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Interaction between Heat Pump Water Heaters or Other Internal Point Source Loads and a Central Heating System

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Summary

Water heating represents approximately 18% of residential energy consumption, or 4.6 quadrillion Btus of source energy use annually. Heat pump water heaters (HPWHs) offer an efficient option for residential water heating, because they have the ability to reduce water heating energy consumption by up to 63%. To achieve such high efficiencies, HPWHs employ a refrigeration cycle to move heat from the ambient air into water stored in a tank. When HPWHs are installed in conditioned space, they remove heat from the conditioned air. During the cooling season, this can decrease the cooling load of the heating, ventilation, and air-conditioning (HVAC) system, and therefore decrease its energy use. However, during the heating season, the HPWH's cool air exhaust can increase the heating load of the HVAC system, and thus increase its energy use.

Previous experiments have indicated that the space conditioning system may not make up 100% of the theoretical amount of energy removed from the air to heat the water. However, only limited data exist to describe the range of interaction factor values we would expect to observe in the field and the theoretical basis for such a reduced interaction.

This project provides an objective evaluation of the space conditioning interactions between a HPWH and the heating system in several locations throughout a home to investigate the impact that HPWHs have on space conditioning loads. To describe this phenomenon, we define the term "interaction factor," as a ratio of the actual space conditioning system interaction over the theoretical energy impact on the space imparted by the point source load. The interaction factor can be less than 1.0 due to three primary factors: 1) removal of latent energy that does not impact the dry-bulb temperature in the same; 2) localized cooling, which is an indicator of the connection or "thermal distance" between the location of the load and the thermostat; and 3) the conversion of excess solar gains to useful solar gains. Some or all of these factors may influence the interaction factor based on the type of point source load (heating or cooling) and the season (heating or cooling).

This report explores the HPWH interaction factor from several perspectives: 1) a theoretical analysis, 2) a review of previous literature, and 3) an experimental assessment. Expanding the work beyond HPWHs, the study also evaluates the impact of a generic point source internal heating load on the space conditioning system energy use.

The experiments summarized in this report were conducted in Pacific Northwest National Laboratory's (PNNL's) side-by-side Lab Homes, which provide a platform for evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes installed on PNNL's campus in Richland, Washington, that aim to represent a typical existing home in the United States. These 1500 ft^2 homes have three bedrooms, two bathrooms, and are heated with an electric forced-air furnace controlled by a single thermostat. Both homes have R-22 floors, R-11 walls, and R-22 ceiling insulation levels, along with double-pane clear glass windows.

This experiment verified that the incremental energy use of the space conditioning system varies

depending on the location of the point source thermal load in the home. That is, for a point source cooling load, like a HPWH, the space conditioning system energy use increased as the load was moved closer to the thermostat. Similarly, as a point source heating load was moved closer to the thermostat, the heating load decreased. For the PNNL Lab Homes, the impact of point source cooling and heating loads was similar and the thermal distance of the load from the thermostat appeared to drive the degree to which the load “interacted” with the space conditioning system. The interaction factor results for each location in the PNNL Lab Homes are shown in Table S.1.

Table S.1. Summary of Internal Point Source Interaction Factors for Different Locations throughout the Home

Thermal Location	Point Source Load	Farthest from Thermostat	Closest to Thermostat	Most Distributed	Least Distributed
Actual Location		*Master Bathroom*	*Living Room*	*Utility Room (where air handler is located)*	*Water Heater Closet (no direct supply or return air duct)*
Relative Interaction Factor	Cooling	0.41 (0.24)	0.58 (0.68)	1.00 (1.00)	0.35 (0.56)
	Heating	0.43 (0.30)	*0.58 (0.68)*[a]	NA	NA
Interaction Factor	Cooling	0.57 (0.57)	0.82 (1.35)	1.40 (1.97)	0.47 (1.11)
	Heating[b]	0.58 (0.71)	0.78 (1.61)	NA	NA

(a) Based on HPWH experimental results.
(b) Normalized with respect to load; presented for same size load as cooling load.

The master bathroom and water heater closet locations both demonstrated low interaction factors and a high degree of localized temperature change, which are indicative of greater thermal distance between the space and the thermostat. In this case, “thermal distance” is influenced both of physical distance from the thermostat as well as presence of thermal buffers or barriers that impede heat transfer and air flow between the location and the thermostat, such as walls and doors. For such locations in the Lab Homes, the heating system only had to make up approximately half of the theoretical cooling load imparted by the HPWH.

The utility room and living room were both well coupled with the thermostat. The utility room was the closest and the most connected to the thermostat; it had an interaction factor greater than one for the HPWH. The relatively high interaction factor is caused by the thermostat sensing the localized cooling surrounding the water heater and continuing to deliver heat, even when the average temperature in the house may have already reached set point. In this case, areas of the house which were not near the thermostat experienced temperatures that were above the set point.

For the PNNL Lab Homes in the heating season, the impact of point source cooling and heating loads was similar when normalized with respect to the size of the load. This similarity indicates that the thermal distance of the load from the thermostat was the dominant factor in determining the degree to which the load “interacted” with the space conditioning system. While theoretically, the cooling load may have less interaction due to the potential for latent removal, which is not sensed by the thermostat, latent removal was not a significant factor in the relatively dry interior conditions that exist during the heating season. The effect of excess solar gains were observed to reduce the interaction factor approximately 30–40% overall and appeared to affect all experimental locations regardless of the direct solar gains experienced in the space, although the data were limited and these results are inconclusive.

An important next step for this work is to evaluate the impact of the interaction factors observed in this study on regional and national estimates of energy savings from HPWHs installed in conditioned spaces. Such an evaluation is best and most efficiently accomplished by detailed energy simulations that rely on experimental results such as these as inputs to and calibration points for the model. How the results from this study, along with other laboratory HPWH evaluation results, can be applied to inform existing single-zone energy models is summarized in Table S.2.

Table S.2. Summary of Simulation Evaluation Framework and Validation Source for Future Population Modeling Studies

Season	Load	Factor	Validation Source
Heating	Cooling	Latent Removal	NREL/NEEA Experimental Evaluations/Simulation
		Thermal Distance	**PNNL Lab Homes Study (HPWH)**
		Excess Solar Gains	Simulation (calibrated based on PNNL Lab Homes Study)
	Heating	Latent Removal	NA
		Thermal Distance	**PNNL Lab Homes Study (Space Heater)**
		Excess Solar Gains	NA
Cooling	Cooling	Latent Removal	NREL/NEEA Experimental Evaluations/Simulation
		Thermal Distance	***PNNL Lab Homes Study (Space Heater)***[a]
		Excess Solar Gains	Simulation
	Heating	Latent Removal	NA
		Thermal Distance	***PNNL Lab Homes Study (HPWH)****
		Excess Solar Gains	NA

(a) While not evaluated directly, a cooling load during the cooling season would be expected to act similarly to a heating load in the heating season with respect to the thermal distance and resultant temperature change in the space. Future experimental work could verify this result.

NREL = National Renewable Energy Laboratory; NEEA = Northwest Energy Efficiency Alliance

Current hourly simulation programs, such as SEEM (Simplified Energy Enthalpy Model) and EnergyPlus, are designed to account for the impact of solar gains. However, these results can be calibrated based on the temperature and energy results observed in this PNNL Lab Homes study. In addition, simulations can account for latent removal based on theoretical enthalpy calculations across the simulated HPWH coil, which can be calibrated based on existing laboratory performance data for HPWHs (e.g., National Renewable Energy Laboratory/Northwest Energy Efficiency Alliance). Finally, results from this study regarding the interaction factor for several locations with various “thermal distances” can be used to estimate the portion of energy introduced by the load that is made up by the space conditioning system based on the thermal distance between the space and the thermostat for several typical water heater installation locations. Based on such a calibrated model, we can estimate the impact on HPWH savings, or the impact of other point source loads, across populations of homes with various installation locations and climates.

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1. Introduction

Water heating represents approximately 18% of residential energy consumption, or 4.6 quadrillion Btus of source energy use annually (EIA 2009). Heat pump water heaters (HPWHs) offer an efficient option for residential water heating; they have the ability to reduce water heating energy consumption by up to 63%.[1] Previous research has demonstrated the laboratory performance of HPWHs and has shown savings of 43 to 62% in water heating energy consumption are possible, based on field tests (Ecotope 2015). To achieve such high efficiencies, HPWHs employ a refrigeration cycle to move heat from the ambient air into water stored in a tank. When HPWHs are installed in conditioned space, they remove heat from the conditioned air. During the cooling season, this can decrease the cooling load of the heating, ventilation, and air-conditioning (HVAC) system, and therefore decrease its energy use. However, during the heating season, the HPWH's cool air exhaust can increase the heating load of the HVAC system, and thus increase its energy use.

Modeling studies indicate that the installation location of HPWHs can significantly affect their performance and the resultant whole-house energy savings (Larson et al. 2011; Maguire et al. 2013). However, previous research has suggested that the space conditioning system may not necessarily make up 100% of the heat removed from the air (Ecotope 2015; Widder et al. 2014). This is due to the spatial variation of thermal impacts, the impact of latent heat removal, and the thermal utility of heat gains or losses. The impact of the HPWH on the space conditioning system has been described as the "interaction factor," which is the ratio of the empirically derived effect on the space conditioning system over the theoretical amount of energy that would be removed from the space based on theoretical energy balances.

This previous work, and in particular work conducted in the Pacific Northwest National Laboratory's Lab Homes (PNNL Lab Homes Study), has informed current estimates of the HPWH interaction factor (Widder et al. 2014). For example, the Pacific Northwest's Regional Technical Forum currently estimates a HPWH interaction factor of 0.65 (RTF 2014). However, previous work was not designed to intentionally measure the HPWH interaction factor or the variability of the interaction factor in various installation locations throughout the home. In these studies, understanding the interaction with the space conditioning system was only a tangential goal and has resulted in many unanswered questions around this topic.

This project provides an unbiased evaluation of the space conditioning interactions between a HPWH and the heating system in several locations throughout the home to further our understanding of the impact that HPWHs have on space conditioning loads. This report explores the HPWH interaction factor from several perspectives: it provides 1) a theoretical analysis, 2) a review of previous literature, and 3) an experimental assessment.

Part of the motivation to conduct this work came from discussions of the HPWH Subcommittee within the Regional Technical Forum. This subcommittee discussed two ways in which the experimental assessment could be conducted. The first way was to move an actual HPWH around the homes and measure the actual interaction experienced by the HVAC system. The

[1] Based on the U.S. Department of Energy test procedure (10 CFR 430.32(d)) and comparison of an electric resistance water heater (Energy Factor, EF = 0.90) versus a HPWH (EF = 2.4).

second way was to move a space heater around the home, trying to simulate the energy removed by the HPWH by adding the same amount of heat to the space, and determining how much less heat was required by the HVAC system. This method could also help quantify interaction factors for other types of heat sources like entertainment centers or appliances.

1.1 Project Scope

This project aims to address some of the fundamental research questions surrounding HPWHs and the general interaction of point source cooling and heating loads that may be located throughout a home.

The following research questions guided decisions related to the setup and execution of this experiment, and are referred to throughout the rest of this report.

- How much latent and sensible heat is removed by a HPWH when it is located in conditioned or semi-conditioned space?
- What is the change in space conditioning system energy use when a HPWH is installed in each of the following installation locations compared to an electric-resistance water heater (ERWH)?
  - master bathroom, door closed
  - living room
  - utility closet
  - water heater closet
- What is the interaction factor of the HPWH in each of four locations throughout the Lab Homes?
- What is the change in space conditioning energy use when a space heater is installed in the master bathroom with the door closed, compared to the living room?

2. Previous Work

There are limited number of studies that consider the impact of HPWHs on space conditioning systems. Many preliminary studies were based on models, which may have over-estimated the interaction by neglecting the potential for some complex interactions between the HPWH, local and whole-house space temperatures, and interior relative humidity (RH). Lab studies have now examined the impact of HPWHs on these important individual variables (i.e., local and whole-house space temperatures, and interior RH). In addition, several field studies have evaluated the impact of HPWHs on the space conditioning system in general.

2.1 Modeling Studies

The National Renewable Energy Laboratory (NREL) has developed modeling capabilities for HPWHs within the BEopt™ (Building Energy Optimization) software using the EnergyPlus simulation engine, which calculates results on an hourly basis and includes transient effects (Wilson and Christensen 2012). Ecotope has also updated the Simplified Energy Enthalpy Model (SEEM)[1] to include HPWH and space conditioning interactions (Larson et al. 2011). In addition, in the 2010 residential water heater energy conservation standard final rule (75 FR 20112 (April 16, 2010)), the U.S. Department of Energy (DOE) accounted for HVAC interactions when calculating the savings associated with HPWHs (DOE 2010).

In general, these models appear to assume a complete energy balance between the water heater and space conditioning equipment. That is, 100% of the thermal energy provided as hot water (Q_{water}) is provided by both the water heater electrical energy consumption (Q_{HPWH}) and thermal energy from the surrounding conditioned space (Q_{HVAC}), as shown in Equation (2.1):

$$Q_{hotwater} = Q_{HPWH} + Q_{HVAC} \tag{2.1}$$

The calculations that occur in the EnergyPlus and SEEM energy models are typically dynamic hourly simulations that also model standby losses from the tank and related impacts on interior temperatures. However, from a simple energy balance perspective the standby losses can be ignored.

The thermal energy provided as hot water can be determined using Equation (2.2), as follows:

$$Q_{hotwater} = V_{water} \times \rho \times C_{p,water} \times (T_{out} - T_{in})/1000 \tag{2.2}$$

where

$Q_{hotwater}$ = the energy provided to the water in kWh,
V_{water} = the average daily hot water volume drawn in gallons,
T_{out} = the measured outlet water temperature in °F,
ρ = the density of water in pounds per gallon (8.34 lb/gal),

[1] The SEEM program is designed to model small-scale residential building energy use. The program consists of an hourly thermal simulation and an hourly moisture (humidity) simulation that interacts with duct specifications, equipment, and weather parameters to calculate the annual heating and cooling energy requirements of the building. SEEM, written at Ecotope, was developed by and for the Northwest Power and Conservation Council and NEEA. SEEM is used extensively in the Northwest to estimate conservation measure savings for regional energy utility policy planners. For more information, see http://rtf.nwcouncil.org//measures/support/seem/.

$C_{p,water}$ = the specific heat capacity of water (1 Btu/lb·°F or 0.2931 Wh/lb·°F), and
T_{in} = the measured inlet water temperature in °F.

The electrical energy required to heat the hot water is modeled directly, based on the performance of the HPWH as a function of surrounding ambient temperature, the set point temperature of the hot water tank, and the frequency and magnitude of hot water draws. The thermal energy contribution from the surrounding conditioned space can then be determined as the difference between these two quantities, as indicated in Equation (2.3).

The relative energy consumed as electricity, versus that extracted from the surrounding environment, is a function of the efficiency of the water heater. The coefficient of performance of the HPWH (COP_{HPWH}) is a measure of the thermal energy provided to the water versus the electrical energy consumed by the HPWH, as shown in Equation (2.3):

$$COP_{HPWH} = \frac{Q_{water}}{Q_{HPWH}} \tag{2.3}$$

Therefore, the total thermal energy provided as hot water and the thermal load on the space (Q_{HVAC}) can also be calculated as a function of the efficiency of the water heater, as shown in Equations (2.4) and (2.5):

$$Q_{water} = Q_{HPWH} \times COP_{HPWH} \tag{2.4}$$

$$Q_{HVAC} = Q_{HPWH} \times (COP_{HPWH} - 1) \tag{2.5}$$

In Chapter 7 of the technical support document for the 2010 residential water heater energy conservation standard final rule, DOE describes a similar calculation for determining a rate of cooling introduced to the space, or heat removed from the space (DOE 2010). Specifically, DOE defined the “cooling input” as described in Equation (2.6):

$$Cooling\ Input = Cooling\ Capacity_{HPWH} \times \frac{V_{water} \times \rho \times C_p (T_{tank} - T_{in,air})}{P_{ON,HPWH} \times RE_{HPWH} \times PA_{HPWH}} \tag{2.6}$$

where,

CoolingInput = the amount of cooling added by the heat pump water heater,
T_{tank} = the set point of tank thermostat,
$T_{in,air}$ = the indoor air temperature,
$P_{ON,HPWH}$ = the rated input power to the water heater,
RE = the recovery efficiency (percentage) as measured by the DOE test procedure for residential water heaters (10 CFR 430.23),
PA_{HPWH} = the performance adjustment factor that accounts for the impact of ambient, temperature on the efficiency of the HPWH,
$CoolingCap_{HPWH}$ = the cooling capacity of heat pump water heater,

and the variables ρ, C_p, and V_{water} are as previously defined.

