurement will be especially important for any ducted or enclosed situations)
4. Air temperature and humidity near the thermostat (when HPWH is installed in conditioned space)

Temperature Measurements

1. Inlet water temperature (immersion or surface-mounted)
2. Outlet water temperature (immersion or surface-mounted)
3. Tank temperature (surface-mounted, affixed to outside of tank, under insulation; if possible, install 2 sensors: one near the upper electric element and one near the lower element)
4. Surface temperature of the evaporator coils at the refrigerant outlet (optional, most applicable for installations that may have freezing concerns)

Flow Rate Measurements

1. Water flow rate on either the inlet or the outlet side (used to determine draw volumes)
2. Natural gas flow rate/consumption for the gas furnace (if applicable)
3. HPWH condensate volume or flow rate (optional)

Other Measurements

1. Outlet airflow rate (short-term test for HPWHs with a single airflow rate)
2. Noise measurement (when HPWH is located in a place where noise would be noticed, most likely relevant only when installed in conditioned space)

Weather Station

1. Outdoor air temperature and humidity
2. Solar radiation (optional, useful only when HPWH is installed in an attic or a garage)

Table 1 lists some common sensors that could be used to take the above data points. These sensors have been used in past Building America research projects, but equivalent sensors with similar operating ranges and accuracies would also be acceptable.

Table 1. Examples of Typical Monitoring Equipment and Accessories[1].

Monitored Parameter	Sensor Description	Sensor Manufacturer and Part Number	Sensor Range	Sensor Accuracy
Electrical Power Measurements				
Whole House Electrical Power	Watt node power meter	Continental Control Systems (CCS) WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-100	0–100 A	± 1.0% for > 10% of rated current
HPWH Electrical Power	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-30	0–30 A	± 1.0% for > 10% of rated current
Electrical Power for HPWH Fan	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-5	0–5 A	± 1.0% for > 10% of rated current
Electrical Power for Recirculation Pump	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-5	0–5 A	± 1.0% for > 10% of rated current
Power for Electric Heaters	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-30	0–30 A[2]	± 1.0% for > 10% of rated current
Electrical Power for Air Conditioning or Heat Pump	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-30, CCS CTS-0750-15	0–30 A (comp)[2] 0–15 A (AH)	± 1.0% for > 10% of rated current
Electrical Power for Dehumidifier	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-15	0–15 A[2]	± 1.0% for > 10% of rated current
Electrical Power for Dehumidifier	Watt node power meter	CCS WNB-3Y-208-P 100HZ output		± 0.5%
	Split core current transformer	CCS CTS-0750-15	0–15 A[2]	± 1.0% for > 10% of rated current

[1] Pieces of measurement equipment that have been commonly used in Building America tests are given here as examples only. We do not recommend or endorse any manufacturer or product.
[2] Current range for electric heaters, air conditioner or heat pump and air handler, and dehumidifier is approximate and should be reconsidered for the specific field test installation, as the size and capacity for this equipment can vary.

		Temperature and Humidity Measurements		
HPWH Inlet Air Temperature and RH	Temperature and humidity sensor	Vaisala HMP60	–40°–60°C 0%–100% RH	± 0.6 °C, ± 3% RH
HPWH Outlet Air Temperature and RH	Temperature and humidity sensor	Vaisala HMP60	–40°–60°C 0%–100% RH	± 0.6 °C, ± 3% RH
Room Air Temperature and RH	Temperature and humidity sensor	Vaisala HMP60	–40°–60°C 0%–100% RH	±0.6 °C, ± 3% RH
Air Temperature and RH Near Thermostat	Temperature and humidity sensor	Vaisala HMP60	–40°–60°C 0%–100% RH	± 0.6 °C, ± 3% RH
		Temperature Measurements		
Inlet Water Temperature	Immersion TC or surface-mounted TC	Omega TMQSS-125U-6 or CO1-T	–270°–400°C	Greater of ± 0.5°C or 0.4%
Outlet Water Temperature	Immersion TC or surface-mounted TC	Omega TMQSS-125U-6 or CO1-T	–270°–400°C	Greater of ± 0.5°C or 0.4%
Tank Temperature	T type surface-mounted TC Thermally conductive epoxy	Omega CO1-T Omega OB-101-1/2	–270°–400°C N/A	Greater of ± 0.5°C or 0.4% N/A
Evaporator Coil Surface Temperature	T type surface-mounted TC	Omega CO1-T	–270°–400°C	Greater of ± 0.5°C or 0.4%
		Flow Rate Measurements		
Water Flow Rate (Inlet or Outlet)	Turbine Flow Meter	Omega FTB-4605	0.15–13.0 gpm	± 1.5% of reading
Natural Gas Flow Rate for Gas Furnace	Diaphragm Gas Flow Meter	Elster American Meter AC-250	0–250 SCFH	± 1 CF/pulse
Condensate Flow Rate	Tipping Bucket	Campbell Scientific TB4-25	1–500 mm/h	± 2%
		Other		
Outlet Airflow Rate	Duct Blaster	The Energy Conservatory	10–1500 cfm	± 3%
Noise Measurement	Sound Level Meter	Extech 407736	35–130 dB	± 1.5 dB

Weather Station				
Outdoor Air Temperature and RH	Temperature and humidity sensor	Vaisala HMP60	-40-60°C 0-100% RH	± 0.6°C, ± 3% RH
	Radiation Shield	Campbell Scientific 41303-5A	N/A	N/A
Solar Radiation	Pyranometer	Campbell Scientific CS300-L50	0-2000 W/m^2	± 5% FS

Sensor Installation Notes

Water Flow Meter Installation

A few considerations should be taken into account when deciding which water line to install the flow meter on. To ensure that the flow meter is subject to laminar flow, it should be installed in a location that has 10 pipe diameters of straight pipe upstream of the flow meter and 5 pipe diameters of straight pipe downstream. For example, if the flow meter is being installed in 1-in. diameter pipe, there should be 10 in. of straight pipe before the flow meter and 5 in. of straight pipe after. This helps to ensure consistent readings, but is not always achievable.

