To Duct or Not to Duct: Evaluating the Space Conditioning Impacts of Heat Pump Water Heaters in the PNNL Lab Homes

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ABSTRACT

Heat pump water heaters (HPWH) are a promising technology for substantially reducing water heating-related energy use in the residential sector. However, concerns have been raised regarding the impact of HPWHs on space conditioning energy when installed in conditioned space, primarily in northern climates. For example, the Northwest Energy Efficiency Alliance (NEEA's) Northern Climate HPWH Specification, which describes the performance criteria a HPWH must have to be incentivized in cold climates in the Pacific Northwest, requires exhaust ducting for their Tier II-specified products and both supply and exhaust ducting for the Tier III-specified product (NEEA 2013). However, these concerns and installation recommendations are based on modeling, and comparative field data are not available to verify modeled performance. This study examines the overall performance and operation of two HPWHs in conditioned space in the matched pair of PNNL Lab Homes[1] with no ducting, exhaust ducting, and full ducting (supply and exhaust), and it explores the interactions between the HPWH and the home's heating/cooling system. The data collected in this field evaluation suggest that previous modeling may not completely characterize the complex interactions of HPWHs, HVAC systems, and ducting. This report discusses the impact on space conditioning and water heater energy use when configuring an HPWH with exhaust only ducting or full ducting, as compared to an unducted HPWH. Additional cost analysis is necessary to assess the cost effectiveness of ducting and to make formal recommendations regarding appropriate installation of HPWHs in more varied scenarios.

Introduction

Water heating represents approximately 18% of residential energy consumption, or 4.86 Quads of source energy use annually (EIA 2009), thus efficient water heater options are necessary to achieve significant energy savings in the residential sector. Heat pump water heaters (HPWHs) offer a relatively low cost and efficient option for the 41% of homes with electrically heated water heaters, with a theoretical energy savings of up to 63%.[2] Previous research has

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[1] http://labhomes.pnnl.gov
[2] Based on the DOE test procedure (10 CFR 4310.32(d)) and comparison of an electric tank water heater (Energy Factor, EF = 0.90) versus a heat pump hot water heater (EF = 2.4).

demonstrated the laboratory performance of HPWHs and has shown considerable savings of 47 to 63% are possible, based on standardized testing protocols (Larson, Logsdon, and Baylon 2011).[3]

The HPWH is the largest savings measure in the residential sector in the Northwest Power and Conservation Council's Sixth Northwest Power Plan at 492 average megawatts (Northwest Power and Conservation Council 2010). There is also considerable energy savings potential nationwide for HPWH technology.

However, numerous barriers must be overcome before HPWHs will reach widespread adoption in the Pacific Northwest region and nationwide, including increamental cost, reliability, consumer awareness, and familiarity of trades with the technology. One significant barrier to more aggressive energy efficiency program promotion is the interaction with the home's space conditioning system for units installed in conditioned spaces, specifically the energy savings penalty associated with the increased space heating load from the cold air exhausted from the HPWH. In an effort to limit the potential for such a space heating penalty, NEEA's Northern Climate HPWH Specification requires exhaust ducting to remove the cold air for their Tier II-specified product (NEEA 2013).[4] NEEA's Northern Climate HPWH Specification requires full ducting for a Tier III product (NEEA 2013).

The current understanding regarding the interaction of HPWHs with space conditioning and current recommendations regarding the installation of ducting in cold climate systems are based on modeling. Comparative field data are not available to verify modeling assumptions or modeled performance. This study is a field demonstration of the overall performance and operation of HPWHs in conditioned space in a number of configurations and the interactions between the HPWH and the home's heating/cooling system, as well as thermal comfort issues that could affect occupant satisfaction and market acceptance of HPWH technology. The project compares the performance of an HPWH with no ducting, exhaust ducting, and full ducting (supply and exhaust) under identical occupancy schedules and hot water draw profiles in the PNNL Lab Homes. The results of this project are independent performance data that can be applied, both regionally and nationwide, to quantify the whole-house energy impacts of installing an HPWH in a conditioned space with and without ducting.