Modeling based on these assumptions has demonstrated that space heating penalties can significantly reduce potential savings in cold climates, depending on the type of heating system installed in the home.

NREL estimates that the heating system impact can decrease savings from a HPWH by 33–67% if the home is heated by an electric-resistance furnace (Maguire et al. 2013). Colder climate regions will experience the most significant impact, while the warmer climate regions will experience smaller impacts because these regions have shorter heating seasons (i.e., time periods in which the household has a heating load).

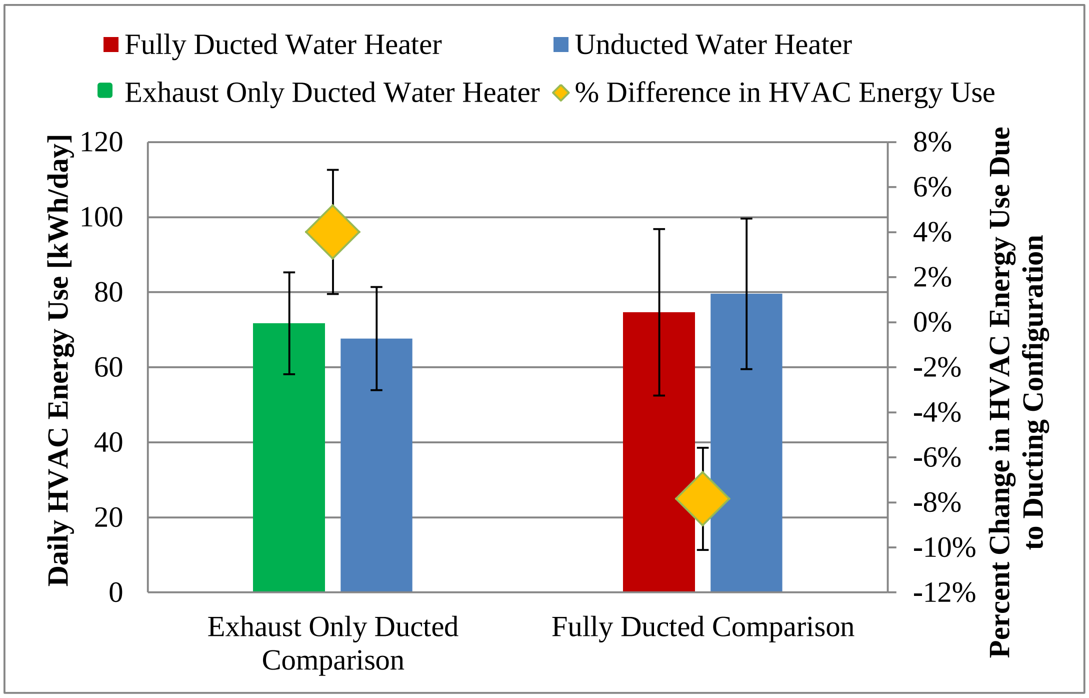
Overall, the NREL study shows that on average, the cooling system interaction is typically smaller than the heating system interaction because of the efficiency of the refrigeration cycle in air-conditioning compared to the heating systems that are typically less efficient, non-heat pump based technologies. (Maguire et al. 2013). Therefore, the impact of a HPWH in conditioned space will have the greatest effect on total energy use in a cold climate, in a home that uses a heat source other than an air source heat pump (ASHP).

2.2 Lab Home and Field Studies

Only a few studies have attempted to directly measure the impact of HPWHs on the space conditioning system and even fewer have evaluated that impact relative to the theoretical cooling load imparted by the HPWH in the conditioned space.

A previous PNNL Lab Homes study evaluated the impact of a GE GeoSpring HPWH on the space conditioning system in several ducting configurations: unducted, exhaust ducted, and with full supply and exhaust ducting (Widder et al. 2014). Compared to an unducted HPWH, the work found that installing exhaust-only ducting on a HPWH in conditioned space increased whole-house energy use 4.0 ± 2.8%, while full ducting decreased whole-house energy use 7.8 ± 2.3%, as shown in Figure 2.1. The research suggests that, compared to the unducted HPWH, exhaust-only ducting increased space conditioning energy use during the heating season experimental period because of the increased infiltration of colder outdoor air, while full ducting was observed to substantially mitigate the impact of the HPWH on the HVAC system.

While the experiment did not directly compare the unducted HPWH performance to an ERWH, the work reasonably assumed that the fully ducted scenario did not interact with the HVAC system and, therefore, represented the “no interaction” case equivalent to an ERWH. Using the fully ducted water heater as a comparison, the study also quantified the impact of installing an unducted HPWH on the space conditioning system, and it was the first report to suggest the impact may not be as large as previous modeling studies suggested. Specifically, the study found that only approximately 43.4 ± 12.2% of the theoretical space conditioning load was made up by the HVAC system during the heating season, and 37.2 ± 4.7% during the cooling season. The study reported average localized cooling in the water heater closet of 8.4 ± 3.4°F in the heating season for the unducted water heater. However, the study did not evaluate other locations beyond the water heater closet.



Source: Widder et al. 2014.

Figure 2.1. Daily HVAC Energy Use (kWh/day) and Difference in HVAC Energy Use (%) for the Exhaust-Only Ducted Comparison and the Fully Ducted Comparison Periods in the Heating Season Experimental Period.

A similar, but converse, study conducted in the twin homes at the Florida Solar Energy Center (FSEC) evaluated the impact of different ducting configurations on space conditioning system energy use (Colon et al, 2016a). The FSEC study evaluated two HPWHs installed in the garage in three ducting scenarios: unducted (garage-to-garage), exhaust-only ducting (garage-to-indoor), and full ducting (indoor-to-indoor). For the "fully conditioned space" configuration (*i.e.*, the unducted situation in the PNNL Lab Homes study and the fully ducted configuration in the FSEC study), the FSEC study observed a 4.3% cooling system benefit as compared to the "fully disconnected" configuration (*i.e.*, the fully ducted situation in the PNNL Lab Homes study and the unducted configuration in the FSEC study), similar to the cooling season results observed in the PNNL Lab Homes study. In the heating season, the FSEC study reported a 5.6% HVAC system energy penalty associated with the "fully conditioned space" configuration, which is also comparable with the results from the PNNL Lab Homes study. The FSEC study did not directly report the "interaction factor," the study reported average cooling loads imparted by the HPWH and measured HVAC loads, which can be compared to determine approximate interaction factors, as shown in

Table 2.1.

Table 2.1. Average Interior Relative Humidity (%RH) for "Fully Disconnected" and "Fully Conditioned" Installations During Cooling and Heating Seasons. Source: Colon et al, 2016a.

Season	Cooling Load Imparted by HPWH (kWh/day)	Measured Difference in HVAC Load with HPWH in "Fully Conditioned" Configuration (kWh/day)	HPWH Interaction Factor
Average Cooling Season (July to Sept)	1.76	0.86	0.49
Average Heating Season (Nov to Feb)	3.66	-0.42	0.11

The FSEC results demonstrate fairly low interaction factors, which is not surprising due to the high humidity and more significant latent removal observed in the heating season, as shown in Table 2.2. The latent removal observed in the cooling season is less significant due to the lower relative humidity associated with warm summer temperatures (see section 7.2 for more discussion). These values are consistent with the sensible heat ratios reported in the study of 0.53-0.72 (*Id.*).

Table 2.2. Average Interior Relative Humidity (%RH) for "Fully Disconnected" and "Fully Conditioned" Installations During Cooling and Heating Seasons. Source: Colon et al, 2016a.

Season	Average Relative Humidity Indoors (%RH)	
	"Fully Disconnected Installation" (i.e. Garage-to-Garage)	*"Fully Conditioned Installation" (i.e., Indoor-to-Indoor)*
Average Cooling Season (July to Sept)	46.7	47.3
Average Heating Season (Nov to Feb)	58.8	55.6

The Heat Pump Water Heater Model Validation Study by Ecotope, conducted on behalf of the Northwest Energy Efficiency Alliance (NEEA; Ecotope 2015), evaluated many aspects of HPWH field energy use, including space heating impacts. The study attempted to investigate space heating interactions through "flip-flop"[2] tests at five sites, where the HPWH was manually switched between heat pump mode and resistance mode at each home. While these tests proved inconclusive, the ambient space temperature depression during water heater operation suggested that the space heating impacts (and penalty) are less than 100%. The report also suggests there is no noticeable interaction for garage and unheated basement installations.

Similarly, a recent study by the Consortium for Advanced Residential Buildings was not able to resolve the space conditioning impact of HPWHs in the Northeast, many of which were installed in basements (Shapiro and Puttaguntha 2016).

Natural Resources Canada has also evaluated the impact of a HPWH on the space conditioning system in a pair of matched homes at the Canadian Centre for Housing Technology (CCHT)

[2] The "flip flop" tests in this study entailed manually switching the HPWH installed in each home between heat pump and electric resistance operating modes to discern the impact of the HPWH on the space conditioning system operation in each home. In this case, the home operating with the water heater in electric resistance mode served as the baseline and the water heater operating in heat pump mode served as the experimental case in each of the five homes.

Twin Homes[3] in Ottawa (Martin et al. 2013). While a final report is not yet complete, the CCHT Twin Homes study found that the homes with HPWHs used approximately 5 kWh/day (4.8–6.6%) more energy than the baseline home (with a gas water heater) in the heating season and reported an observed localized cooling of approximately 3.6 °F. A heating penalty of 5 kWh/day suggests a HPWH interactor factor of 0.65–0.87, based on the simulated water heating load, although the report did not quantify or discuss the interaction factor as a function of the theoretical HPWH cooling load.

Similarly, a recent study by the Florida Solar Energy Center used regression analysis to determine the heating system interaction of HPWHs installed in eight homes that received HPWHs as part of retrofit packages. The study reported an observed heating system penalty of -0.76 kWh/day (8.9%) with a heat pump heating system, but the data were variable and sporadic, partially due to the intermittent heating demand in Florida (Colon et al. 2016b). The report did not attempt to quantify the HPWH interaction factor.

While not a direct measurement of space conditioning system interaction the Florida Solar Energy Center has evaluated the latent heat removal of HPWHs, which impacts the interaction of HPWHs on the space conditioning systems (see discussion in Section 3). With the HPWH set to deliver 120 °F water and operate under either the draw profile specified in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.2 standard (64.3 gallons/day) or the monthly dynamic NREL/Building America draw profile (ASHRAE 1993; Hendron and Burch 2008), alternating every 2 weeks, the study found that the HPWHs removed approximately 3.2 pints/day of moisture at an ambient temperature of approximately 90°F (Colon and Parker 2013).

[3] http://www.ccht-cctr.gc.ca/eng/facilities/twin_houses.html

3. Theoretical Interaction between HPWH and Residential HVAC Systems

When installed in conditioned space, HPWHs introduce a cooling load (i.e., negative gain). This load may affect the HVAC system differently, depending on where the HPWH is located with respect to the thermostat and a central duct system return grille. This interaction can be quantified through the use of an interaction factor.

An energy balance diagram is one way to envision the interaction that a HPWH with the space around it. Figure 3.1 shows an energy balance diagram around the HPWH.

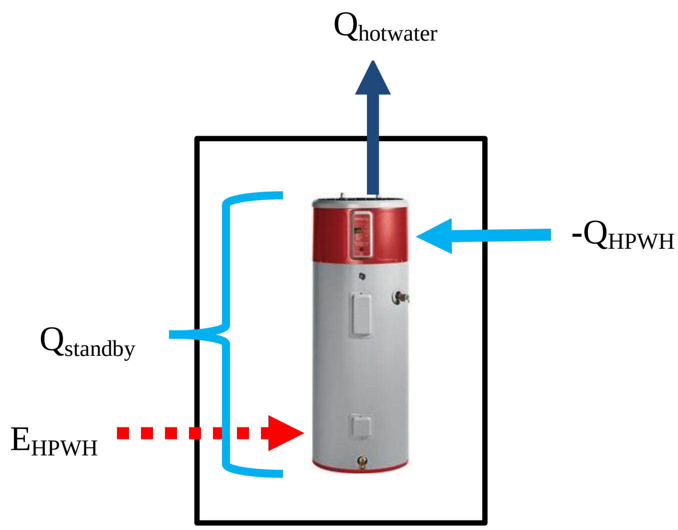


Figure 3.1. Diagram of Energy Balance around a HPWH

On a very basic level, the HPWH uses electrical energy to power the heat pump, which transfers heat energy from the surrounding air to the water stored in the tank. Energy leaves the water heater in two ways: as heat in the water during a water draw, and the standby losses of the tank. Equation (3.1) shows this energy balance:

$$E_{HPWH} + Q_{HPWH} = Q_{hotwater} + Q_{standby} \tag{3.1}$$

where,

E_{HPWH} = electric energy use from HPWH;
Q_{HPWH} = energy removed from air by heat pump, composed of both sensible and latent heat;
$Q_{hotwater}$ = previously defined in Equation (2); and
$Q_{standby}$ = standby losses from water heater tank.

As shown in Figure 3.1, the HPWH interacts positively and negatively with space. That is, the HPWH imparts both positive internal gains in the form of standby losses, and negative internal gains in the form of energy removed from the space to heat the water. The net HPWH impact is a sum of the standby and cooling loads, as shown in Equation (3.2):

$$Q_{HPWH,net} = Q_{HPWH} + Q_{standby} \tag{3.2}$$

where,

QHPWH,net = the net cooling load imparted by the HPWH on the space,
QHPWH = the gross cooling load imparted by the HPWH on the space, and
Qstandby = the standby losses of the HPWH.

The net HPWH load generally acts as a net negative gain because the quantity of energy removed from the space to heat the water is larger than the amount of standby energy introduced to the space under typical usage conditions

From a simple energy balance perspective, one might expect the cooling load introduced by the HPWH to be 100% made up for by the space conditioning system. That is, one assumes that each Btu of energy imparted to the water heater tank represents a Btu of energy that must be provided by the space conditioning system. Therefore, from a whole-house perspective, load on the HVAC system would be composed of the thermal load on the house due to the outdoor air temperature (UAΔT), the solar energy introduced into the home (Q_{solar}), the contribution of any internal gains, and the net load imparted by the HPWH, as shown in Equation (3.3):

$$QHVAC = QUA\Delta T + Qsolar + QIntGains - QHPWH,net \qquad (3.3)$$

where,

Q_{HVAC} = energy introduced by the space conditioning system,
$Q_{UA\Delta T}$ = heat load on the building envelope due to the difference between indoor and outdoor temperatures,
Q_{solar} = solar heat gains in the home,
$Q_{IntGains}$ = internal gains (occupancy, lighting, miscenllaneous electric loads, etc.), and
$Q_{HPWH,HVAC}$ = portion of the sensible cooling load introduced by the HPWH that is made up by the space conditioning system.

Figure 3.2 illustrates this whole-house energy balance diagram.

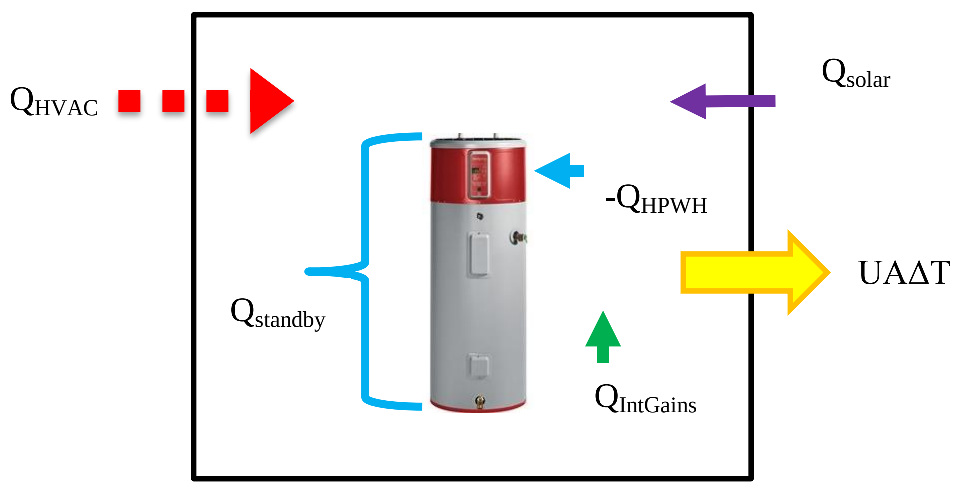


Figure 3.2. Diagram of the Energy Balance of a Whole House

However, the theoretical net impact of the HPWH ($-Q_{,HPWH} + Q_{standby}$) may not be completely made up by the space conditioning system. This is because the space conditioning system operation is dictated by the home's thermostat. Therefore, the degree to which the space conditioning system is affected by the HPWH cooling load is directly related to the ability of the thermostat to sense the thermal deficit. The thermostat may not sense all of the heat the HPWH removed from the space for a number of reasons.