Also, installing the flow meter on the outlet pipe is preferred because the inlet pipe can be subject to thermal expansion flow discrepancies where the hot water in the tank expands and pushes water out the inlet. However, some water heaters are installed with heat traps, which eliminate this issue. When flow meters are installed on the outlet pipe, the plastic components found in turbine flow meters can experience fatigue after being immersed in hot water.

Measuring Inlet and Outlet Water Temperatures: Immersed or Surface-Mounted Thermocouples?

In cases where the HPWH was installed before the monitoring equipment, it may be preferable to use a surface mounted TC for the inlet and outlet water temperature measurements to keep the pipes intact. Past laboratory tests have shown that surface-mounted TCs measure temperatures to within 2% of temperatures measured by immersed TCs. One of the pipes (inlet or outlet water line) will need to have an in-line flow meter installed, so an immersion TC can be installed at the same time, if desired. However, these TCs will be used to calculate a change in temperature, so the type of TC used on the inlet and outlet should match.

Insulating Around Thermocouples

A surface-mounted TC on the inlet and outlet water lines needs to have insulation wrapped around the pipe and the TC, as shown in Figure 1 with surface-mounted TCs.

Figure 1. Pipe insulation covers the surface-mounted TCs on the inlet and outlet water pipes

The surface-mounted TCs installed to measure tank temperature also need to be insulated. In most cases, the TC will be installed under existing insulation, which can be replaced. Once power to the unit has been turned off, remove the covers for the electric resistance heaters and the piece of insulation underneath (specific notes for the HPWHs tested at NREL in 2011 are given below). Affix the TC to the tank surface with thermally conductive epoxy. Wait until the epoxy is dry before replacing the insulation and the cover.

Installing Tank Thermocouples for the Different HPWH Brands

In 2011, NREL tested the first five integrated HPWHs on the U.S. market (Sparn, Hudon, & Christensen, 2011). There have been one or two new entrants to the market, but the water heaters listed below make up most of the options available. If a field test involves an HPWH that is not discussed here, the researchers will need to investigate how many electric elements there are and make suitable adjustments to the tank temperature measurement method if needed.

- **General Electric (GE) GeoSpring HPWH (first generation):** Two electric resistance elements provide access to the tank wall at two places. Removing the heater covers requires a security or tamperproof Torx bit. The Styrofoam insulation should be put back after the TCs are installed, as shown in Figure 2 through Figure 4.

- **Rheem Hybrid HPWH:** Two electric resistance elements provide access to the tank wall at two places. The heater covers can be removed with a standard Phillips head screwdriver. The fiberglass insulation should be returned to the heater access port after the TCs are installed.

Figure 2. Surface-mounted TC is secured while the epoxy cures.

Figure 3. The insulation is replaced and the TC wire is directed through a hole in the insulation.

Figure 4. The cover is replaced, with the lower screw not fully tightened to give TC wire clearance.

NREL Image Gallery 23089, 23090, and 23091
Credit: Bethany Sparn

Figure 5. The Rheem HPWH with heater covers shown.

Figure 6. The top heater access point with the cover removed. The fiberglass insulation can be removed.

Figure 7. After the insulation is removed, the tank wall is accessible for installing a TC.

NREL Image Gallery 23092, 23093, and 23094
Credit: Bethany Sparn

- **A.O. Smith Voltex HPWH:** Two electric resistance elements provide access to the tank wall at two places. The heater covers can be removed with a standard Phillips head screwdriver. The Styrofoam insulation should be put back after the TCs are installed (see Figure 8 through Figure 10).

Figure 8. The A.O. Smith Voltex HPWH with the upper heater cover shown.

Figure 9. The Styrofoam insulation that covers the upper heater access point.

Figure 10. After the insulation is removed, the tank wall is accessible for installing a TC.

NREL Image Gallery 23095, 23096, and 23097
Credit: Bethany Sparn

- **AirGenerate AirTap Integrated HPWH:** The AirGenerate HPWH has two electric resistance heaters, but only the top one is wired for regular use. The second backup heater below the main electric heater can be wired for use in the event that the heat pump and main electric element fail. The covers can be removed with a standard Phillips head screwdriver. The upper heater access port is encased in plastic and does not provide access to the tank (see Figure 11). The lower heater's access port has a thin layer of insulation covering the tank, but that can be pulled back to expose the tank wall (see Figure 12). With only a single access point located below the midpoint of the tank, measuring average tank temperature will not be possible with this particular HPWH without modifying the tank.

Figure 11. The AirGenerate HPWH with the heater covers shown.

Figure 12. Both heater covers removed. The upper heater is the main heater and the lower heater is the backup (not connected).

NREL Image Gallery 23098 and 23099
Credit: Bethany Sparn

- **Stiebel Eltron Accelera 300 HPWH:** The Stiebel Eltron HPWH has a single electric resistance element that points down into the tank from the top. There are no points to access the tank wall, so measuring average tank temperature will not be possible with this particular HPWH.

Short-Term Testing

1. **Sound level measurement**. One common consumer concern with HPWHs is noise. After the HPWH is fully installed and operating, take sound measurements at several locations at a 1-m radius from the HPWH and average the readings. The sound measurement should be taken at a height of 1.5 m (head height) off the ground. See the Northwest Energy Efficiency Alliance (NEEA) Northern Climate Specification for more details (NEEA, 2011). Repeat measurement 3 times while heat pump is running. To measure the sound generated by the HPWH alone, ensure that all nearby appliances are off and no one enters the space while testing is in progress. A background sound reading should also be taken while the HPWH (and everything else) is off for comparison.

2. **Airflow rate measurement**. If cooling capacity is desired, the airflow rate must be measured. For most HPWHs, the airflow rate is constant during operation. Other than the first-generation GE HPWH, all others operate a single flow rate. Use the duct blaster to measure the outlet flow rate. Repeat the test 3 times during heat pump operation to verify constant flow rate.