Research Equipment and Protocol

This study evaluates the energy performance of GE's second-generation GeoSpring™ hybrid water heater in PNNL's Lab Homes. The research protocol consists of two primary experiments designed to measure the performance and impact on the Lab Home HVAC system of:

1) an HPWH configured with exhaust ducting compared to an unducted HPWH and
2) an HPWH with both supply and exhaust air ducting as compared to an unducted HPWH

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[3] Standardized testing protocols include the DOE Test Procedure for Residential Water Heaters, as well as alternative test protocols using different hot water use profiles and standardized testing conditions.

[4] NEEA incorporates three product Tiers into their Northern Climate HPWH Specification to recognize variations in product performance and supported applications. In addition to ducting configuration, the Northern Climate HPWH Specification also has noise, efficiency, and reliability requirements (NEEA 2013). There are currently only two manufacturers offering a total of five models of equipment meeting NEEA's Tier II specification and no manufacturers offered equipment certified to meet NEEA's Tier III specification (NEEA 2014).

during heating and cooling season periods.[5] Both homes deployed identical simulated occupancy and hot water use schedules so that the performance and effects of the HPWH will be isolated from all other variables.

GE Generation II GeoSpring Hybrid (Heat Pump) Water Heater

The HPWH selected for evaluation in this project is the second-generation GE GeoSpring Hybrid Water Heater (model GEH50DEEDSR). The GE GeoSpring HPWH has a nominal 50-gallon tank and two methods of heating water: a highly efficient compressor and two 4,500-Watt (W) electric elements (GE Appliances 2014a). The unit is equipped with onboard controls that dictate which heating mode is used to heat water. These modes consist of "Heat Pump," "Hybrid," "High Demand," "Standard," and "Vacation."[6] In general, different modes will use the electric elements more or less frequently to attempt to provide greater thermal comfort or maximize energy savings. For these experiments, the HPWH is operated in "Heat Pump" mode, to maximize the impact on the space conditioning system.[7]

PNNL Lab Homes

The PNNL Lab Homes are a unique platform in the PNW region for conducting experiments on residential-sector technologies. These electrically heated and cooled 1,500-ft^2 homes are sited adjacent to one another in Richland, Washington, are constructed to represent typical 1970's-era construction, and are fully instrumented with end-use metering (via a 42-circuit panel), indoor and outdoor environmental sensors, and remote data collection. The homes can be operated to simulate occupancy, and thus can evaluate and manage any occupant effects on equipment performance using the control features in the homes. The unique nature of this side-by-side comparison means the homes experience the same weather. This allows for direct comparison of an experimental treatment in the experimental home with a control scenario in the baseline home under identical environmental conditions over the same time period. The specific configuration and construction specifications of the Lab Homes have been described elsewhere (Widder et al. 2012).

Monitoring Approach

The monitoring approach included metering and system-control activities taking place at both the electrical panel and at the point-of-use. Table1 highlights the performance metric (the equipment/system being monitored), the monitoring method and/or point, the monitored variables, and the data application.

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[5] Note that HPWHs may also interact with the space conditioning systems during swing season. Heating and cooling seasons were evaluated to capture the periods of highest HVAC energy use and, potentially, the highest degree of interaction. Detailed energy models based on these results could be used to predict annual impacts without significant additional data collection.

[6] The specific control strategies employed in each of these modes are explained in detail on the GE website (GE Appliances 2014b) and have been evaluated in the laboratory by Larson and Logsdon (2012).

[7] Note that, although only the heat pump was used to heat water, limited impact on hot water deliver temperature was observed in the heating and cooling season.