First, it is important to note that the net theoretical energy removed from the space has both a sensible and latent component. HPWHs remove sensible heat from the air as well as condense water on the evaporator coil to remove heat from the air. Because thermostats only sense the dry-bulb temperature, any latent heat removal will not affect the dry-bulb temperature and will not be observed by the thermostat. We refer to this as the “HPWH latent load” ($Q_{HPWH,latent}$).

Second, the HPWH will remove heat from the space in which it is located. Because the HVAC thermostat cannot sense and immediately compensate for any localized cooling in the HPWH location, this will result in localized cooling of that area and associated decreased thermal losses through the building envelope. Essentially, the HPWH is decreasing the temperature difference between the home and the outdoors, which decreases the driving force for heat loss. In this way, the energy removed from the space by the HPWH would serve to decrease envelope heat loss, which would decrease the load on the home’s HVAC system. We refer to this as the “localized cooling load” ($Q_{localcool}$).

Third, some of the heat imparted to the HPWH that is scavenged from the space may be “free heat” from solar gains. On sunny days, the solar gains may be larger than the house heating load, in which case the house will drift off set point. When this occurs, the heat loss through the envelope increases (due to an increased temperature differential between indoors and outdoors). Although the solar heat imparted to the home will serve to offset the space conditioning system energy use, it will also increase the overall heat loss and the amount of solar gains will not exactly offset the decreased HVAC system energy use. Solar gains that increase overall heat loss are not useful internal gains. However, when the HPWH is operating and imparting a negative cooling load, this will decrease the degree to which the thermostat drifts off set point and, thus, decrease the degree to which the excess solar gains increase heat loss through the home. In effect, the HPWH will turn some of the “excess solar gains” into useful internal gains.
The impact of this “excess solar load” ($Q_{extrasolar}$) is shown in Figure 3.3.

In the figure, the thermal load on the house is illustrated in yellow. The internal gains (shown in green) offset the total heat load throughout the day. In the figure the internal gains are shown as a fixed value throughout the day, but in reality they will likely vary based on occupancy and use. The solar load (shown in purple) further offsets the total thermal load when the sun is out, in this case completely offsetting the thermal load on the house in the afternoon hours. The total HVAC load (red dashed areas) in this scenario is the difference between the yellow total thermal load and the sum of internal gains and solar load (the green and purple lines) integrated throughout the day. Because the solar load exceeds the thermal load, some of that energy is returned to the space, offsetting the HVAC load; this is illustrated by the dashed purple areas. The HPWH acts as a negative gain (shown in blue) that offsets the positive heat gains. This adds to the HVAC load and offsets the degree of overheating. With the HPWH, the excess solar energy (purple dashed area) is reduced and, therefore, the associated thermal losses are also reduced.

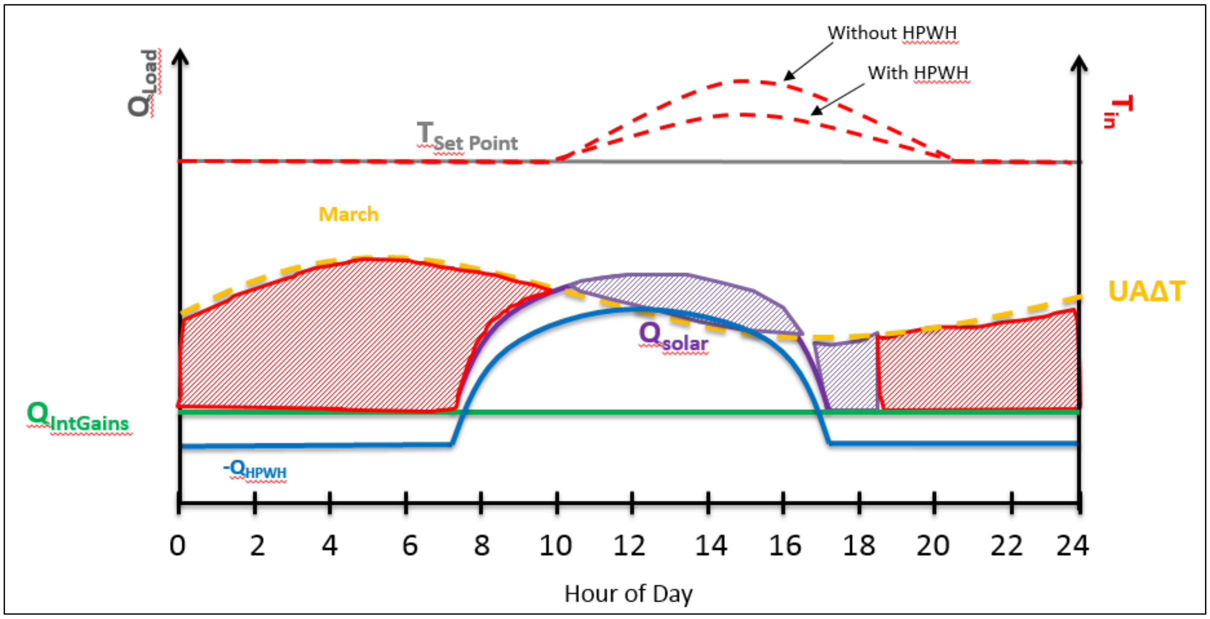


Figure 3.3. Interaction of Various Loads on an HVAC System

Taking these impacts in aggregate, the net theoretical cooling load imparted by the HPWH ($Q_{HPWH,theoretical,net}$) is a sum of four components, shown in Equation (3.4):

$$Q_{HPWH,net} = (Q_{HPWH,HVAC} - Q_{localcool} - Q_{extrasolar})_{sensible} + Q_{HPWH,latent} \quad (3.4)$$

where,

$Q_{HPWH,\ net}$ = net theoretical cooling load imparted by the HPWH on the space;
$Q_{HPWH,HVAC}$ = portion of the sensible load that is provided by the space conditioning system;
$Q_{localcool}$ = portion of the sensible load that decreases the home's heat loss, but is not sensed by space conditioning system;
$Q_{extrasolar}$ = portion of the sensible load provided by solar gains that increases the home's heat loss, but is not sensed by space conditioning system; and
$Q_{HPWH,latent}$ = latent heat removed from the space and imparted to the hot water.

As Equation (10) illustrates, the degree to which the space conditioning load is affected by the HPWH is less than the theoretical cooling load imparted by the HPWH. The "HPWH interaction factor" (F_{HPWH}) is defined as the ratio of the portion of the net theoretical cooling load introduced by the HPWH that is sensed by the space conditioning system over the entire net theoretical HPWH cooling load, as shown in Equation (3.5), with all terms previously defined.

$$F_{HPWH} = \frac{Q_{HPWH,HVAC}}{Q_{HPWH,theoretical,net}} \quad (3.5)$$

Recall that the net theoretical HPWH cooling load can also be determined based on an energy balance around the water heater (as shown in Figure 3.1). Therefore, the HPWH interaction factor can also be determined as a ratio of the portion of the HPWH cooling load that is sensed by the space conditioning system, divided by the difference of the hot water load delivered to the house, minus the electrical energy provided to the HPWH, as shown in Equation (3.6), with all terms previously defined.

$$F_{HPWH} = \frac{Q_{HPWH,HVAC}}{(Q_{hotwater} - E_{HPWH})} \tag{3.6}$$

To quantify the HPWH interaction factor, the experimental approach relies on the side-by-side comparison possible in the PNNL Lab Homes. During each experimental period, the water heater was operated in heat pump mode in one home (the experimental home) and electric-resistance mode in the other home (the baseline home). Therefore, the net theoretical cooling load imparted by the HPWH was imposed in one home, but not the other. By evaluating the difference between the space conditioning system energy use in the baseline and experimental Lab Homes, the portion of the HPWH cooling load that is made up by the space conditioning system can be determined, as shown in Equation (3.7).

$$Q_{HPWH,HVAC} = E_{HVAC,experimental} - E_{HVAC,baseline} \tag{3.7}$$

where,

$Q_{HPWH, HVAC}$ = defined in Equation (9),
$E_{HVAC,experimental}$ = electricity use of the space conditioning system in the experimental home, and
$E_{HVAC, baseline}$ = electricity use of the space conditioning system in the baseline home.

The delivered hot water ($Q_{hotwater}$) and the electricity consumption of the HPWH (E_{HPWH}) in the experimental home are measured directly. Therefore, for each experimental period, the HPWH interaction factor can be determined based on Equation (3.8).

$$F_{HPWH} = \frac{(E_{HVAC,experimental} - E_{HVAC,baseline})}{(Q_{hotwater} - E_{HPWH})} \tag{3.8}$$

Equation (3.8) is a steady-state equation and assumes the system has reached equilibrium. However, at any given time in the day, this will not be the case. The increased space conditioning system energy use will occur after the HPWH cooling load is introduced to the space, which will occur after a hot water draw causes the heat pump in the water heater to turn on, as illustrated in Figure 3.4. However, the longer the analysis period is, the more the temporally disparate loads can be assumed to be in equilibrium and analyzed comparatively. The analysis period was determined to be 1 day (24 hours), beginning and ending at midnight. This time period allowed for averaging of temporal impacts over many HPWH and HVAC cycles, while providing multiple data points per experiment (rather than a week, which would only provide one data point per experiment). Because the simulated water heater load is concentrated during the daytime hours, the water heater is able to reheat the tank to set point by the end of the 24-hour period thereby beginning the next day in a consistent state. The consistent daily hot water demand usefully yields water heater energy consumption within the cycle.

. Consequently, F_{HPWH} cannot be measured on an instantaneous basis, but is instead measurable on longer time intervals spanning full water heater reheat and space heat cycles.

However, the longer the analysis period is, the more the temporally disparate loads can be assumed to be in equilibrium and analyzed comparatively. The analysis period was determined to be 1 day (24 hours), beginning and ending at midnight. This time period allowed for averaging of temporal impacts over many HPWH and HVAC cycles, while providing multiple data points per experiment (rather than a week, which would only provide one data point per experiment). Because the simulated water heater load is concentrated during the daytime hours, the water heater is able to reheat the tank to set point by the end of the 24-hour period thereby beginning the next day in a consistent state. The consistent daily hot water demand usefully yields water heater energy consumption within the cycle.

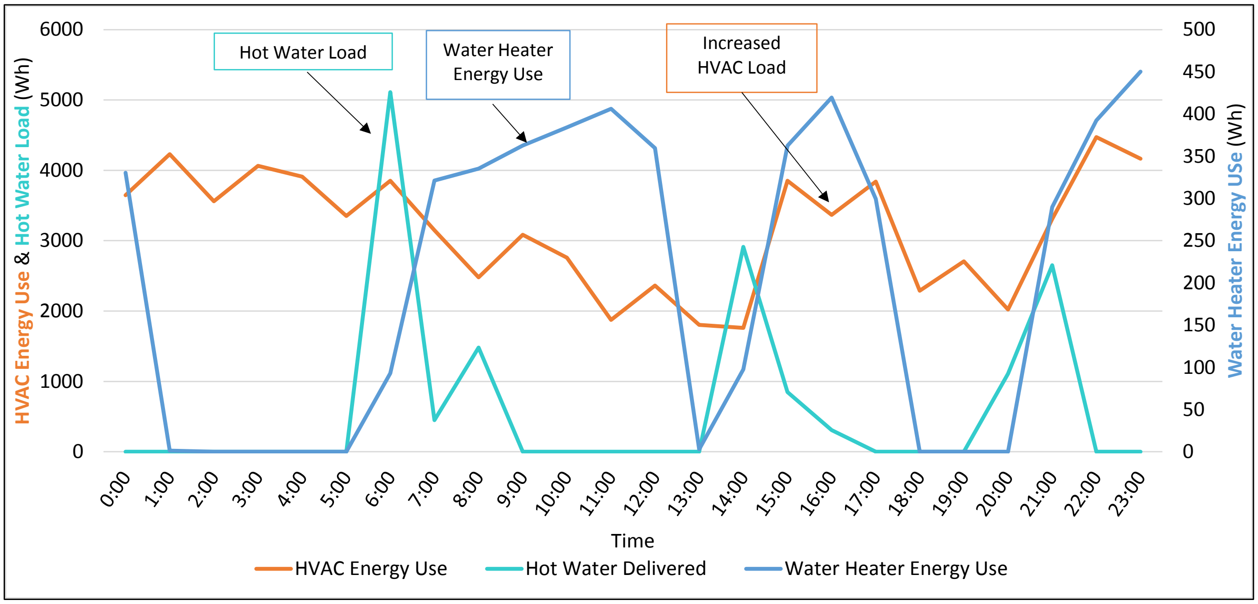


Figure 3.4. Example of General Interaction between a HPWH and a Heating System. On this day, the average interior temperature was 69.1°F (range of 68.8–69.3°F) and the outdoor temperature was 33.0°F (range of 29.4–36.6°F).

4. Experimental Setup

The two Lab Homes in which the experiments were conducted, the associated metering and system control activities, the simulation of occupancy in the homes, and the setup of the HPWH and space heater experiments are described in the following sections.

4.1 PNNL Lab Homes

The experiments were conducted in side-by-side Lab Homes: two factory-built homes installed on PNNL's campus in Richland, Washington, that aim to represent a typical existing home in the United States. These 1500 ft^2 homes have three bedrooms, two bathrooms, and are heated with an electric forced-air furnace. Both homes have R-22 floors, R-11 walls, and R-22 ceiling insulation levels, along with double-pane clear glass windows. Figure 4.1 illustrates a floor plan of the Lab Homes.

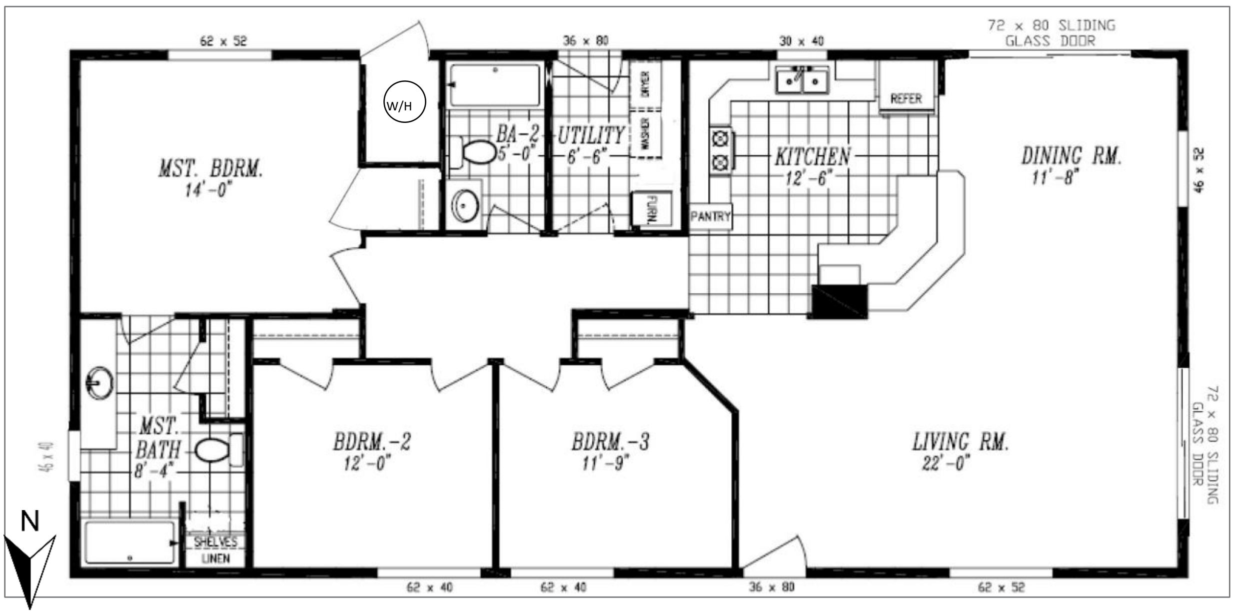


Figure 4.1. Floor Plan of the Lab Homes as Constructed

The two houses provide a "control" and "experiment" environment that reduce uncertainty due to weather variations that typically exist in field experiments in which one home is used to test an existing and retrofitted technology across two different time frames. The Lab Homes are also equipped to simulate occupancy, which eliminates uncertainty due to unknown occupant behavior and operation practices.

Certain factors related to the experimental setup have the potential to influence the results, but these factors were kept identical in both homes to ensure they would not. These factors include:

- water heater type and set point temperature
- whole-house set point temperature
- hose length to and from the water heaters
- solenoid type and settings (i.e., flow rate and timing)

- all relevant sensors are the same brand and age and were professionally re-calibrated prior to this experiment if necessary
- simulated occupancy, lighting, and equipment loads.