   Because duct blasters are intended for use with flat, rectangular ducts, it may be necessary to construct a plenum between the HPWH and the duct blaster. See the Mini-Split Heat Pump Field Monitoring Protocol for detailed instructions (Christensen, Fang, Tomerlin, & Winkler, 2011).

Long-Term Monitoring

1. EE and hot water use should be monitored over heating and cooling seasons.

2. Daily system COP should be calculated as a function of inlet wet bulb temperature. Correlation to daily hot water volume should also be noted, as should the relationship to the mains water temperature. The factor that has the largest impact on system COP will depend on the specific situation, so all should be considered during the analysis.

3. Cooling capacity can be measured if airflow rate has been characterized.

4. Calculate the heat removed from the surrounding space by looking at the difference between EE added to the water heater and useful energy transferred to the water, as shown in Equation 14. The heat removed from the surrounding space will not be equivalent to the impact on the heating and cooling systems, but it will give the maximum possible impact on peak heating and peak cooling days. Depending on climate and season, differentiating between sensible and latent heat removed from the space may be relevant.

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Appendix: Field Test for Protocol Validation

Objective

The protocol described in this report was used for a validation field test at a local home to ensure that the methods are reliable and the documentation is thorough. The main objective of this field validation was to verify that monitoring recommendations, which were based on NREL's past experiences with testing HPWHs in a laboratory setting, were feasible for a field installation. Some of the recommended calculations and uncertainty analysis were also performed to provide researchers with examples based on actual field test data.

Description of Field Test

The field test was conducted at a townhouse in Arvada, Colorado, beginning in October 2012. A first-generation, 50-gal GE GeoSpring HPWH was installed in the house one year before the field test took place. The water heater is located in a closet inside the home's two-car garage (see Figure 13). The water heater shares the closet with the furnace and air handler.

NREL Image Gallery 23100
Credit: Ed Hancock

Figure 13. GE GeoSpring HPWH installed in garage closet

The HPWH is not in the home's conditioned space, so there was no need to monitor the energy consumption of the furnace or air conditioning to determine the impact on the other space conditioning equipment. Because the water heater is installed in the garage in a cold climate, the homeowner closes the closet doors (which do not have louvers) in the winter so that the air drawn by the heat pump is warm from the furnace. This configuration (when the closet doors are closed) does not meet the manufacturer's recommendations for adequate airflow.

The homeowner keeps the HPWH in hybrid mode, which means the heat pump is the primary heat source, unless it cannot keep up with demand or if the ambient temperature drops below

45°F or rises above 110°F. The tank set point was 120°F, but the homeowner indicated that he may increase the set point to 125°F or 130°F during the winter months to help compensate for colder mains temperatures.

Installing Monitoring Equipment

All the sensors used in this field test match the recommendations listed in Table 1, though not all the sensors listed there were needed.

At the start of the field test, the electricity for the HPWH was turned off (see Figure 14). The breaker for the HPWH was turned off, the breaker was locked out, and a volt meter was used to verify that the circuit was de-energized (see Figure 15). Once the electrical hazard was removed, monitoring equipment could be installed.

Figure 14. Turn off the breaker for the HPWH.

Figure 15. Lock out the electricity panel and verify that the circuit is de-energized

NREL Image Gallery 23101 and 23102
Credit: Lieko Earle

Alternatively, unplug the HPWH if it is installed using cord-and-plug instead of being hardwired. Lock out the plug while the HPWH is being worked on.

Install Flow Meter

Installing the in-line flow meter requires one of the water lines to be disconnected. In many cases where the water lines are soldered together, this step will require a plumber. In this particular field test, there were threaded connections between the inlet and outlet water lines and the home's plumbing. If this is the case for your test site, it may be helpful to have a variety of fittings and pipe lengths readily available to avoid multiple trips to the hardware store. The inlet pipe had a valve to turn off the water, so the flow meter was installed on the inlet side.

To reduce the amount of water spilled, some water was drained from the tank after the inlet valve was closed. A hose was attached to the tank drain and a fixture inside the house was opened and a few gallons of water were drained from the tank (see Figure 16). Then the flexible hose on the water inlet was disconnected from the tank and the flow meter was installed. An additional section of flexible hose was needed after adding the length of the flow meter to the inlet pipe (see Figure 17).

Figure 16. Connecting the hose to the drain in preparation for installing the flow meter

Figure 17. Final plumbing configuration with the flow meter and an extra length of flexible pipe installed

NREL Image Gallery 23103 and 23104
Credit: Ed Hancock, Bethany Sparn

Surface-Mounted Thermocouples

Four surface-mounted TCs were installed for this field test on the inlet water pipe (Figure 18), the outlet water pipe, the upper tank surface (Figure 19), and the lower tank surface (Figure 20). The thermally conductive epoxy takes some time to cure, so whenever possible, the TCs should be put in place and taped so the installer does not have to hold it in place while the epoxy cures. This was done on the inlet and outlet water pipes, but was not possible for the TCs used to measure tank temperature because the TC had to be recessed into a small hole and there was not a suitable surface to tape it to.

Figure 18. Surface-mounted TCs installed on the inlet and outlet water pipes

Figure 19. Surface-mounted TC at the upper tank surface

Figure 20. Surface-mounted TC at the lower tank surface

NREL Image Gallery
23105, 23106, and 23089
Credit: Bethany Sparn, Ed Hancock

Insulation should be installed around any surface-mounted TC to ensure that the TC is measuring the water temperature, with minimal influence from the room air temperature. The surface-mounted TCs that were installed on the inlet and outlet water pipes were insulated with pipe insulation (shown in Figure 21) and the insulation for the electric element access ports were replaced after the TCs were glued to the tank (Figure 22).