Table 1. Metering strategy and equipment

Monitored Parameter	Monitoring Method/Points	Monitored Variables	Data Application
Electrical Power Measurements			
Whole House Electrical Power and Circuit Level Power HPWH Electrical Power Electric Power for HPWH Fan Power for Electric Heaters Electric Power for Air Conditioning or Heat Pump	1 Campbell data acquisition system with 42 circuit transducers (CTs) at electrical power mains and panel	kW, amps, volts	Comparison and difference calculations between homes of power profiles time-series energy use differences and savings
Temperature and Humidity Measurements			
Space Temperatures	13 ceiling-hung thermocouples/1-2 sensors per room/area, and 1 HVAC duct supply temperature per home	Temp., °F	Comparison and difference calculations between homes of: temperature profiles time-series temperature changes
Space Relative Humidity (RH)	2 relative-humidity sensors per home (main living area, hall outside of bathroom)	RH, %	Comparison and difference calculations between homes of: RH profiles time-series RH changes
Water Heater Closet Supply Air Temperature and RH	Thermocouple or thermistor directly in front of supply air grille or in duct (if ducted)	Temp., °F	Determine impact of supply air temp on HPWH performance
Return Air Temperature and RH	Thermocouple or thermistor directly in front of return air grill or in duct (if ducted)	Temp., °F RH, %	Determine HPWH temperature and humidity difference across the coil and impact of exhaust air temp and humidity on conditioned space
Water Heater Closet Air Temperature and RH	4 thermocouples equally spaced approximately 2 ft. apart to capture the vertical temperature gradient in the water heater closet	Temp., °F	Assess impact of HPWH on water heater closet and determine extent of stratification
Crawlspace Temp	Thermocouple(s) or thermistor(s) to measure temperature in at least one location (near duct inlet) and one at each end (east and west)	Temp. °F	Determine impact of crawlspace air temp on supply-ducted HPWH performance
Meteorological Measurements	Package station mounted on Lab Home B	Temp., °F Humidity, % Wind speed, m/s Wind direction Barometric pressure, mm Rainfall, inches	Analytical application to quantify setting and develop routines for application to other climate zones
Temperature Measurements			
Inlet Water Temperature	Insertion thermocouple	Temp., °F	Characterize impact of incoming water temperature on

Monitored Parameter	Monitoring Method/Points	Monitored Variables	Data Application
			HPWH performance
Outlet Water Temperature	Insertion thermocouple	Temp., °F	Monitor outlet water temperature to determine impact on delivered hot water
Tank Temperature	Thermocouple(s) on tank near upper and lower elements	Temp., °F	Monitor tank temperature
Flow Rate Measurements			
Outlet Water Flow Rate	Turbine flow meter, in line with hot water outlet prior to mixing valve	Flow rate, gpm	Verify water draws are in accordance with specified profile
Exhaust Air Flow Rate	Exhaust fan flow meter	Flow rate, cfm	Measure airflow rate from HPWH in different duct configurations

All metering was done using Campbell® Scientific data loggers and matching sensors. Two Campbell data loggers were installed in each home, one allocated to electrical measurements and one to temperature and other data collection. Technical information on the metering protocols and relevant sensors is included in prior publications (Widder et al. 2012).

HPWH Installation

Two HPWHs were installed in accordance with regional protocols developed by NEEA for the Northern Climate Specifications (NEEA 2013) and the manufacturer's installation instructions (GE Appliances 2014a). The water heater closet was modified to allow free airflow with two sets of two 25- × 20- inch metal transfer grilles into the master bedroom closet (adjacent to the water heater closet) and the hallway (adjacent to the master bedroom closet), as indicated in Figure 1. One grille was installed low on the wall and one high, to help induce mixing. Each grille area is greater than 100% of the requirement specified in the GE product literature of 240 square inches (GE Appliances 2014a).