4.2 Measurements

Metering and system-control activities take place at both the electrical panel and the end-use location. All metering was completed using Campbell Scientific data loggers and matching sensors. Two data loggers were installed in each home, one allocated to electrical measurements and one to temperature and other data collection. (Tables B.1 and B.2 in Appendix B shows the details of the measurements taken with each data logger.) All data were collected via network modems connected to each of the loggers.

All data were captured at 1-minute intervals and subsequently averaged over hourly and daily time intervals to afford different analyses.

4.3 Occupancy Simulation

Sensible heat was added to the homes to help simulate both occupant behavior (lighting, appliances, etc.) and occupants themselves. Lighting was simulated using the actual lighting in the homes. Equipment was simulated using wall heaters, and occupants were simulated using incandescent light bulbs on small floor stands. Solar heat gains naturally occur through the identical windows in both homes and did not need to be simulated.

The schedules for all loads use the profiles described in the 2014 Building America House Simulation Protocols for a three-bedroom, two-bathroom home. A programmable commercial lighting breaker panel (one per home) used motorized breakers to automate the schedules for all occupancy simulation profiles. Appendix A provides detailed information related to the occupancy and lighting schedule.

4.4 HPWH Experimental Setup

For the HPWH experiment, both homes received the same experimental apparatus (**Table 4.1**) with minor component differences.

Power was drawn from the wall receptacle in the existing water heater closet location using a 75’ power cable. Using two 75’ industrial hoses, water was drawn from the existing connections in the water heater closet from the city water (cold side) and fed back to the homes’ internal plumbing (hot side). The pressure relief value was connected using a 50’ hot water hose to the nearest drain as the water heaters changed location for each experiment. The dolly provided the ability to move the HPWH from space to space on plywood boards.

Table 4.1. Equipment Used for the HPWH Experiment

Component	Model Number (If Applicable)
50-gallon heat pump/electric-resistance water heater	GE – Geospring Model: GEH50DEEJSCB
Heavy-duty rolling cart	
Plywood boards	
Ratchet tie downs	
75’ 240VAC electrical extension cable	
2 – 75’ inlet (cold) and outlet (hot) industrial hoses	
Swagelok flow control needle valves Cv 2.4	
Drain pan	
50’ relief valve hose ran to the nearest drain	
Condensate PVC tube	
Tipping bucket (Lab Home B – Only)	Rainwise LLC. Rainew 111 Single Counter
Stand for ambient RH sensor	
Ambient RH sensor solar shield	Campbell Scientific Rad Shield
Ambient RH sensor	Campbell Scientific HC2S3
Inlet RH sensor (Lab Home B – Only) w/ bracket	Campbell Scientific HC2S3
Exit RH sensor (Lab Home B – Only) w/ bracket	Campbell Scientific HC2S3

Figure 4.2. PNNL Lab Home B Experimental Apparatus Setup in the Living Room Location

4.5 Space Heater Experimental Setup

The purpose of this experiment was to verify the space conditioning interaction of a point source load that is 1) isolated from the thermostat and 2) closer to the thermostat. A space heater was placed in one home, while the second home did not have a space heater. In this experiment, to ensure that the strongest thermal signal originated from the space heater itself, no occupancy was simulated.

The point load heater chosen was a Homeleader NSB-200C3H ceramic heater able to produce a constant 750 W or 1500 W of heat. For this experiment, an estimated 750 W load was introduced to the space throughout the day. This smaller load was chosen to be more representative of entertainment centers or the compressor of a HPWH than the 1500 W option.

5. Experimental Plan

The Lab Homes experiments were divided into two complementary experiments based on the research questions referenced in the scope section of this report. The room-by-room HPWH experiments helped to answer the first three research questions, while the space heater experiment helped to answer the final research question.

5.1 HPWH Experiments

To answer the research questions presented in Section 1.1, the GE HPWH was installed in both homes. The controls were overridden in the baseline home, and the water heater was run in electric-resistance mode. The water heater was run in the heat pump-only mode in the experimental home. The water heaters in both homes were then rolled to each test location using the setup described in Section 4.4. Table 5.1 and Figure 5.1 present the locations of water heater installations and the reasoning for each location. In each test location, the exhaust from the HPWH was pointed toward the exterior wall, as is typical of installation in the field.

Table 5.1. Water Heater Installation Location and Reason for Test Case

Test Case Description	Test Location (on Floorplan)	Reason to Include Test Case
Master Bath, Door Closed	A	Most buffered from the thermostat within the conditioned space. Most connected to the latent load
Living Room	B	Includes effects of solar gains
Utility Closet	C	Most connected to the return duct
Water Heater Closet	D	Most representative of semi-conditioned space

As Figure 5.1 illustrates, the volume of each installation location varied, as did the distance from the thermostat. The volume of each room is important because it is related to how much localized cooling we might expect in that space due to HPWH operation. In addition, the volume of the HPWH installation location has the potential to affect the operation of the HPWH if there is not enough air available for the HPWH to circulate in accordance with the manufacturer's specifications. However, in all cases, the HPWHs were installed in locations that met manufacturer specifications for the water heaters. The volume of air in each room is listed in Table 5.2. The water heater closet has the least amount of air volume available, but two, passive, transfer grilles were installed to increase air exchange with the master bedroom. The utility room has the second least amount of air volume available, but the utility room does not have a solid door, so air is allowed to exchange with hallway air. Some of the experiments were conducted with a zipper door dividing the utility room from the rest of the home, and some did not have a door. The results showed the difference was minimal and the results reported in subsequent sections are averaged between the two scenarios.

The 84-gallon per day (gpd) water draw profile, currently the High Usage profile in the U.S. Department of Energy Uniform Energy Factor Test, was chosen to ensure a large signal to help determine the interaction factor (DOE 2014). Grundfos flow sensors were used to verify that the flow rates were within <1% of 84 gpd for each home.

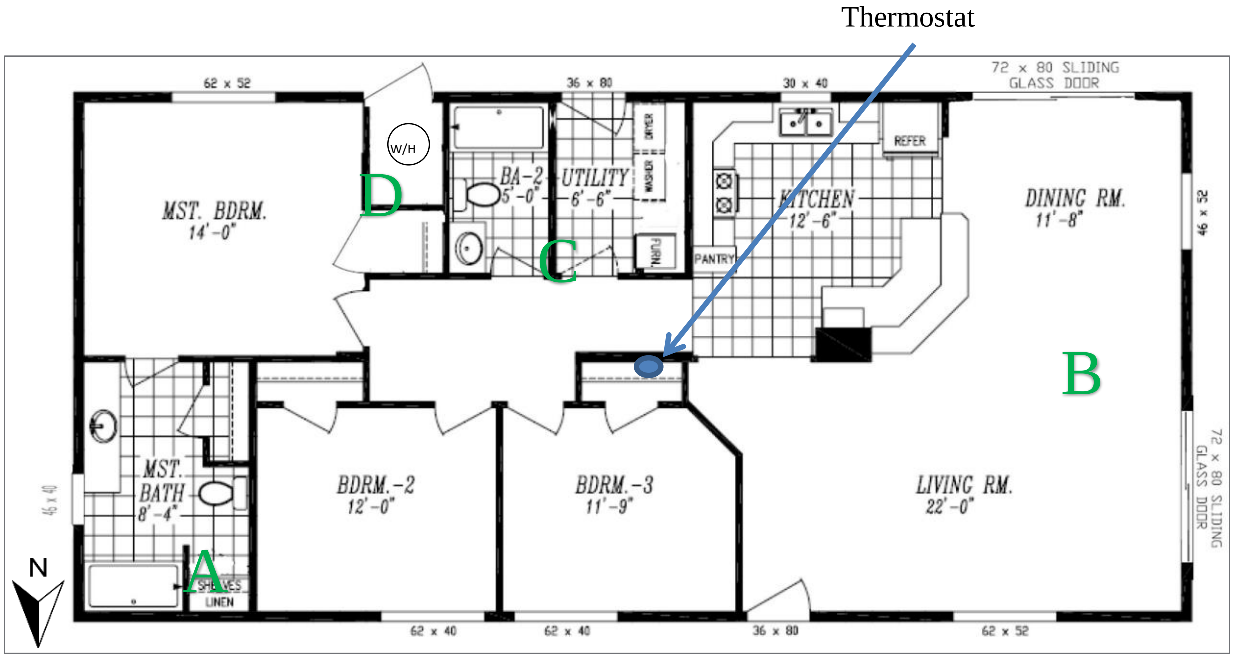


Figure 5.1. Lab Homes Floor Plan Identifying Test Case Locations (green letters) and Thermostat (blue circle)

Table 5.2. Volume of Each Room in the HPWH Experiment

Test Case Description	Test Location (on Floorplan)	Volume (ft^3)
Master Bathroom	A	952
Living Room	B	3197
Utility Room	C	464
Water Heater Closet	D	31[(a)]

(a) Transfer grill added to ensure adequate air from master bedroom

To create a draw profile, time sequences were programmed using a Campbell Scientific SDM-CD16AC relay, which opened and closed a solenoid at designated time increments. The solenoid was powered using a 24 V power supply. Swagelok 2.4 Cv needle valves were used inline post solenoid to measure the exact flow rate.

Figure 5.2 shows the draw profile that was selected and the total gallons per draw. Higher draws in the morning were representative of an occupant showering. Higher draws at night time represent typical water use at night (e.g., showers, dishwasher use, clothes water use, etc.). Water temperature was measured at the solenoid.

Understanding the RH of the space was very important for this experiment. Two ambient RH sensors (CS215 CampbellSci RH Sensors) already existed in the homes. Upon initiation of this experiment, it was assumed that data from these sensors would be helpful, so they received new chips and filters. RH accuracy for the CS215 sensor is ±2% (10% to 90% range) and ±0.3°C (at 25°C).

The higher accuracy sensors (Campbell Scientific HC253 RH Sensors) were used near the air streams of the HPWH system inlet and exhaust to monitor the operation of the system. The accuracy of these sensors was ±0.8% RH and ±0.1°C at 23°C. Before the experiment started, the RH sensors that PNNL already owned were sent back to Campbell for calibration. Additional sensors were purchased as needed. One RH was also placed 6” from the face of the controls on the water heaters as a calibration point that was especially useful when both water heaters were in electric-resistance mode.

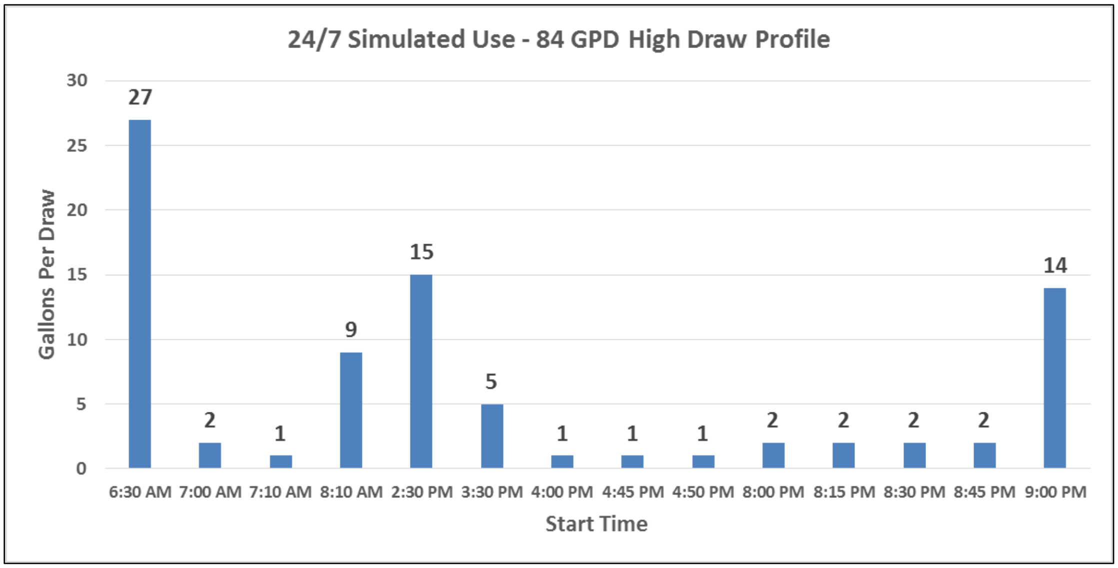


Figure 5.2. 84 Gallon per Day Draw Profile

Indoor temperature was set to 71°F to maintain representative home living conditions. The fans were set to AUTO with no temperature setbacks in accordance with the 2014 Building America House Simulation Protocol (Wilson et al. 2014). Existing thermocouples were all tested throughout each home and confirmed to be in correct operational condition. Minor naming and table definition code changes were made to install more thermocouples throughout the homes. Thermocouples were measured to be 1 foot from the center of the ceilings in all locations of the homes.

5.2 Space Heater Experiments

Table 5.3 and Figure 5.3 show the locations that were tested during the space heater experiment. The number of locations in this experiment were minimized in order to maximize the time available for the primary HPWH experiment. The thermostats in both homes were set to 85°F in this experiment to compensate for warmer outdoor temperatures during the time of the testing. The overall quantity of concern is the heat loss rate (UAΔT), which is largely affected by the temperature differential (ΔT) between the indoors and outdoors. Consequently, if it is 50°F outside and 85°F inside, the effect is similar to the result if it is 35°F outside and 70°F inside.

Table 5.3. Test Locations for the Supplemental Space Heater Experiment			
Test Case Description	Test Location (on Floorplan)	Notes	Reason to Include Test Case
Master Bath, Door Closed	A	Door Closed	Even more buffered from the thermostat
Livingroom	B	Similar orientation as the HPWH	Most impactful location on the thermostat

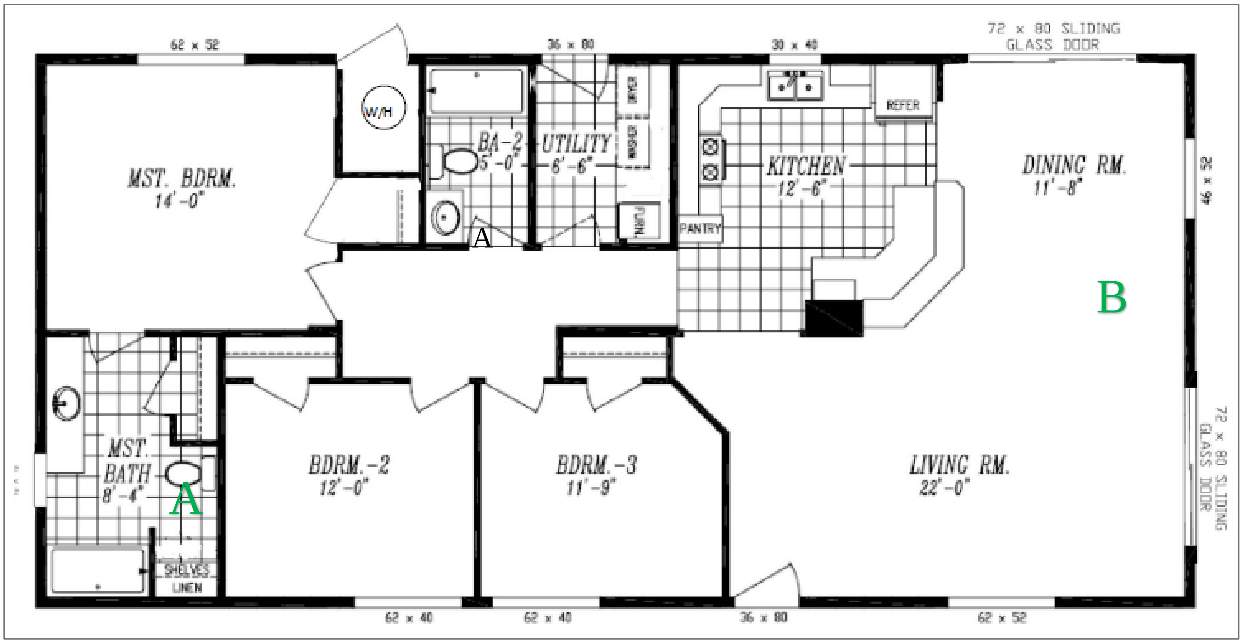


Figure 5.3. Lab Homes Floor Plan Identifying Test Case Locations (green letters) for the Space Heater Experiment

5.3 Experimental Timeline

Table 5.1 shows the timeline that was followed for the experiment, including both the HPWH and space heater experimental periods.