Figure 21. Pipe insulation covering the surface-mounted TCs on the inlet and outlet water pipes

Figure 22. Insulation covering the tank where one surface-mounted TC was installed

NREL Image Gallery 23088 and 23090
Credit: Bethany Sparn

Temperature and Relative Humidity Sensors

Three T&RH sensors were installed to monitor air conditions during this field test. Performance of the heat pump is largely driven by the wet bulb temperature of the air when the coils are wet, a quantity that depends on the air T&RH. The air entering the heat pump, the air leaving the heat pump, and the air inside the garage were monitored using T&RH sensors. In this particular location, the homeowner kept the closet doors closed during the colder periods of the year, so the garage temperature and the inlet air temperature were often significantly different.

For the T&RH sensors measuring inlet and outlet air conditions, a wire mount was taped to the HPWH body and the sensor was taped to the wire mount, as shown in Figure 23. This brand of HPWH pulls air in through the side grilles and from under the annulus. The furnace was located just to the right of the HPWH, as shown in Figure 26, so the T&RH sensor was mounted at the front intake area to measure the average inlet air temperature. The side of the wire mount that is taped to heat pump casing is bent into a wide U shape to provide a stable base for the tape. The wire used was 14-gauge galvanized steel wire and the tape used was a 10-mil polyvinyl chloride pipe wrap tape, but a number of other tape and wire types would also work. A similar procedure was used for the T&RH sensor for the outlet air attached to the back of the heat pump casing.

NREL Image Gallery 23107
Credit: Bethany Sparn

Figure 23. T&RH sensor is mounted on the front of the HPWH to measure inlet air conditions.

Electrical Energy Measurement

Most field tests will include EE measurements for the whole house and the HPWH, in addition to any other EE measurements that are dictated by the research questions. The HPWH was installed outside the conditioned space, so it was not necessary to measure the EE consumption of any other space conditioning equipment. Also, a PV system was installed during the retrofit project that included the HPWH installation, and monitoring equipment was installed to measure the EE generated by the PV system and the EE consumed by the house. Because those measurements were already being taken and the data were available, there was no need to duplicate them. So it was only necessary to install monitoring equipment for the EE consumption of the HPWH.

A disconnect switch for the HPWH was in the same closet as the HPWH, providing a convenient location to install current transformers (CTs). The WattNode Watt-hour transducer was mounted in a separate box above the disconnect switch. CT wires and voltage sensing wires were run from the disconnect box and the WattNode box through a short length of conduit.

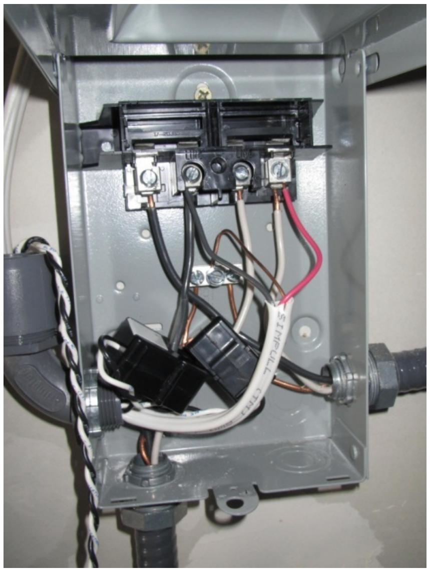


Figure 24. CTs and voltage taps for measuring the EE consumption of the HPWH

Figure 25. The wires from the CTs and the voltage tap are connected to the WattNode Watt-hour transducer.

NREL Image Gallery 23108 and 23109
Credit: Lieko Earle

Once all the monitoring equipment was installed, all the sensor wires were terminated at a Campbell data logger, which was enclosed in box along with its power supply. Water was turned back on first; a fixture inside the house was also turned on to get the air out of the supply line. Anywhere the plumbing was altered was monitored closely for leaks until the researchers could be sure that all the connections were sound. The first installation of the flow meter was not watertight and so was reconfigured. Once the integrity of the water lines has been verified and all the covers exposing electrical connections have been replaced (the WattNode box, the HPWH disconnect switch, and the covers for the two electrical resistance heaters in the tank), the breaker to the HPWH can be turned back on. The HPWH will likely turn back on immediately.

A cellular modem was connected to the Campbell Scientific data logger to provide remote access to the data. The antenna was mounted near the WattNode box, because that elevated location provided the best signal. The remote connection was tested to ensure that the signal was strong and data were updated as expected. The values being reported by all the recently installed sensors should be verified as well. It should be simple to determine if the T&RH readings are reasonable. If the power consumption of the water heater is not known, check the user manual before the field test to determine a reasonable range. In general, the heat pump will use 700–1000 W and the electric resistance elements will increase the power consumption to 2000–4500 W.