Table 5.4. Experimental Timeline

Date Range	Location of Point Source Load	State of Water Heater in Lab Home A	State of Water Heater in Lab Home B
1/13/2017 – 1/18/2017	Calibration #1: Master Bedroom	ER	ER
1/18/2017 – 1/23/2017	Master Bathroom	ER	HPWH
1/23/2017 – 1/31/2017	Living Room	ER	HPWH
1/31/2017 – 2/6/2017	Utility Room	ER	HPWH
2/6/2017 – 2/9/2017	Utility Room – Swap	HPWH	ER
2/9/2017 – 2/16/2017	Bad Data, flow sensor issue		
2/13/2016 – 2/16/2017	Calibration #2: Living Room	HPWH	HPWH
2/16/2017 – 2/20/2017	Living Room – Swap	HPWH	ER
2/20/2017 – 2/21/2017	WH install in WH closet		
2/21/2017 – 3/1/2017	WH Closet Commissioning, copper shards stuck in flow meter		
3/1/2017 – 3/10/2017	Water Heater Closet	HPWH	ER
3/10/2017 – 3/17/2017	Water Heater Closet – Swap	ER	HPWH
3/17/2017 – 3/22/2017	Thermostat – Swap		
3/22/2017 – 3/24/2017	Calibration #3: Water Heater Closet	ER	ER
3/24/2017 – 3/31/2017	Space Heater – Master Bathroom	No Extra Loads[(a)]	No Extra Loads[(a)]
3/31/2017 – 4/11/2017	Space Heater – Livingroom		

(a) No water heating, or other occupancy loads were included in the space heater experiments.

6. Analysis Approach

This section of the report includes information about the analytical steps that were taken to determine the relative and absolute interaction factors, including calibration periods, and calculations related to the energy associated with the hot water and the space conditioning system.

6.1 Calibration Periods

Three calibration periods were used to help understand the inherent differences between the two homes. In these periods, the homes were operated with equivalent settings. Any differences in the heating system energy use between the homes then formed the basis of an adjustment factor to be applied during experimental periods.

The first calibration period used both water heaters in electric-resistance mode in the master bedroom. The weather on these days was so cold that the heating system in both homes was rarely off. Therefore, the results were only somewhat relevant to the rest of the experiments, which took place during warmer outdoor conditions.

A second calibration period conducted in the middle of the experiment coincided with outdoor temperature conditions that better matched the experimental periods. In this calibration period, both of the water heaters were in heat pump-only mode and placed in the living room. These results indicated Lab Home B consumed approximately 11% +/- 3% more heating energy than Lab Home A. This difference is slightly larger than Lab Home experiments conducted in previous years. It is assumed that a sensor in one of the thermostats was floating out of calibration and was the culprit for this bias. However, because the thermostats were consistently located in each home throughout the whole experiment, an adjustment to account for this bias could be applied to the HVAC energy use throughout the rest of the experiment.

The third calibration period was right before the space heater experiment, after the thermostats were swapped. In this calibration period, the water heaters were in the water heater closet and in electric-resistance mode. The results from this period show that with the thermostats swapped, Lab Home A used 8% +/- 0% more heating energy than Lab Home B, further verifying that the issue is likely related to the thermostats. This calibration factor was applied to all of the space heater results.

6.2 Calculations and Adjustments

As described in Section 3, the HPWH interaction factor can be determined generally based on Equation (6.1) for each period or location of interest:

$$F_{HPWH} = \frac{(E_{HVAC,experimental} - E_{HVAC,baseline})}{(Q_{hotwater} - E_{HPWH})} \qquad (6.1)$$

The experimental approach included simulation of occupancy, lighting, and internal gains. While the simulated loads were intended to be identical from day to day, maintaining exact equivalency between the homes is difficult due to the limited and uncertain lifetime of incandescent lightbulbs that are used for lighting and to simulate occupancy in both homes. Therefore, a better comparison of the heating energy added to the space is based on the aggregate amount of measured electrical and space heat loads used across the entire house, excluding the water heater load ($E_{Heating,NonDHW}$). That is, the combined electrical energy use of the HVAC system, occupancy, lighting, and equipment were calculated for each home, as shown in Equation (6.2):

$$E_{Heating,NonDHW} = E_{HVAC} + E_{occupancy} + E_{lighting} + E_{equipment} \tag{6.2}$$

where,

$E_{Heating,NonDHW}$	=	electrical energy of every load in the house except water heating;
E_{HVAC}	=	electric energy use of the HVAC system, including the electrical elements, air handler fan, and associated auxiliary equipment;
$E_{occupancy}$	=	electrical energy use of the lightbulbs used to simulate occupancy;
$E_{lighting}$	=	electrical energy use of the lighting circuits; and
$E_{equipment}$	=	electrical energy of the space heaters used to simulate equipment loads.

As mentioned previously, all analysis was performed on a 24-hour basis to allow the system to approach steady-state within each analysis time-step.

6.2.1 Embodied Energy of Hot Water

The amount of energy embodied in the hot water delivered to each home was determined based on the supply water temperature (T_{supply}), the delivered hot water temperature (T_{hot}), the water mass (m), and the specific heat capacity of water (c_p), as shown in Equation (6.3):

$$Q_{hotwater} = mc_p(T_{hot} - T_{supply}) \tag{6.3}$$

Several adjustments had to be made to the measured delivered hot water temperature to accurately represent the actual energy supplied to the water by the HPWH. As described in Section 4.4, the HPWHs were equipped with long hoses to allow the water heaters to be moved throughout the home without needing to re-plumb the system each time. These hoses provided flexibility to run the experiment, but upon conducting the analysis, it was evident that this distance (75 ft) between the water heater outlet and the thermocouple (located in the solenoid at the sink) in both homes, was resulting in the thermocouple reading a reduced delivered temperature value due to cooling that occurred in the hoses. To account for this in the calculation of thermal energy transferred to the hot water ($Q_{hotwater}$), the HPWHs were assumed to deliver hot water that was at set point (125°F for both water heaters). The maximum temperature measurements for each draw were adjusted the appropriate amount to account for cooling that was occurring in the length of hose. Applying this bias to the measured data was assumed to accurately adjust the data to account for any impact of the hose on the temperature measurement, but still retain any differences between the HPWH and ERWH delivered water temperatures over the course of the day.

6.2.2 HVAC Analysis

To ensure consistent comparison of the experimental and baseline homes, the homes were calibrated twice during the HPWH study: prior to initiating any experiments (initial calibration) and at a midpoint in the experimental period (midpoint calibration). Although the thermostats were set equivalently to maintain 71.0°F in both homes, Lab Home B was observed to maintain a slightly higher and less variable average interior temperature than Lab Home A, which affected the comparison of HVAC energy usage between the homes.

To account for this difference in thermostat operation between the homes, the difference between the space conditioning energy consumption for the two homes was determined during these calibration periods and used to adjust the experimental results accordingly. Specifically, the difference between the energy use in Lab Home A and Lab Home B was determined both 1) as a function of degree days and 2) as unique heat loss coefficient, and was offset based on linear regression of the relevant data.

For the primary analysis, the difference in HVAC energy consumption between the Lab Homes was computed on heating degree day (HDD) basis (using a HDD basis of 65°F; HDD_{65}). The Lab Home B offset based on this analysis was 145.6 Wh/HDD, which was applied directly to the measured HVAC usage in Lab Home B. That is, Lab Home B used more energy to maintain the same thermostat set point than Lab Home A. This offset is reflective only of the second calibration period because the outdoor temperatures and temperature differentials during the midpoint calibration were more representative of the experimental periods, whereas the initial calibration period featured unusually cold outdoor temperatures that may not be applicable to the experimental data or may otherwise bias the adjustment.

For the secondary analysis, all of the relevant days when Lab Home A was in a “baseline” configuration were regressed with respect to HDD_{65} to determine analytically the thermal characteristics of the home (). Similarly, all of the relevant days when Lab Home B was in a “baseline” configuration were assessed to determine the baseline thermal characteristics of Lab Home B. This allowed more days to be used in the determination of the calibration than with the previously described method. More days have the potential to improve the accuracy of the comparison. In the regression, the slope of the line represents the heat loss rate of the home, in terms of Wh/°F/day and the y-intercept reflects any fixed loads in the home, in terms of Wh/day.

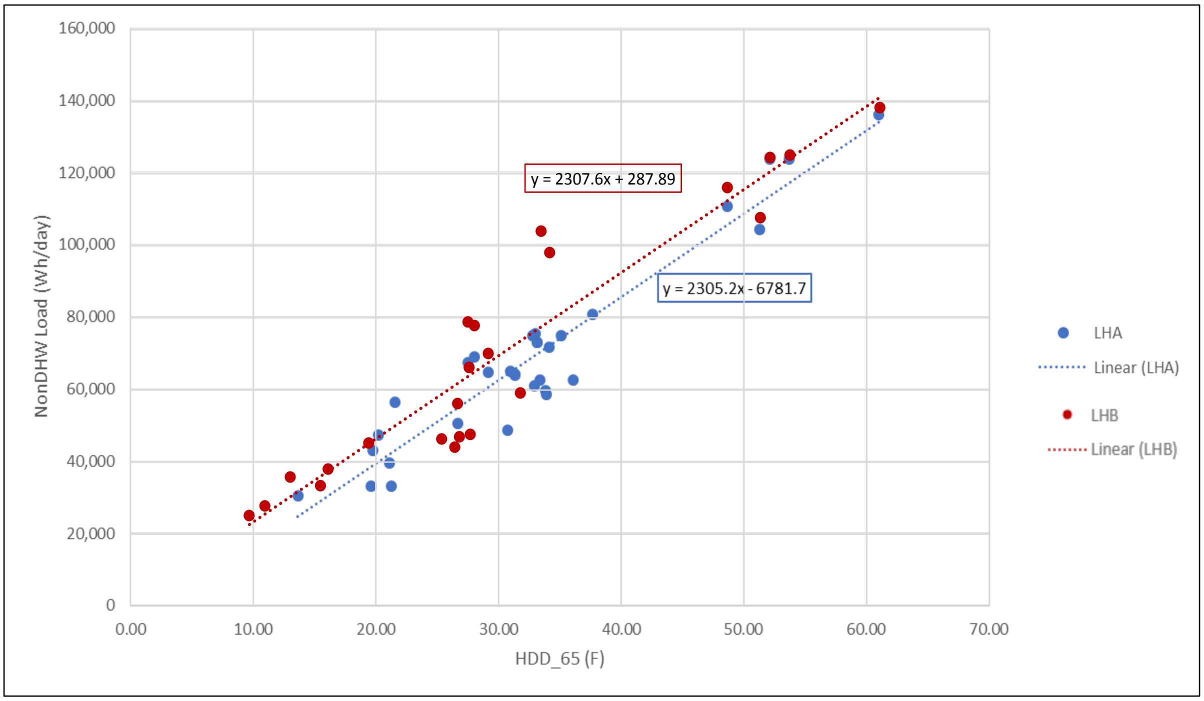


Figure 6.1. Calibration Curves for Lab Home A and Lab Home B

The results of this regression analysis are summarized in Table 6.1. The heat loss rates of the Lab Homes agreed quite well, but Lab Home B has about a 7 kWh/day offset compared to Lab Home A.

Table 6.1. Regression Analysis Details

Lab Home	Number of Days for Regression (N)	UA (Wh/F/day)	B (Wh/day)
A	32	2305.2	-6781.7
B	23	2307.6	287.89
Difference	NA	-2.4	-7069.59

To improve the robustness of the experimental results, the experiments were also performed in both Lab Homes. That is, most of the experimental locations were evaluated twice, once with Lab Home A as the baseline, and once with Lab Home B as the baseline. Because one would assume that the F_{HPWH} would agree between the experiments conducted in Lab Home A and Lab Home B for the same location, this flip-flop data also offer an opportunity to assess the integrity of the calibration approach. The regression-based calibration improved the overall agreement between the F_{HPWH} measured in Lab Home A versus the F_{HPWH} measured in Lab Home B for a given location. With the HDD-based calibration approach, the location-specific F_{HPWH} values from the flip-flop experiments were, on average ±46% different. The regression-based calibration approach improved the agreement between the F_{HPWH} values from the flip-flop experiments to within ±33%.

After calibration, two different fundamental analysis approaches were pursued to determine the

HPWH interaction factor: 1) based on the adjusted space heating load delivered to each home (thermal adjustment), and 2) based on results of the calibration based on the linear regression (linear regression).

For the first approach (thermal adjustment), the difference between the entire space heating load delivered to each home was computed and the difference between the experimental and baseline home was determined to be the incremental space heating load on the experimental home. In this analysis, the energy use by the electric-resistance furnace, as well as the energy introduced by the simulated occupancy, lighting, and equipment loads, were considered as "heat delivered to the space." Notably, all of these loads are purely resistive, including incandescent light bulbs and electric-resistance wall heaters, so the heat delivered to the space is equivalent to the electricity used by the equipment. Using this "whole-house space heating load," which is an aggregate of multiple heat sources in the home, is a more accurate method for computing the difference in space heating load imparted by the HPWH, because it accounts for any difference between the simulated lighting, occupancy, and equipment loads. The "whole-house space heating load" was adjusted in Lab Home B based on the results of the calibration period (using the Wh/HDD adjustment). This "adjusted whole-house" space heating load was compared to the theoretical net cooling load from the HPWH, which was determined to be the difference between the hot water delivered and the electricity consumption of the HPWH (as discussed in Section 2), to determine the HPWH interaction factor for each experimental period.

In the second approach (linear regression), the whole-house space conditioning load was also used. However, in this case, the results of the calibration based on the linear regression were applied to the whole-house space conditioning load in each home to determine the impact on the fixed load (i.e., y-intercept) in the home. Specifically, the calculated space heating load was determined for each home based on the UA (i.e., heat transferred through the envelope) for each home, determined in the calibration and the measured temperature differential between the indoor and outdoor air. The calculated space heating load was subtracted from the measured whole-house heating load to determine the remaining fixed portion of the load for each experimental day, as shown in Equation (6.4).

$$B_x = Q_{HeatLoad_{Measured},X} - UA_{LHX} \times \left(T_{in,X} - T_{out}\right) \tag{6.4}$$

where

B = the fixed daily load in Lab Home X, in Wh/day;
$Q_{HeatLoad\_Measured,X}$ = the measured whole-house space conditioning load in Lab Home X (HVAC + occupancy + lighting + equipment loads), in Wh/day;
UA_{LHX} = the heat loss rate of Lab Home X, as determined during the calibration, in Wh/F/day;
$T_{in,X}$ = the floor-area-weighted average interior temperature in Lab Home X, in °F; and
T_{out} = the measured outdoor air temperature, in °F.

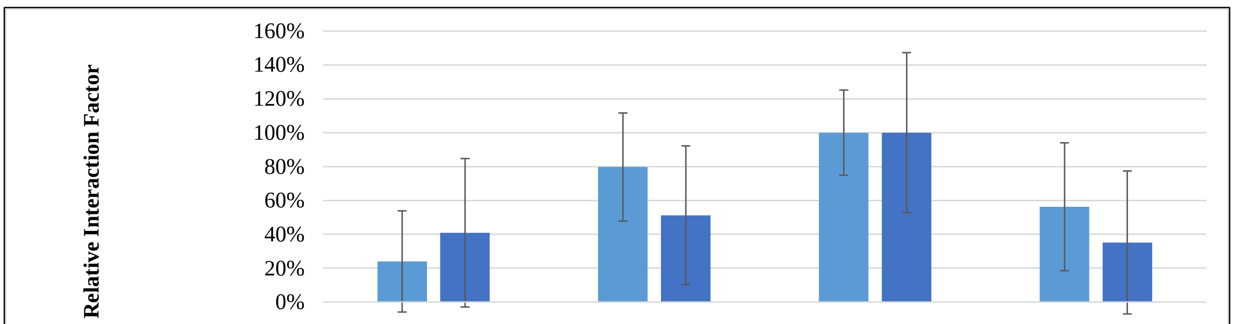
The difference between the fixed daily load (B parameter) was determined for each experimental day and adjusted based on the difference in the fixed load observed between the homes during the calibration period. The adjusted B parameter, or fixed load, was then treated as the difference in space conditioning energy use between the homes and compared to the net theoretical HPWH cooling impact to determine the HPWH interaction factor. Because the HPWH operates on a set schedule in the experiments, independent of temperature, the HPWH appears as a fixed load, or bias, in the regression, rather than as an HDD-dependent parameter.

7. Results and Discussion

Both the thermal adjustment and linear regression analysis methods were used to determine the HPWH interaction factor for the various experimental locations throughout the Lab Homes. Using both methods provides a confirmation of the quantitative and qualitative findings for each location, and informs the range of reasonable estimates for each location. The following sections present the general HPWH interaction factor findings, discuss the impact of localized cooling and solar insolation on the results, and discuss the attributes of each location to allow for the application of these findings to future studies and simulations.

7.1 Relative Interaction Factors

One of the primary findings of the experiment is the variability of the HPWH interaction factor among the different experimental locations. This confirms our hypothesis that the HPWH interaction factor can be less than 1.0 (100%), as discussed in Section 3, and that it will vary throughout a home based on the "thermal distance" between the HPWH installation location and the thermostat, where "thermal distance" represents the degree to which the HVAC system is influenced by energy added to or removed from the space. While this result was not unexpected, it is notable to observe the extent and range of the variability observed. Analyzing the measured space heating load compared to the theoretical cooling impact imparted by the HPWH for each experimental location, the data clearly demonstrate a trend where locations that are thermally distant from the thermostat are associated with interaction factors that are 44 to 76% lower than the location that is most connected to the thermostat. That is, the Lab Home experiments indicate that locations thermally distant from the thermostat may have as low as one quarter of the impact on the space conditioning system as locations close to the thermostat. To illustrate this relationship, Figure 7.1 depicts the interaction factor for each location normalized with respect to the location with the greatest interaction (the utility room). As shown in Figure 7.1, the master bedroom and water heater closet are associated with the least interaction and the utility room is associated with most interaction.



	MasterBath	LivingRoom	UtilityRoom	WHC
Thermal Adjustment Method	0.24	0.80	1.00	0.56
Linear Regression Method	0.41	0.51	1.00	0.35

Figure 7.1. Relative Interaction Factors for Experiments in the PNNL Lab Homes. The error bars represent the standard deviation of the calculated HPWH interaction factor for each experimental location, where each data point is 1 day.

It is important to note that in all cases energy is conserved and locations with interaction factors less than one indicate that more energy is being provided by solar or latent sources, or that the overall float temperature and heat load on the house is changing due to localized cooling. The source of this variability in observed HPWH interaction factor is the relative magnitude of different factors that contribute to the HPWH interaction factor: latent heat removal, localized cooling, and excess solar insolation. The impact of each of these factors is discussed in Sections 7.2, 7.3, and 7.4.

7.2 Latent Heat Removal

One of the factors that contributes to a HPWH interaction factor being less than 1.0 is latent heat removal. As discussed in Section 3, when the conditioned air is near the dew point temperature, additional cooling of the airstream across the HPWH coil will result in condensation of water from the air. This process also removes energy from the air and will result in less sensible cooling (i.e., the HPWH will remove energy from the air in the form of condensed water vapor instead of further reducing the dry-bulb air temperature). Because the HVAC system thermostat responds to changes in dry-bulb temperature, and typically not RH, energy removed in the form of condensate will not affect the HVAC system.

However, during the Lab Homes experiments, no condensate generation was observed. The reason for this becomes clear when looking at a psychometric chart as seen in Figure 7.2. During the experimental period, the average interior RH varied between approximately 20 and 35% RH. The average interior temperature and RH are also plotted in the figure as blue (Lab Home A) and red (Lab Home B) dots. As the figure shows, the interior temperature was significantly above the dew point temperature and, therefore, it is unlikely that condensation would occur during the experiment. In fact, even for the wettest conditions observed, the dry bulb temperature would have to drop about 30°F for the water vapor to condense on the evaporator coil. The coil temperature was not measured as part of the experiment. However, the average temperature drop across the coil was approximately 15 to 20°F, as shown by the green arrow in Figure 7.2.

These RH values are typical for cold climates in winter, because cold air cannot hold very much moisture. As the outdoor air is heated in the home, the absolute amount of moisture does not change and the RH decreases. For reference the average outdoor temperature was 43°F (range of 20 to 57°F) with an average RH of 68% RH (range of 47 to 90% RH). The outdoor air conditions during the experiment are also shown in Figure 7.2 as orange dots.

To verify this effect, the amount of latent heat removed by the HPWH was calculated using the measured change in temperature and RH across the coil with the equations from the Psychrometric chapter in ASHRAE Fundamentals (ASHRAE 2013). The results showed that the percent of latent energy removed over the total energy removed, for a given heat pump cycle, is 0.0% +/- 1.6%. Therefore, latent energy removal was not an important factor in influencing the HPWH interaction factor observed in the Lab Homes. In environments with interior temperature conditions near the dew point, latent energy removal may be a significant factor and would further decrease the HPWH interaction factor beyond the values observed in the Lab Homes.

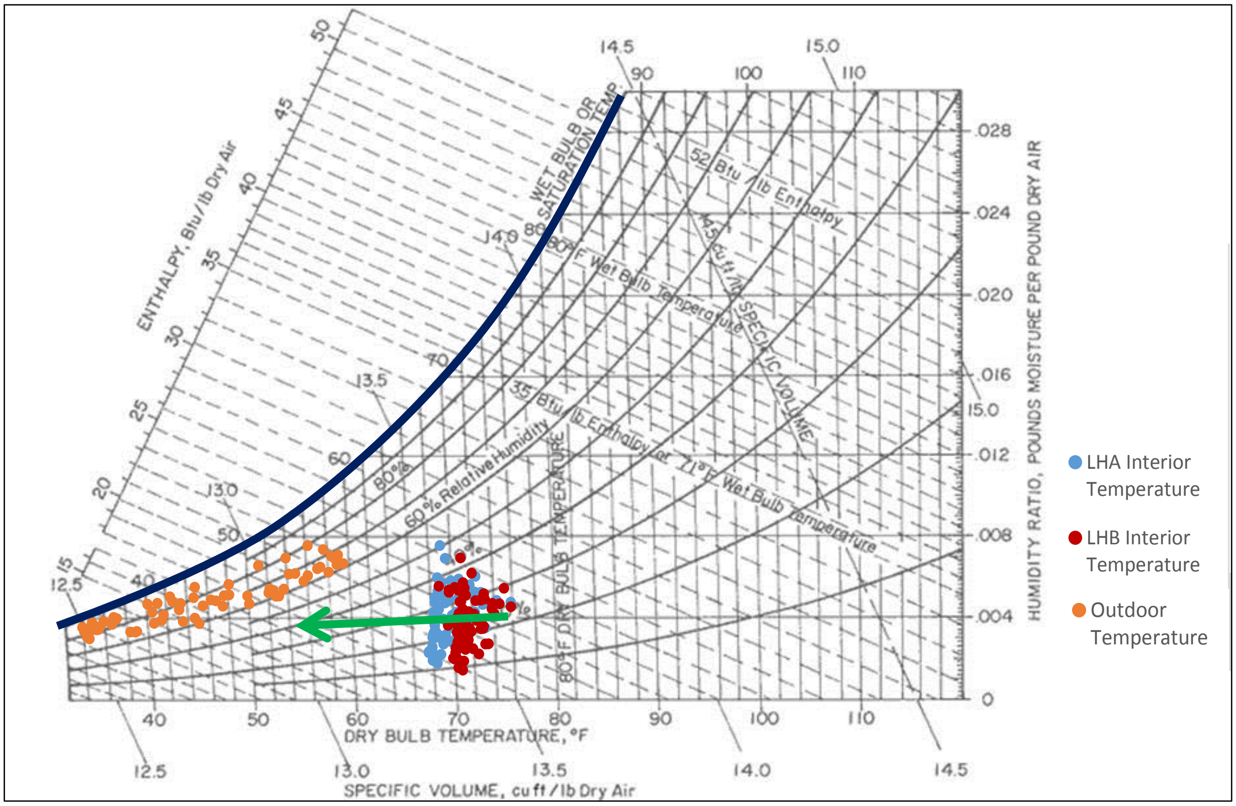


Figure 7.2. Summary of Interior and Outdoor Temperature and Relative Humidity Values during the Lab Home Experimental Period. The interior average temperature and relative humidity from the experimental data are shown as blue (Lab Home A) and red (Lab Home B) dots. The outdoor temperature and relative humidity are shown by the orange dots. The green line indicates the typical temperature drop across the coil. The saturation temperature, or dew point temperature, is shown by the dark blue line.

7.3 Localized Cooling

In addition to latent energy removal, localized cooling is a second important factor influencing the magnitude of the interaction factor. During the experiments, localized cooling was observed in each HPWH location. **Table 7.1** summarizes the average and maximum hourly temperature depression observed in each of the installation locations.

As expected, localized cooling varied based on the size of the room, presence of interior walls separating the HPWH from the thermostat, and the degree to which the HPWH is closed off. Generally, smaller locations demonstrated larger maximum and average temperature depression. However, there is not a direct relationship between the volume of the space and the magnitude of localized cooling because the relationship is confounded by other factors. In particular, localized cooling is an indication of both the size of the space, as well as the degree of coupling between the space and the main zone of the house (where the thermostat is located). For example, the presence of thermal buffers, such as interior walls and doors, between the HPWH location and the thermostat and the lack of a dedicated return in the HPWH installation location serve to further decouple the HPWH installation location from the thermostat central zone. Sustained temperature depression in spaces would be an indication of a space that is not well coupled to the thermostated zone. These factors in combination represent a quantity we are referring to as "thermal distance" that describes the degree of coupling between the HVAC system and the HPWH installation location.

Table 7.1. Summary of Average and Maximum Hourly Temperature Depression in Each Space per 24-Hour Period. Variability (±) is presented as the standard deviation among days for each experimental period.

Location	Conditioned Volume (ft^3)	Average Temperature Depression per 24 hr Period (°F)	Maximum Hourly Temperature Depression per 24 hr Period (°F)
Master Bathroom	952	13.8 ± 2.1	21.8 ± 3.0
Living Room	3197	1.7 ± 1.9	3.2 ± 2.3
Utility Room	464	2.1 ± 1.9	3.2 ± 1.8
Water Heater Closet	31*	9.9 ± 2.8	18.0 ± 5.1

(a) Transfer grill added to ensure adequate air from master bedroom

Figure 7.3 and Figure 7.4 illustrate these factors in the master bathroom and utility room.

The temperatures in the master bathroom (door closed) experiment dropped each time the HPWH cycled on. The average temperature drop was about 17°F for the long morning running cycle and then 10°F for each subsequent cycle during the day. Overall, the temperature is consistently lower than during the calibration period. This indicates that there is significant localized cooling while the HPWH is running, but also a residual temperature depression even when the HPWH is off. The graph below (Figure 7.3) shows the temperature differences for a typical day (January 20) of the experiment in the master bathroom.

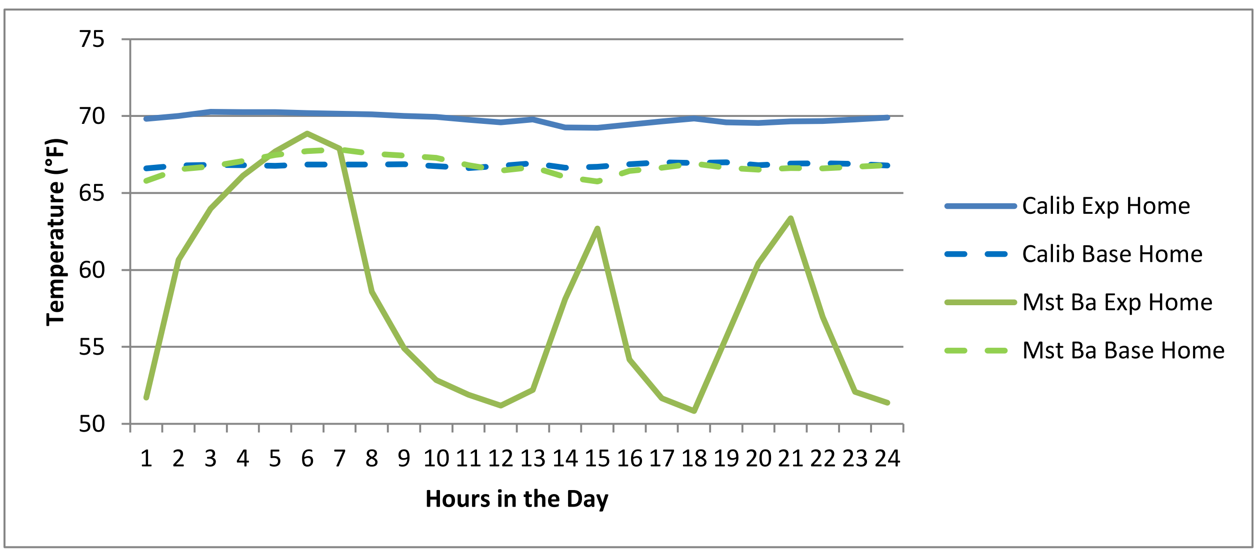


Figure 7.3. Example of Localized Cooling in the Master Bathroom

In the utility room, a similar temperature drop is observed during the long morning water draw (Figure 7.4). However, the temperature was observed to recover during periods when the HPWH was not operating. This is readily explained by recognizing that the utility closet is where the duct return grill is located. All the air flowing through the air handler must pass through the utility room, which essentially guarantees the room temperature will not drop unless the HPWH is running. Even so, the utility room *average* temperature is less than the baseline case and, with its exterior wall area, suggests the house heating load should decrease slightly during this experiment.

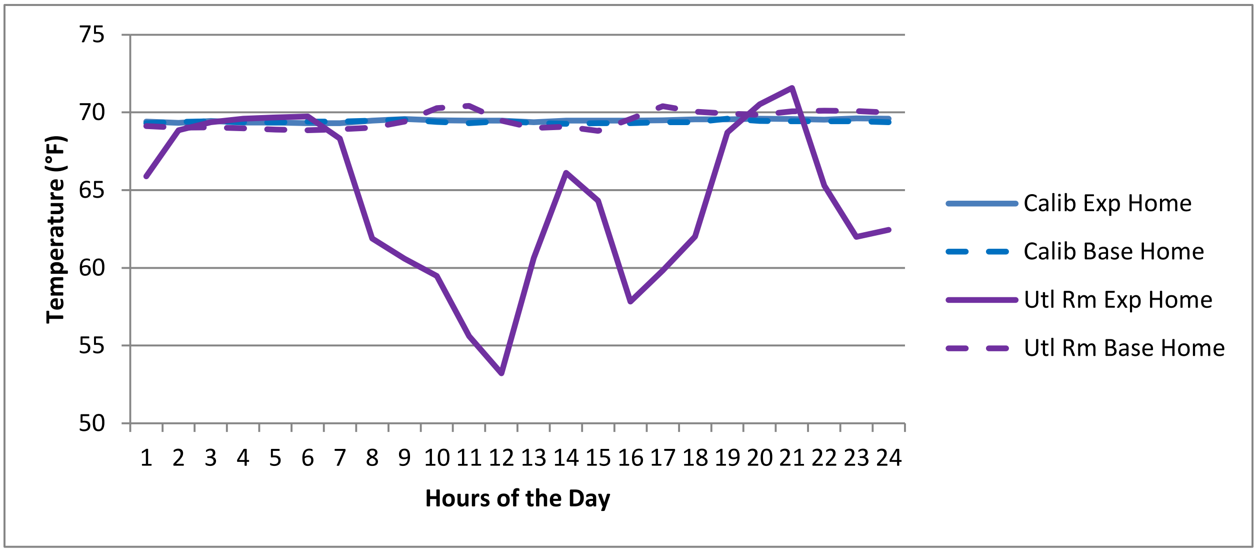


Figure 7.4. Example of Localized Cooling in the Utility Room

Figure 7.5 helps to visualize how the localized cooling would affect the comfort in the home. The images do not depict real temperature distributions taken during the experiment, but do depict a general sense of the localized cooling, and in the case of the utility room, wide spread overheating.