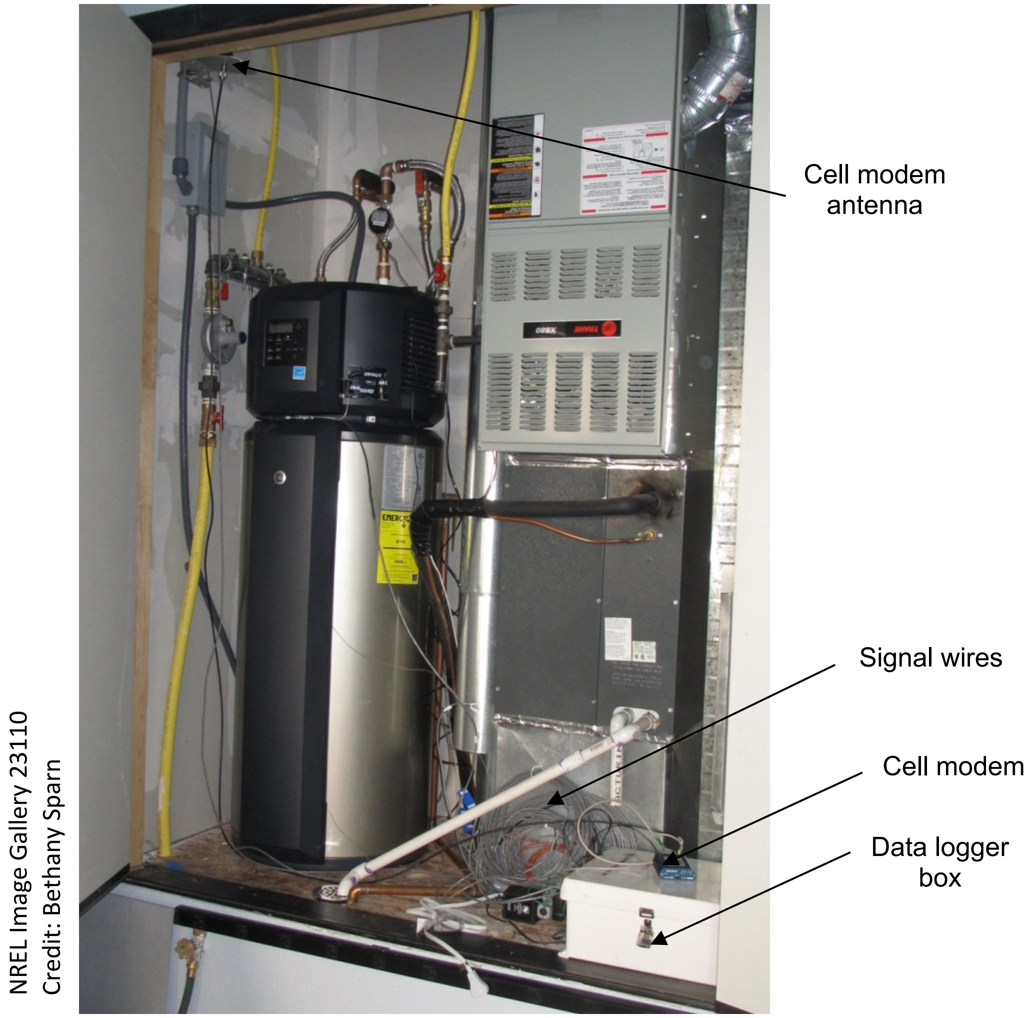


Figure 26. Monitoring equipment is installed and connected to the data logger. The cell modem and antenna are also installed.

Sound Test

After all the monitoring equipment was installed, a sound test was performed (see Figure 27). A baseline sound test was performed while the HPWH was still disconnected from power. Based on the NEEA test specification, sound readings were taken at two places on a radius 1 m from the water heater. Sound was measured at only two points, because the area around the water heater was mostly taken up by the surrounding walls and furnace. The garage door was also closed and all HVAC equipment was off during this baseline measurement to ensure the lowest ambient noise. Then the water heater was turned back on. Because we drew some hot water and then had the water heater turned off for several hours, the heat pump turned on immediately to reheat the tank. The fan came on first for a few minutes, followed by the compressor with the fan. Once both the compressor and fan were on, the second set of sound measurements were taken at the same two points.

The average baseline or ambient noise was measured to be 33 dB, which is measured for comparison purposes. The sound measured when the heat pump was on was 58.5 dB. The manufacturer claims that the average operating sound level should be 58 dB, so our measurement is well-aligned with expectations.

NREL Image Gallery 23111
Credit: Lieko Earle

Figure 27. Performing a sound test for the HPWH

Sample Calculations

A couple weeks after the monitoring equipment was installed, data were analyzed to ensure the readings were in line with expectations. A few of the common calculations are shown here for examples.

Daily System COP

The daily system COP is calculated for each day, with the day defined to begin and end at 4:00 a.m., which should ensure that all heating to compensate from the previous day's draws have been completed. A single day's calculation is shown below, specifically to show how the thermal energy should be calculated.

$$COP = \frac{\rho_{water} \cdot V_{draws} \cdot C_{p,water} \cdot \Delta T_{draws}}{W_{input}}$$

Constants:

ρ_{water} = 998 kg/m^3.

$C_{p,water}$ = 4.182 kJ/kg-C.

To capture the difference in temperature between the inlet and outlet water lines, it is necessary to calculate Q_{draws} (the numerator of the COP equation) at small intervals. In this case, Q_{draws} was calculated every minute, as shown in Table 2. A small chunk of a day of data is shown to illustrate how this is done.

Table 2. Example of Q_{draws} Analysis for COP Calculation

	Data			***Calculations***	
Timestamp	T_{inlet} (°C)	T_{outlet}(°C)	V_{draws} (m^3)	ΔT_{draws} (°C)	$Q_{draws}= \rho_{water} C_{p,water} V_{draws} \Delta T_{draws}$ (kJ)
9:18	20.3	45.7	0.00	25.4	0.0
9:19	20.3	45.5	0.60×10^3	25.2	63.2
9:20	19.6	47.1	4.60×10^3	27.5	527.6
9:21	19.4	47.1	4.50×10^3	27.7	521.0
9:22	19.8	47.1	4.40×10^3	27.2	500.1
9:23	19.5	47.0	4.40×10^3	27.6	506.1
9:24	19.4	47.0	4.40×10^3	27.6	506.7
9:25	19.8	47.0	4.40×10^3	27.2	499.5
9:26	19.9	47.0	4.40×10^3	27.0	496.2
9:27	19.9	46.9	4.40×10^3	27.0	495.6
9:28	19.8	46.8	4.35×10^3	27.0	489.8
9:29	19.8	46.7	4.40×10^3	26.9	494.0
9:30	19.8	46.6	4.45×10^3	26.8	497.4
9:31	19.8	46.5	4.40×10^3	26.6	489.0
9:32	19.8	46.3	3.25×10^3	26.5	359.2
9:33	19.9	46.0	0.00	26.1	0.0
…	…	…	…	…	…
9:44	20.1	41.6	0.00	21.4	0.0
9:45	19.9	44.7	1.80×10^3	24.8	186.5
9:46	19.9	45.6	1.00×10^3	25.7	107.1
9:47	19.9	45.5	0.00	25.6	0.0
9:48	19.9	45.3	0.45×10^3	25.3	47.6
9:49	20.1	45.8	2.30×10^3	25.7	246.8
9:50	20.1	45.4	0.00	25.3	0.0
…	…	…	…	…	…
12:15	17.2	22.5	0.00	5.3	0.0
12:16	18.1	36.1	2.00×10^3	18.0	150.3
12:17	19.2	48.9	0.35×10^3	29.6	43.3
					ΣQ_{draws} = 7226.9