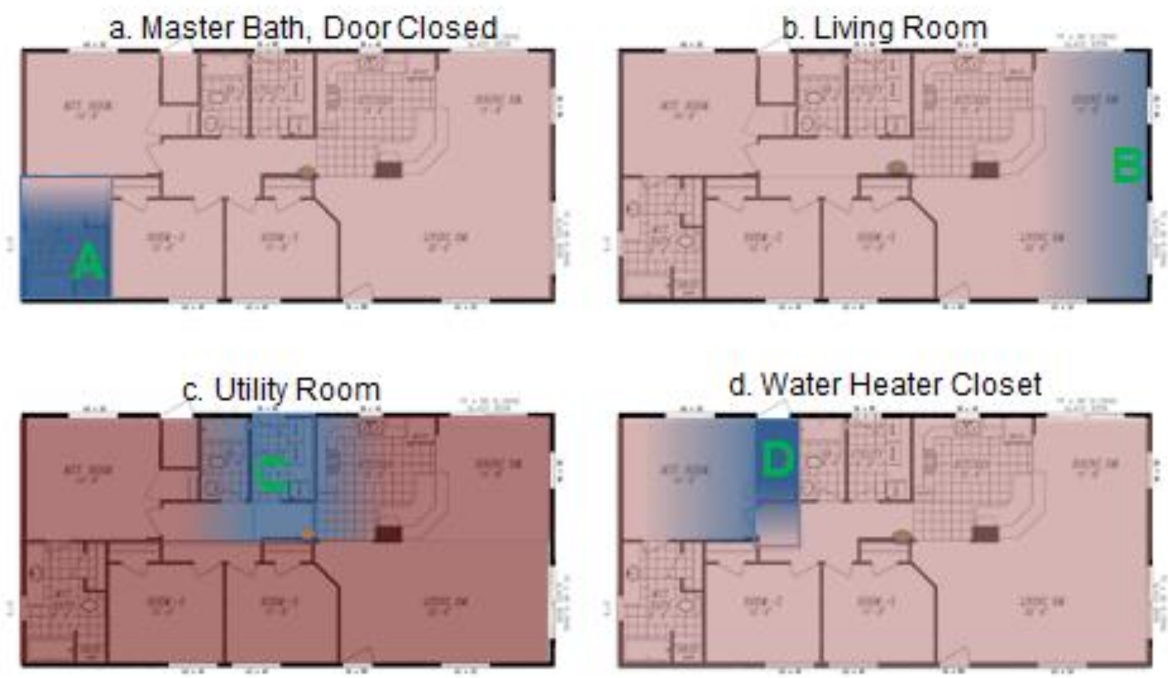


Figure 7.5. Visualization of Localized Cooling and Heating Depending on Installation Location (darker blue indicates relatively colder temperatures, and darker red, indicated relatively warmer temperatures)

7.4 Solar Impacts

As discussed in Section 3, solar insolation can also influence the HPWH interaction factor. When the sun increases the thermal gains such that the interior temperature drifts off set point, the HPWH is able to use some of the heat and turn otherwise not useful gains into useful solar gains. By decreasing the overheating of the home, this should also decrease the HPWH interaction factor compared to cloudy days. Figure 7.5 illustrates this effect during one sunny day when the HPWH was located in the utility room of Lab Home B (February 4, 2017). As shown in Figure 7.5, as the sun's intensity increases, the HVAC system turns off in both homes at the same time (~11 AM). The house interior temperature floats off of set point during mid-day. However, because the HPWH is running concurrently, some of the solar gains are harvested to heat the water and the amount the temperature drifts off set point is decreased (~2°F). As a result, the HVAC system turns on sooner in Lab Home B than in Lab Home A.

Conversely, the energy use results for a comparable cloudy day when the HPWH was also installed in the utility room in Lab Home B are shown in Figure 7.6 (February 5, 2017). On this day, the HVAC systems in both homes operated consistently throughout the day and the temperatures remained near set point in both homes with no significant difference between them.

While these charts are illustrative, the impact was similar on other days and in other experiments. In particular, the presence of a HPWH was observed to decrease the amount of temperature overshoot by approximately 2°F. In addition, the HPWH interaction factor was observed to be approximately 30 to 40% less, on average, on sunny days than on cloudy days for all experimental periods.

One would expect the extent of solar insolation to vary among locations. That is, some HPWH installation locations, such as the living room, would experience the greatest influence from solar gains. Other locations, such as the master bathroom and water heater closet, have limited window exposure and do not experience the impact of excess solar gains as strongly. One would, therefore, expect the HPWH interaction factor to be more significantly influenced (lowered) in high-solar-gain locations than in low-solar-gain locations. However, due to limited data, it was not possible to quantify the relative change in HPWH interaction factor by experiment. Although the data were limited, they suggest that the low-solar-gain locations are just as strongly influenced as the high-solar-gain locations. This may be due to mixing caused by the air handler (when it is on). In addition, it is worth noting that the HPWH interaction factor is influenced by a number of factors, as discussed previously, and the relative comparison of sunny and cloudy days in some locations may be confounded by other factors.

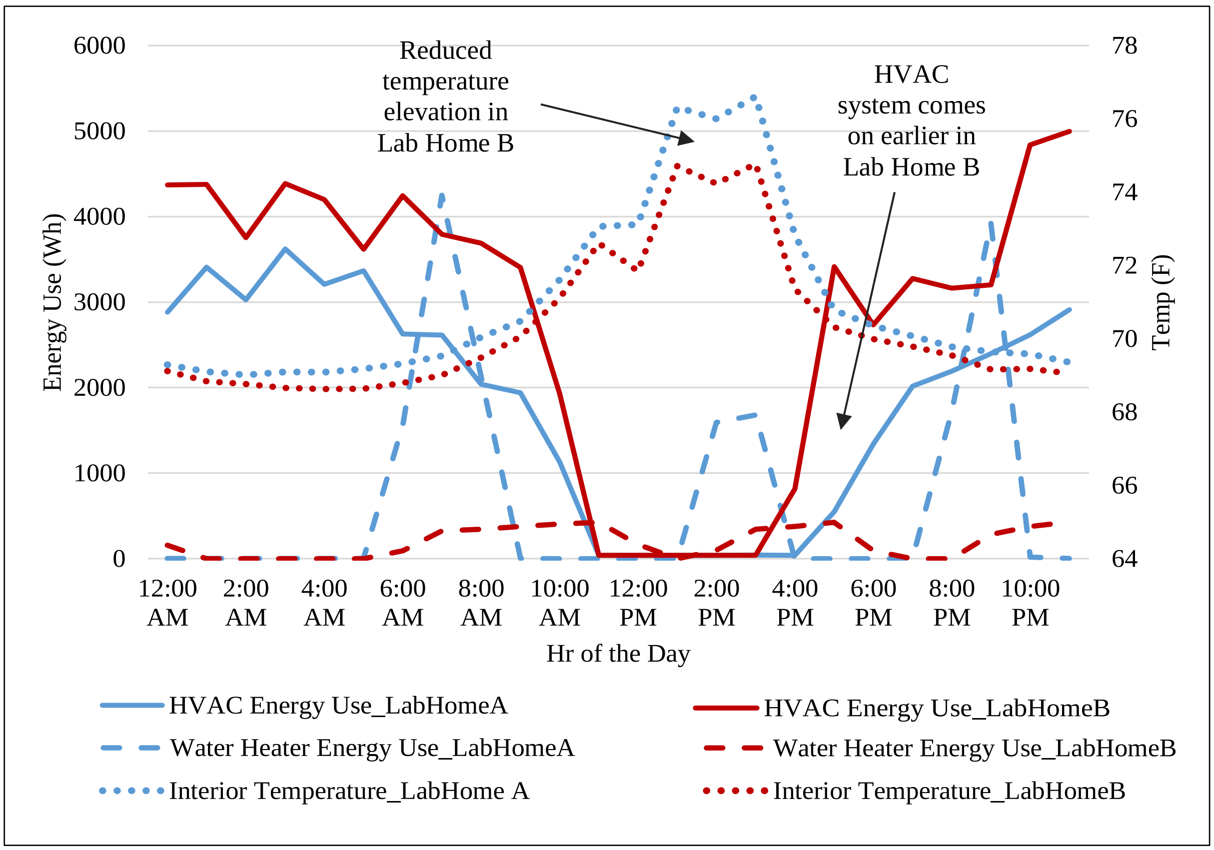


Figure 7.5. Sunny Day HVAC and Water Heater Energy Use, as Well as Interior Temperatures When the HPWH Was in the Lab Home B Utility Room (February 4, 2017)

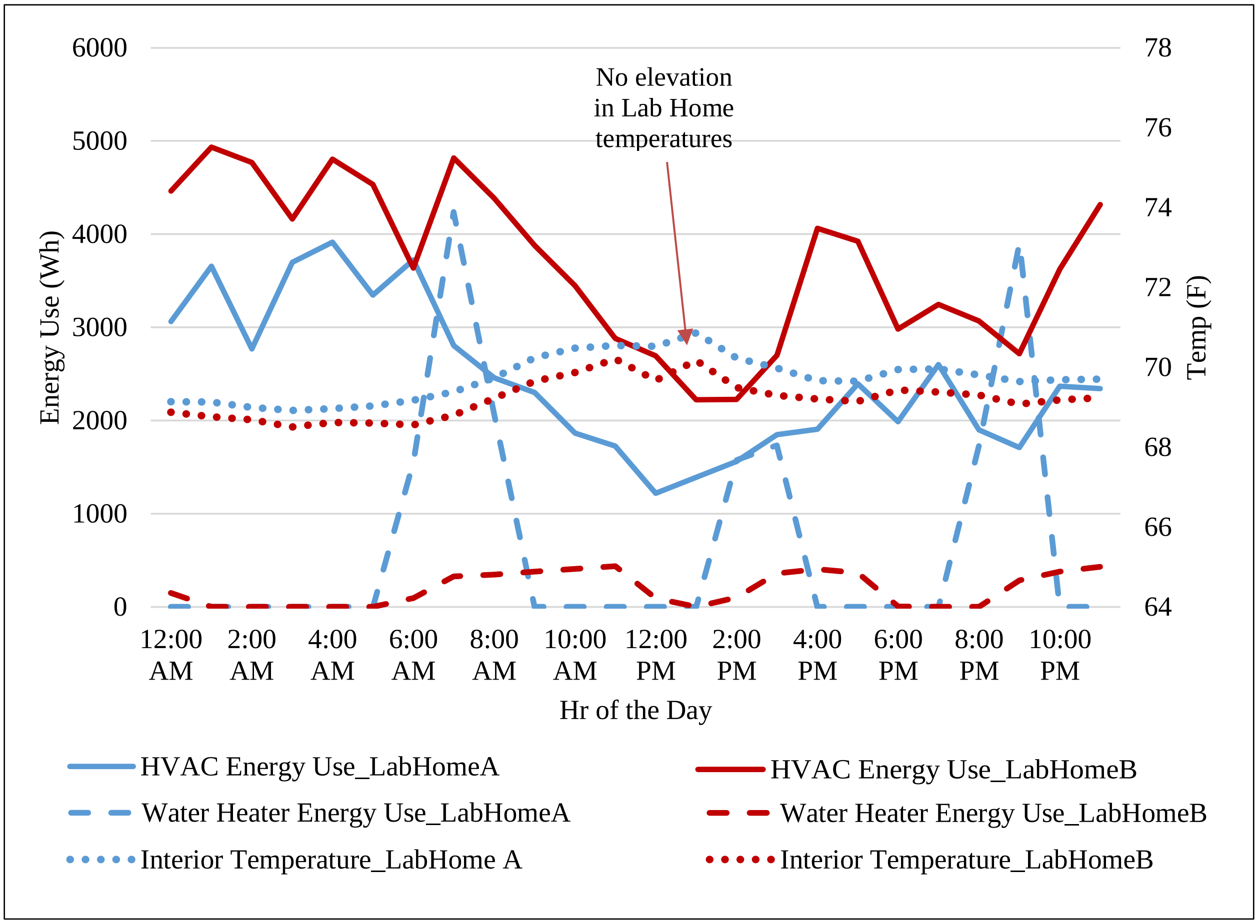
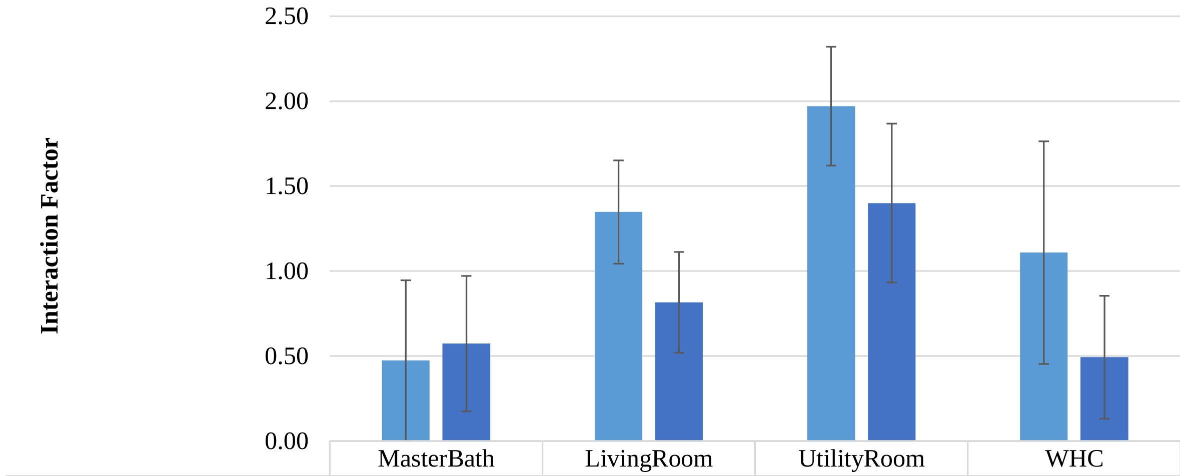


Figure 7.6. Cloudy Day HVAC and Water Heater Energy Use, as Well as Interior Temperatures (February 5, 2017) When the HPWH Was in the Lab Home B Utility Room

7.5 Absolute Interaction Factors

As discussed in Section 7.1, the HPWH interaction factor was observed to vary based on the installation location. Based on the thermal adjustment method and the linear regression method discussed previously (see Section 6.2.2), the absolute interaction factors varied from approximately 0.5 to 1.4, as shown in Figure 7.7. The authors believe that the linear regression method yields more reasonable results, but the results generated with the thermal adjustment method are shown for comparison and to verify the trends observed with the linear regression approach.

The master bathroom exhibits an interaction factor of 0.57, based on the linear regression method. The master bathroom is the farthest from the thermostat (in terms of absolute distance), is a small space, and is also fairly thermally isolated, as is illustrated by the sustained temperature depression of ~14°F (as discussed in Section 7.3). Localized cooling is the most significant factor influencing the low HPWH interaction factor in this case, which is an indicator of the relatively large “thermal distance” between the thermostat and this space. The master bathroom has only one small window (on the east side of the home) and, therefore, is not strongly influenced by direct solar gains, although the data indicate that some excess solar energy is getting to the HPWH, possibly from the adjacent master bedroom, and decreases the HPWH interaction factor on sunny days even in this low-solar-gain location.



	MasterBath	LivingRoom	UtilityRoom	WHC
Thermal Adjustment Method	0.47	1.35	1.97	1.11
Linear Regression Method	0.57	0.82	1.40	0.49

Figure 7.7. Absolute Interaction Factors for Experiments in the PNNL Lab Homes

The living room was selected as a location within the home that has strong coupling to the thermostat, because it is located in the central zone. Not surprisingly, the living room exhibited a fairly high HPWH interaction factor of 0.82 based on the linear regression method, meaning that most of the energy removed by the HPWH was made up by the HVAC system. The living room did not exhibit strong localized cooling, due to the size of the space. As such, the HPWH interaction factor is primarily influenced by excess solar gains in this high-solar-gain location. The majority of experimental days with the HPWH in the living room were cloudy, which may indicate that the reported HPWH interaction factor is slightly higher than would be expected on sunny days. Extrapolating the aggregate solar impact from Section 7.4 of 30–40%, one might expect an interaction factor of ~0.55 on sunny days, but this was not evaluated in the experiment.

As discussed previously, the utility room exhibits the highest interaction factor, an interaction factor of 1.40. The utility room represents a very well-coupled space, because the air handler and central return are located in the utility room. In addition, the utility room is closest to the thermostat (directly across the hall), such that the thermostat was influenced by some of the localized cooling occurring around the water heater. In this extremely coupled installation location, an interaction factor larger than 1.0 is not surprising. Because of the proximity of the HPWH to the thermostat, the local cooling is constantly signaling the thermostat to call for heat, which causes the outer zone house temperatures to rise, essentially overheating the home and increasing the house heat loss rate. Because of the increased heat loss, the interaction factor shows a value greater than 1.

Finally, the water heater closet exhibited the lowest HPWH interaction factor of 0.49 based on the linear regression method. The water heater closet is the smallest space and experiences a significant amount of localized cooling, both on a temporary and a sustained basis. In addition, the average temperature in the water heater closet is typically 1–2°F cooler than the average temperature of the conditioned spaces, even in the baseline home without a HPWH operating. This indicates that the water heater closet is not very well coupled to the conditioned space and the thermostat. Although a sufficient number of grates are installed in the water heater closet wall to allow for free air movement, there are no supply or return registers in the space, which may be the reason for the decreased thermal coupling in this case. It is also worth noting the that 0.49 HPWH interaction factor determined in this experiment agrees well with the interaction factor of 0.43 ± 0.12 found in the previous PNNL Lab Homes study (Widder et al. 2014).

7.6 Space Heater Experimental Results

As discussed previously, this experiment also expanded the findings related to the HPWH as a cooling point source load to examine the interaction of point source internal loads more generally. Specifically, the study also evaluated the interaction factor for a point source heating load for a limited number of spaces (one close to the thermostat and one far from the thermostat). The experiments simulated this load with an electric-resistance space heater, although such a load could represent many internal gains, such as lighting, appliances, and other miscellaneous electric loads.