At every time step, the product of the volume of hot water drawn during that minute and the difference in temperature between the outlet and inlet water lines is multiplied by the density and specific heat of water to calculate the heat removed from the tank during each minute. The sum of Q_{draws} over the entire day is used as the numerator in the COP equation. Similarly, W_{input} is found by taking the sum of the EE consumed by the HPWH during the day. When evaluating the entire day, the results for the numerator and denominator for the COP calculation are:

Q_{draws} = 22823.5 kJ (the total from the full day, not just the segment shown in Table 2)
W_{input} = 2.61 kWh

$$\Rightarrow COP = \frac{22823.5\ kJ}{\left(2.61\ kWh \cdot \frac{3600s}{h}\right)} = \mathbf{2.43}$$

The COP on this day was 2.43, which is the highest observed thus far during the field test. During the first two weeks of monitoring, the average daily system COP is 1.89.

Coefficient of Performance Versus Draw Volume

A number of factors affect system COP, including ambient air temperature and humidity, daily draw volume, and inlet temperature. In this case, for the short period of data analyzed, the draw volume stands out as a major factor. Table 3 and Figure 28 show the relationship between daily draw volume and daily system COP. One day had no hot water draws at all, leading to a daily COP of 0.

Table 3. Daily COP Compared to the Daily Hot Water Draw Volume

	COP	Draw Volume (liters)
10/5/2012	2.431	208.4
10/6/2012	2.022	137.5
10/7/2012	1.898	155.8
10/8/2012	1.983	111.0
10/9/2012	2.025	138.4
10/10/2012	1.976	115.0
10/11/2012	1.745	72.3
10/12/2012	0.000	0.0
10/13/2012	1.390	71.7
10/14/2012	1.540	60.1

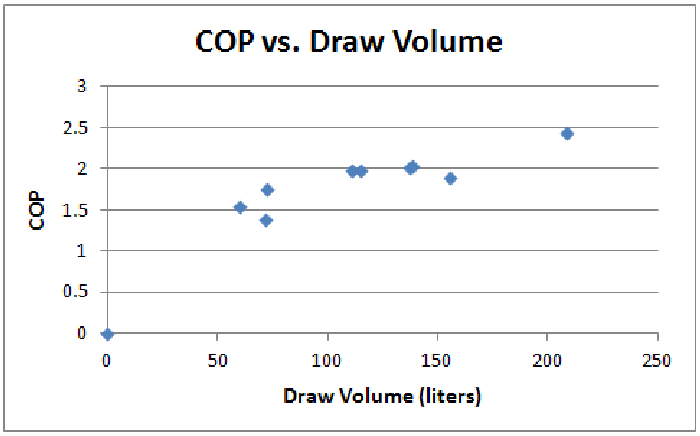


Figure 28. Daily COP versus daily hot water draw volume

Heat Added to Space, $Q_{net,space}$

Even though the HPWH was installed outside the conditioned space and the cooling produced by the heat pump does not affect the space conditioning load, the cooling effect was calculated here for examples. On days with the largest draw volumes, the heat removed from the space is greater because the heat pump has to run longer to compensate for the draws.

$$Q_{net,space} = W_{Input} - \rho_{water} \cdot V_{draws} \cdot C_{p,water} \cdot \Delta T_{draws}$$

This calculation uses the same measurements that were used to calculate COP, so this example will use the same day of data used to calculate COP. As previously described,

$Q_{draws} = \rho_{water} \cdot V_{draws} \cdot C_{p,water} \cdot \Delta T_{draws}$= 22823.5 kJ
W_{input} = 2.61 kWh

$$\Rightarrow Q_{net,space} = \left(2.61\ kWh \cdot \frac{3600s}{h}\right) - 22823.5\ kJ = \mathbf{-13434.3\ kJ}$$

As expected, the heat added to the space is a negative number, indicating that heat pump has removed the heat from the air. Even though the heat was not removed from the conditioned space, it is still useful to put this cooling effect into perspective. The heat removed from the space is roughly 13,000 Btu over the course of an entire day. For comparison, window air conditioners can have the capacity to remove 13,000 Btu/h. Furnaces, on the other hand, have the capacity to produce heat at a rate of 50,000–100,000 Btu/h. So, even though the heat pump is removing heat from the air to heat the water, the amount of energy needed to compensate for this heat loss will be only a fraction of the total heating load during the winter.

Standby Heat Loss Coefficient

As seen in Table 3, one day during the current monitoring period had no hot water draws, but the heat pump came on to compensate for tank losses. This is an ideal situation for calculating the tank's UA. During this day and into the next, there were three periods of time between heating cycles without draws, as shown in Figure 29.