Because the space heater is a purely resistive load, the theoretical load imparted to the space by the space heater can be calculated directly based on the measured energy used by the space heater. The interaction factor for the space heater experiments can then be calculated directly by comparing the measured space heater energy use to the adjusted difference in HVAC energy use (using both the thermal adjustment and linear regression calibration approaches previously discussed in Section 6.2.2). The results of the space heater experiments are presented in **Table 7.1**, in comparison to the HPWH experimental results.

Table 7.2. Summary of Interaction Factor Results for HPWH and Space Heater Experiments

Calibration Method	Location	HPWH Interaction Factor	Space Heater Interaction Factor	Space Heater Interaction Factor Normalized with Respect to Load
Thermal Adjustment	Master Bathroom	0.47	0.42	0.71
	Living Room	1.35	0.94	1.61
Linear Regression	Master Bathroom	0.57	0.34	0.58
	Living Room	0.82	0.46	0.78

As the table indicates, the master bathroom experiment, with an average adjusted HVAC energy difference of 8,474 Wh +/- 3,908 Wh, demonstrated an interaction factor of 0.42 when calculated based on the thermal adjustment method and 0.34 when determined using the regression approach. The low interaction factor observed in the master bathroom is explained by the increased temperature in that space during the experiment. Notably, the master bathroom exhibited localized heating of 30°F in the small and thermally distant space. This resulted in significantly increased thermal losses through the building envelope relative to the baseline condition and mitigates some of the "benefit" imparted by the space heater. That is, not every unit of heat added by the space heater in the bedroom is useful throughout the entire house. This is similar to the "localized" cooling phenomenon discussed with respect to the HPWH experiments and is indicative of the degree of thermal coupling between the experimental location and the thermostat.

For the living room experiment, with an average adjusted HVAC energy difference of 22,063 Wh +/- 4,696 Wh, the interaction factor was 0.94 when calculated based on the thermal adjustment method and 0.46 when determined using the regression approach. For the living room experiment, similar to the HPWH, limited localized temperature change was observed (the weighted average interior temperature was within 0.1°F of each other and the thermostat). As a result, the space conditioning system more directly sensed and benefited from the additional heating source.

Comparing the space heater interaction factor results to the HPWH interaction factor results, the space heater interaction factors appear to be slightly lower than the master bedroom interaction factors for the same location and calibration approach, as shown in Figure 7.8. The space heater imparted a point source load of approximately 18 kWh/day, while the HPWH imparted a load of only 10.5 kWh/day, on average; approximately 58% of the space heater load.

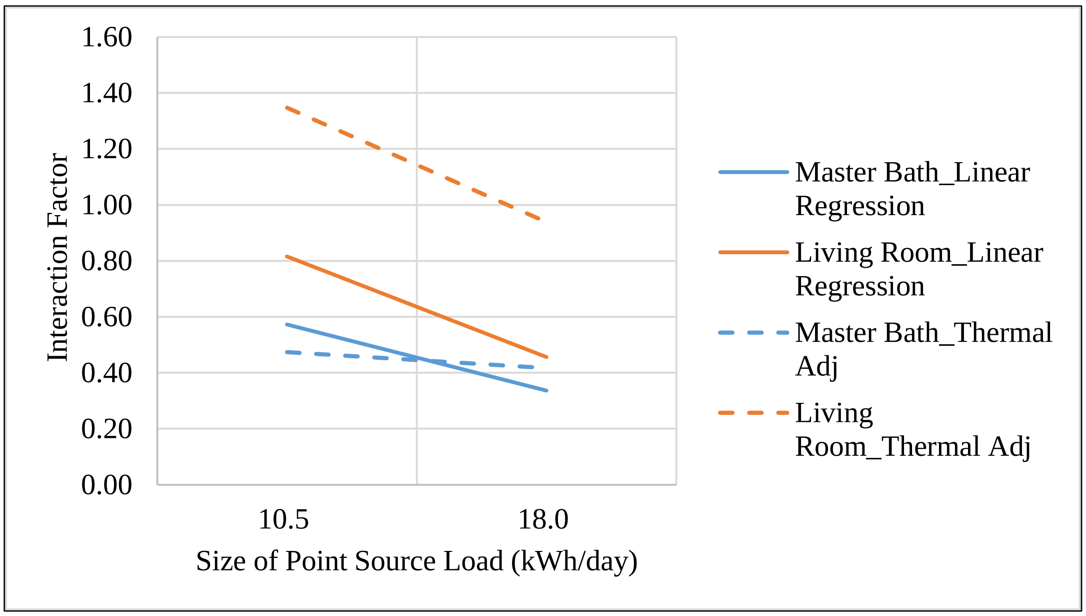


Figure 7.8. Interaction Factor in Master Bathroom and Living Room as a Function of Point Source Load Magnitude (Wh/day) for Both Thermal Adjustment and Linear Regression Approaches

Normalizing the calculated interaction factor, with respect to load, results in interaction factors that agree very well with the values determined for the HPWH experiment, as shown in **Table 7.2**. This indicates that the interaction factor may also vary based on the size of the load. For example, the linear regression approach yields interaction factors of 0.58 and 0.71 for the master bathroom and living room, respectively, compared to 0.57 and 0.82 for the HPWH experiment.[1]

[1] Based on the thermal regression approach, the normalized interaction factors are 0.71 and 1.61 for the master bathroom and living room, respectively, which are slightly higher than the values obtained from the HPWH experiment. However, as discussed previously, the linear regression method is believed to generate more reasonable results.

This can be explained by the fact that the degree of localized temperature change (cooling or heating) will be a function of both the amount of thermal distance between the space and the thermostat, as well as the size of the load. For example, with the larger space heater load, the localized heating in the master bathroom was 31°F compared to the maximum localized cooling of 18°F for the HPWH experiment. It is interesting to note that the degree of localized temperature change (18°F for the HPWH and 30°F for the space heater) is directly related to the size of the point source load, as shown in **Table 7.3**.

Normalizing the interaction factor results by the greatest interaction (the living room in this case), the "relative" interaction factor is 0.35 or 0.74 for the master bathroom (based on the thermal adjustment or linear regression calibration methods, respectively) and 1.0 for the living room. These relative results are slightly higher than the relative results observed in the HPWH experiment, but they are normalized to the living room, whereas the HPWH experiment found the utility room to have the greatest interaction. Assuming the relative interaction observed in the HPWH experiment is correct for the living room (0.68 or 0.58 based on the two calibration methods), the relative interaction factor for the master bathroom is 0.30 or 0.43 for the thermal adjustment and linear regression calibration approaches, respectively, compared to 0.24 and 0.41 for the HPWH experiments.

Table 7.3. Relative Size of Point Source Load (kWh/day) and Maximum Localized Temperature Change (°F) for HPWH and Space Heater Experiments

Point Source Load	Size of Point Source Load (kWh/day)	Relative Size of Load	Maximum Localized Temperature Change (°F)	Relative Localized Temperature Change
HPWH	10.5 kWh/day	0.58	18.3	0.59
Space Heater	18.0 kWh/day	1.00	31.0	1.00

It is worth noting that it is expected that the cooling and heating interaction factors agree for the space heater and HPWH experiments conducted in the Lab Homes, because localized temperature change and "thermal distance" appeared to be the dominant factors driving the interaction factor in both experiments. As previously discussed, latent heat removal was not a significant factor and excess solar gains, while observed during the experiment, did not appear to significantly affect the interaction factor value. The localized temperature change is especially determinant in the relative interaction factor among the tested locations, because solar gains were observed to influence all spaces similarly based on these data. Latent heat removal, while not evaluated, would also not be expected to vary greatly among conditioned spaces within a home, with exception of semi-conditioned spaces, such as basements, that regularly experience cooler and more humid conditions than the remainder of the conditioned space.

8. Conclusions

Previous experiments have indicated that the space conditioning system may not make up 100% of the theoretical amount of energy removed from the air to heat the water (Widder et al. 2014; Ecotope 2015). However, only limited data exist to describe the range of interaction factor values we would expect to observe in the field and the theoretical basis for such a reduced interaction.

This report defines the "interaction factor," as a ratio of the actual space conditioning system interaction over the theoretical energy impact on the space imparted by the point source load. The interaction factor can be less than 1.0 because of three primary factors: 1) removal of latent energy that does not affect the dry-bulb temperature in the same; 2) localized cooling, which is an indicator of the connection or "thermal distance"[1] between the location of the load and the thermostat; and 3) the conversion of excess solar gains to useful solar gains. Some or all of these factors may influence the interaction factor based on the type of point source load (heating or cooling) and the season (heating or cooling).

This experiment evaluated these dynamic interactions for both a HPWH (cooling load) and a space heater (heating load) in the heating season to determine representative interaction factors for a range of typical spaces throughout the home where such loads might be installed. The results of this experiment verified that the incremental energy use of the space conditioning system varies depending on the location of the point source thermal load in the home. That is, for a point source cooling load, like a HPWH, the space conditioning system energy use increased as the load was moved closer to the thermostat. Similarly, as a point source heating load was moved closer to the thermostat, the heating energy decreased. The interaction factor results for each location in the PNNL Lab Homes are shown in **Table 8.2**.

[1] As defined previously, "thermal distance" is influenced both of physical distance from the thermostat as well as presence of thermal buffers or barriers that impede heat transfer and air flow between the location and the thermostat, such as walls and doors.

Table 8.1. Summary of Internal Point Source Interaction Factors for Different Locations throughout the Home Based on the Linear Regression Method (Thermal Adjustment Method Results in Parentheses)

Thermal Location	Point Source Load	Farthest from Thermostat	Closest to Thermostat	Most Distributed	Least Distributed
Actual Location		*Master Bathroom*	*Living Room*	*Utility Room (where air handler is located)*	*Water Heater Closet (no direct supply or return air duct)*
Relative Interaction Factor	Cooling	0.41 (0.24)	0.58 (0.68)	1.00 (1.00)	0.35 (0.56)
	Heating	0.43 (0.30)	*0.58 (0.68)*[a]	NA	NA
Interaction Factor	Cooling	0.57 (0.57)	0.82 (1.35)	1.40 (1.97)	0.47 (1.11)
	Heating[b]	0.58 (0.71)	0.78 (1.61)	NA	NA

(a) Based on HPWH experimental results.
(b) Normalized with respect to load; presented for same size load as cooling load.

For the PNNL Lab Homes in the heating season, the impact of point source cooling and heating loads was similar when normalized with respect to the size of the load. This indicates that the thermal distance of the load from the thermostat was the dominant factor in determining the degree to which the load "interacted" with the space conditioning system. While, theoretically, the cooling load may have less interaction because of the potential for latent heat removal, which is not sensed by the thermostat, latent heat removal was not a significant factor in the relatively dry interior conditions that exist during the heating season. The impact of excess solar was observed to reduce the interaction factor approximately 30–40% overall and appeared to affect all experimental locations regardless of the direct solar gains experienced in the space, although the data were limited and these results are inconclusive. This would not be a factor for the heating load; therefore, the interaction of the cooling load with the heating system may be expected to be slightly lower than for a heating point source load.

8.1 Applications and Future Work

This work evaluated the interaction factors for heating and cooling point source loads in the heating season in four locations in the PNNL Lab Homes. An important next step for this work is to evaluate the impact of the interaction factors observed in this study on regional and national estimates of energy savings from HPWHs installed in conditioned spaces. Determining these population-level impacts and applying these results to a variety of different installation locations and homes is best and most efficiently accomplished by detailed energy simulations, that rely on experimental results such as these as inputs to and calibration points for the model.

Therefore, to apply these results to the population of HPWHs in the field, one needs to interpret them to determine the representative interaction factor for heating and cooling point source loads during both heating and cooling seasons, for a variety of representative installation locations. Current hourly simulation programs, such as SEEM and EnergyPlus, are designed to account for the impact of solar gains. Simulations can also be designed to account for latent heat removal based on theoretical enthalpy calculations across the simulated HPWH coil, which can be calibrated based on existing laboratory performance data for HPWHs (e.g., NREL/NEEA). However these simulations assume a single, well-mixed zone. This assumption misses the variation in “thermal distance” among spaces throughout the home, which was the dominant factor driving the interaction factor observed in this study. Results from this study regarding the interaction factor for several locations with various “thermal distances” can be used to estimate the “thermal distance” interaction factor for several typical water heater installation locations. While this work only evaluated interaction factors in the heating season, the results could be used to estimate interaction factors for the cooling season, based on the fundamental contributing phenomena. Future work could verify the interaction factors in the cooling season experimentally and validate any modeling results.

Therefore, based on the solar gains framework in existing energy models, latent energy removal that has been validated based on laboratory test results (as applicable), and the results of this study, existing single-zone energy models can be “calibrated” or modified to accurately account for the interaction of point source loads in various locations throughout a home. Specifically, the impact of point source cooling loads on solar gains in the simulation can be verified based on the PNNL Lab Homes results found in this study. The latent removal of a cooling load can be verified based on existing laboratory results to ensure the simulation is accurately accounting for these impacts. In addition, the “thermal distance” of different zones within the home can be approximated based on a “thermal distance” interaction factor that describes the portion of energy introduced by the load that is sensed by the space conditioning system based on the thermal distance between the space and the thermostat alone. We note that the “thermal distance is likely influenced not only by distance itself, but also by the number of intervening surfaces and the barriers to free airflow relative to the thermostat location. This modeling framework is summarized in **Table 8.2**.

Based on such a calibrated model, we can estimate the impact on HPWH savings, or the impact of other point source loads across populations of homes with various installation locations and climates.

Table 8.2. Summary of Simulation Evaluation Framework and Validation Source for Future Population Modeling Studies

Season	Load	Factor	Validation Source
Heating	Cooling	Latent Removal	NREL/NEEA Experimental Evaluations/Simulation
		Thermal Distance	**PNNL Lab Homes Study (HPWH)**
		Excess Solar Gains	Simulation (calibrated based on PNNL Lab Homes Study)
	Heating	Latent Removal	NA
		Thermal Distance	**PNNL Lab Homes**

			Study (Space Heater)
		Excess Solar Gains	NA
Cooling	Cooling	Latent Removal	NREL/NEEA Experimental Evaluations/Simulation
		Thermal Distance	***PNNL Lab Homes Study (Space Heater)***[a]
		Excess Solar Gains	Simulation
	Heating	Latent Removal	NA
		Thermal Distance	***PNNL Lab Homes Study (HPWH)****
		Excess Solar Gains	NA

(a) While not evaluated directly, a cooling load during the cooling season would be expected to act similarly to a heating load in the heating season with respect to the thermal distance and resultant temperature change in the space. Future experimental work could verify this result.

NREL = National Renewable Energy Laboratory; NEEA = Northwest Energy Efficiency Alliance

8.2 Lessons Learned

In addition to the primary interaction factor results described above, the research team had a number of observations and lessons learned related to conducting the experiment that may be useful for future researchers. These lessons learned included the following:

- The hot water temperature measurement should have been taken close to the exit of the water heater. This would have allowed a direct measurement of the hot water temperature with no adjustments required.
- A high precision manufacturing needle valve worked well to accurately maintain water flows at 1.5 gpm. Previously we have used both a gate and a ball valve to fine-tune the flow rate, but had only had temporary success because as both the ball and gate valve allowed the flow rate to fluctuate due to inaccuracy within the equipment. However, the needle valve is prone to clog if there is any type of blockage within the water lines. This was observed during experiment when the HPWHs were moved from inside the Lab Homes, to the water heater closet, when copper shavings were entrained in the domestic hot water lines. Both the control solenoid and needle had to be removed from the system, cleaned of the copper shavings, and reinstalled. This could be prevented in the future by removing the needle valve directly after a new location installation, and flushing the lines. PEX piping could also be used instead of copper, which would likely be faster to install and mitigate the issue with copper shavings.
- It is important to verify interior temperature profiles as well as HVAC energy consumption during the baseline period. While the HVAC energy consumption appeared to be extremely consistent during the baseline period and both thermostats were set to maintain identical temperatures, subsequent analysis showed that the temperature profiles in Lab Home B were slightly warmer than Lab Home A, which had to be accounted for in the analysis.
- Using standard HPWH equipment installed on rolling dolly carts worked well to enable collection of data that was both (a) representative of market-available equipment and (b) consistent home-to-home and in different locations throughout the home.

- The location of the thermocouple measuring the supply air temperature to the HPWH was located too close to the exhaust air stream, such that it was influenced by the cool exhaust air and did not accurately capture the supply air temperature. In future experiments, the thermocouple could be located closer to the supply air grille and/or shielded from the exhaust air stream.

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