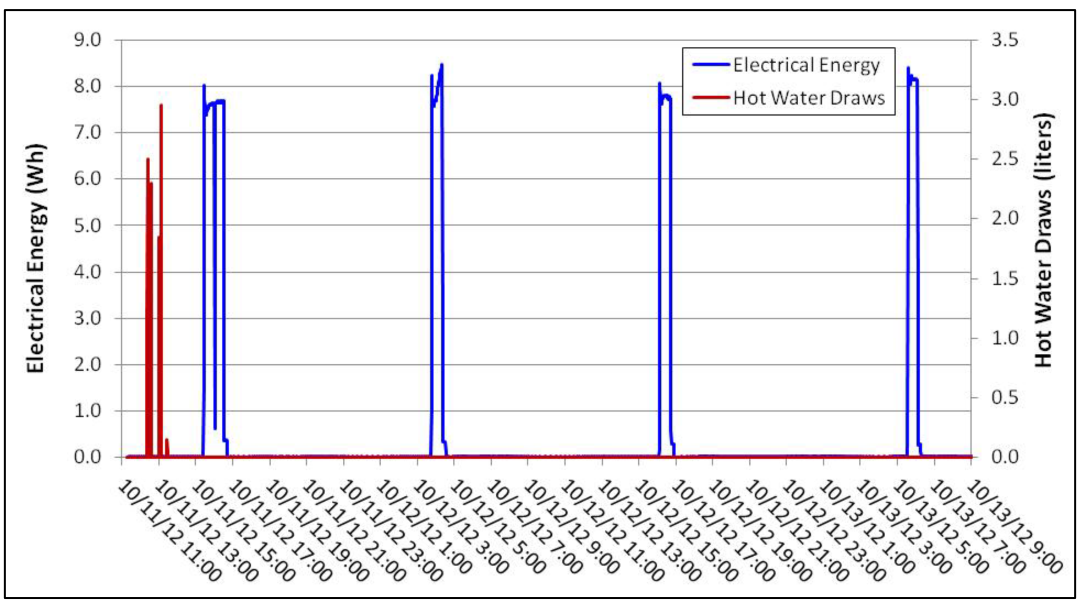


Figure 29. Hot water draws and EE use over two days in October 2012

Tank UA was calculated for each period and averaged. The UA calculation for one of these drawless periods is shown below.

$$UA = \frac{V_{st} \cdot \rho_{water} \cdot C_{p,water} \cdot (\bar{T}_i - \bar{T}_f)}{\tau_{stdby} \cdot (\bar{T}_{tank} - \bar{T}_{amb})}$$

$\bar{T}_i = (T_{tank,upper} + T_{tank,lower})/2$ at beginning of the standby period.
$\bar{T}_f = (T_{tank,upper} + T_{tank,lower})/2$ at end of the standby period.
$\bar{T}_{tank}$ is the average of the upper and lower tank TCs over the standby period.
$\bar{T}_{tank}$ is the average ambient temperature over the standby period.
τ_{stdby} is the length of the standby period in hours.

Constants:

ρ_{water} = 998 kg/m^3
$C_{p,water}$ = 4.182 kJ/kg-C
V_{st} = 45 gal = 0.1703 m^3

For the standby period beginning at 5:00 p.m. on October 12, 2012 and ending at 5:35 a.m. on October 13, 2012:

τ_{stdby} = 12.6 h
$\bar{T}_i$ = 49.4°C
$\bar{T}_f$ = 46.3°C
$\bar{T}_{tank}$ = 47.9°C
$\bar{T}_{amb}$ = 22.8°C

$$\Rightarrow UA = \frac{(0.1703\ m^3)\cdot\left(998\frac{kg}{m^3}\right)\cdot\left(4.182\frac{kJ}{kgC}\right)\cdot(49.4℃ - 46.3℃)}{(12.6hr)\cdot(47.9℃ - 22.8℃)} = \mathbf{7.0}\,\frac{\boldsymbol{kJ}}{\boldsymbol{hrC}}$$

For this particular standby period, the tank UA was calculated to be 7.0 kJ/hrC. The average UA from all three standby periods analyzed was 7.0 kJ/hrC. This is consistent with the tank UA measured during NREL's laboratory testing of this make and model of HPWH, which was 7.1 kJ/hrC.

There are a few things to note from this exercise. The tank volume, V_{st}, is listed as 45 gal even though the tank is rated as 50 gal. The actual tank volume was measured during our laboratory tests to be 45 gal. This is consistent with the rule of the thumb that the actual tank volume is likely 10% less than the rated volume. If a field test involves a new HPWH model and the flow meter is installed while the tank is empty, it would be good to measure the actual tank volume during the initial filling.

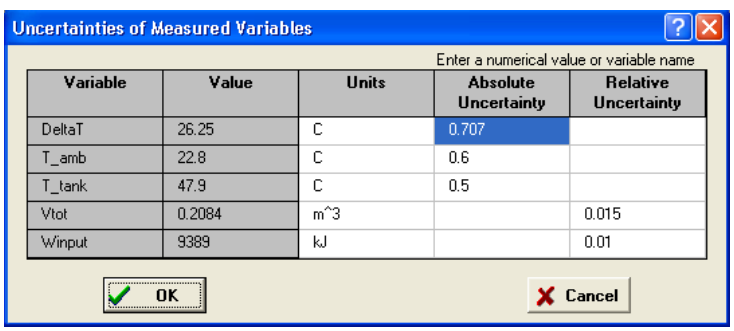
Also, it is important to mark the beginning of the standby period for the calculation about 10 min after the heat pump turns off to ensure that the tank temperature measurements are not artificially high.

Uncertainty Calculations

Three calculations were presented in the previous section, and uncertainty analysis for those calculations is shown in Figure 30 through Figure 32. Error propagation was done using a program called Engineering Equation Solver (EES), but could also be done manually using the general formula for error propagation (Taylor, 1997).

The values for specific heat and density of water are assumed to be constant in all of the calculations. The tank volume and the duration of the standby period used in the UA calculation are also assumed to be constant. The uncertainty for each of the measured values comes from manufacturer information about the sensor. The stated error for each sensor, shown in Table 1, is used as the uncertainty for that measurement.

Figure 30. Uncertainty propagation analysis using EES software

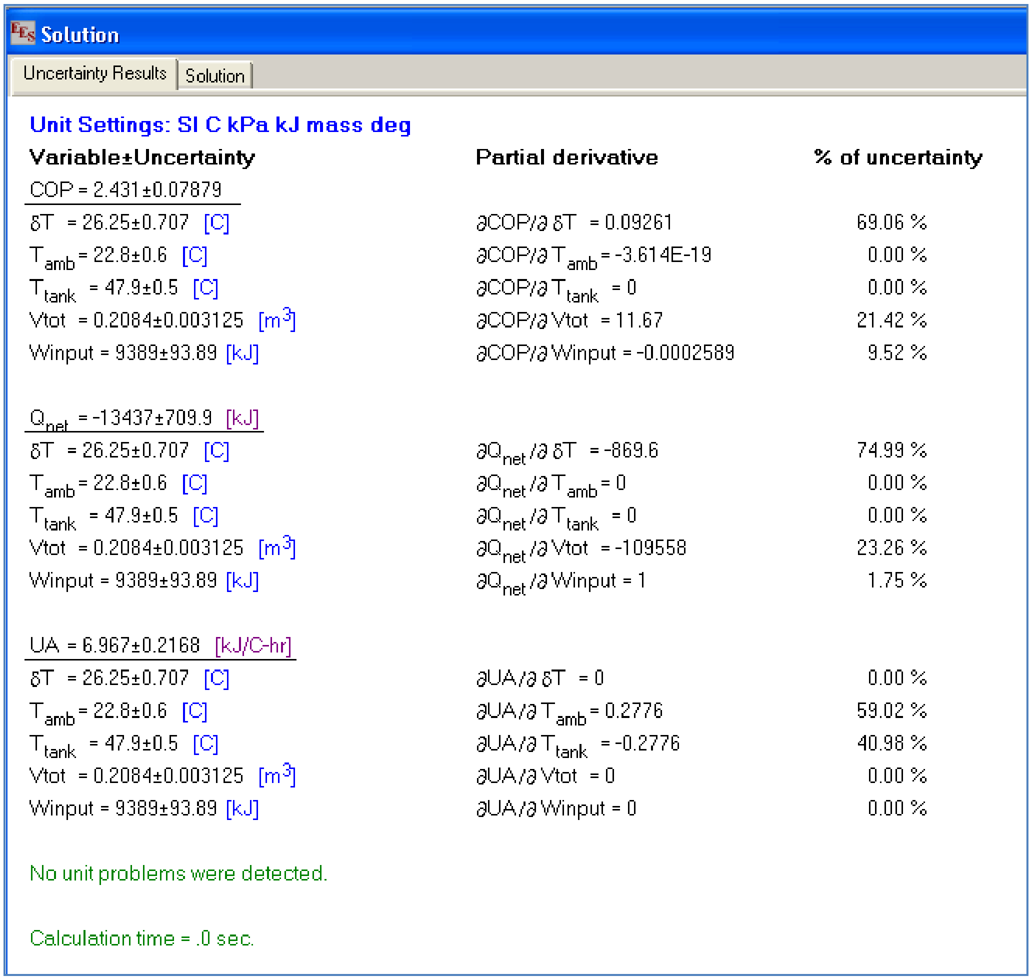

Uncertainties of Measured Variables

Enter a numerical value or variable name

Variable	Value	Units	Absolute Uncertainty	Relative Uncertainty
DeltaT	26.25	C	0.707	
T_amb	22.8	C	0.6	
T_tank	47.9	C	0.5	
Vtot	0.2084	m^3		0.015
Winput	9389	kJ		0.01

OK   Cancel

Figure 31. Uncertainty for measured values



Solution

Uncertainty Results | Solution

Unit Settings: SI C kPa kJ mass deg

Variable±Uncertainty	Partial derivative	% of uncertainty
COP = 2.431±0.07879		
δT = 26.25±0.707 [C]	∂COP/∂δT = 0.09261	69.06 %
T_{amb} = 22.8±0.6 [C]	∂COP/∂T_{amb} = -3.614E-19	0.00 %
T_{tank} = 47.9±0.5 [C]	∂COP/∂T_{tank} = 0	0.00 %
Vtot = 0.2084±0.003125 [m^3]	∂COP/∂Vtot = 11.67	21.42 %
Winput = 9389±93.89 [kJ]	∂COP/∂Winput = -0.0002589	9.52 %
Q_{net} = -13437±709.9 [kJ]		
δT = 26.25±0.707 [C]	∂Q_{net}/∂δT = -869.6	74.99 %
T_{amb} = 22.8±0.6 [C]	∂Q_{net}/∂T_{amb} = 0	0.00 %
T_{tank} = 47.9±0.5 [C]	∂Q_{net}/∂T_{tank} = 0	0.00 %
Vtot = 0.2084±0.003125 [m^3]	∂Q_{net}/∂Vtot = -109558	23.26 %
Winput = 9389±93.89 [kJ]	∂Q_{net}/∂Winput = 1	1.75 %
UA = 6.967±0.2168 [kJ/C-hr]		
δT = 26.25±0.707 [C]	∂UA/∂δT = 0	0.00 %
T_{amb} = 22.8±0.6 [C]	∂UA/∂T_{amb} = 0.2776	59.02 %
T_{tank} = 47.9±0.5 [C]	∂UA/∂T_{tank} = -0.2776	40.98 %
Vtot = 0.2084±0.003125 [m^3]	∂UA/∂Vtot = 0	0.00 %
Winput = 9389±93.89 [kJ]	∂UA/∂Winput = 0	0.00 %

No unit problems were detected.

Calculation time = .0 sec.

Figure 32. Results from the uncertainty propagation analysis

The error propagation shows that the uncertainty for the calculated values ranges between 3% and 5% of the results. The temperature measurements account for most of the uncertainty associated with each calculation. Thus, all TCs and TC wires should be rated to special limits of error to ensure the lowest error in the temperature measurements.

Uncertainty analysis can be used to help guide the choice of sensors used in a field test. For instance, if a different flow meter were being considered, a preliminary uncertainty analysis could be performed to see how different flow meters with different rated accuracies would affect the uncertainty in the COP calculation. It is always desirable to use sensors with high accuracy, but since higher accuracy equates to a higher cost, the uncertainty analysis can help determine if a higher level of accuracy has an appreciable effect on the desired calculation.