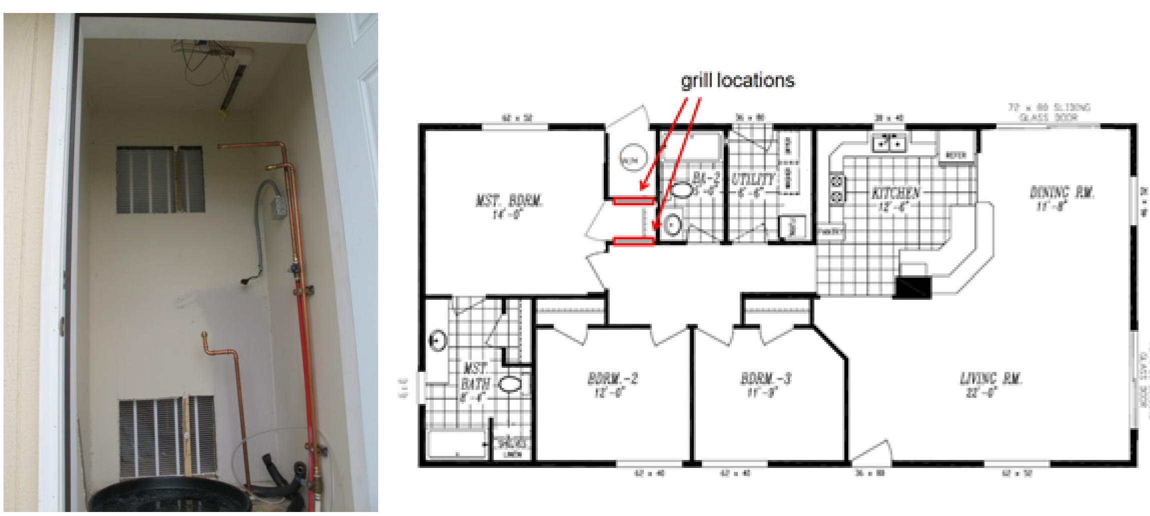

Figure 1. Location of transfer grills in the lab homes.

The water heater in Lab Home A[8] was modified for supply and/or exhaust ducting. The ducting was designed to be easily connected and disconnected based on the experiment. The design for exhaust and supply ducting was developed in coordination with the project collaborators, including GE technical staff who reviewed the proposed approach. The exhaust ducting conforms with GE patent information on exhaust ducting for a GE HPWH (Nelson et al. 2012). Off-the-shelf duct components were used to construct a 6-inch diameter exhaust duct, which connects to a shroud designed to fit over the HPWH fan housing with the HPWH cover removed.

However, due to the location of the water heater closet exterior access door, the exhaust ducting had to be configured through the exterior access door which required a longer, more circuitous exhaust ducting path to allow the door to remain operable. Because of the increased flow resistance caused by such configuration, and to overcome the additional static pressure requirements of drawing supply air, an inline 120-V, 2-speed exhaust fan was installed in the exhaust duct and wired to the HPWH compressor fan to only operate when the HPWH compressor fan is running. With 0.25-inches of static pressure, the fan is designed to deliver 163 cubic feet per minute (CFM) of air at the low speed setting and 250 CFM of air at the high speed setting.[9]

The supply ducting used a novel approach, with the airflow path coming from the top of the HPWH and drawing air from the crawlspace. A shroud was constructed that could be fastened to the top of the HPWH air intake, over the filter. An insulated 8-inch duct drops straight down from the shroud to the water heater closet floor and penetrates through the floor to the crawlspace (see Figure 2).

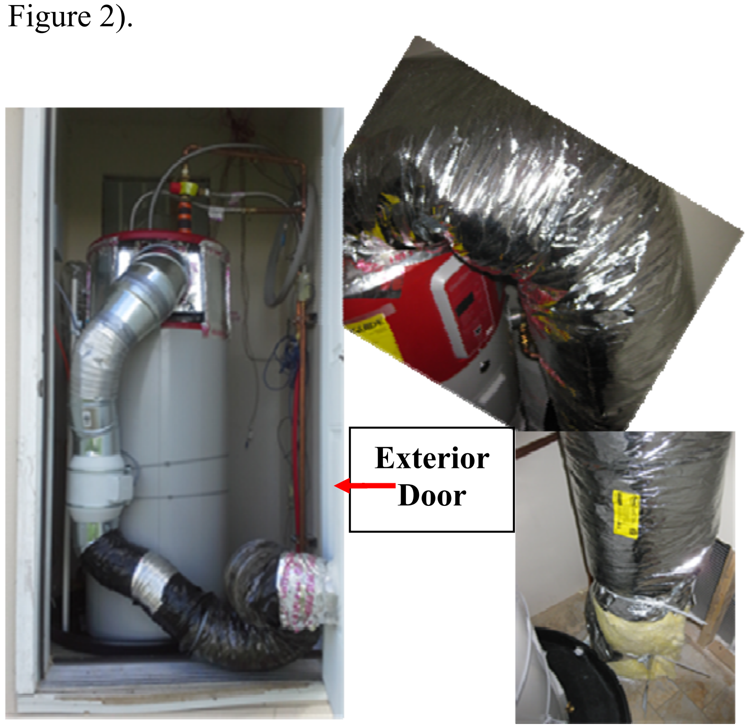

Figure 2. Left: Exhaust-only ducting approach on HPWH. Right: Supply ducting configuration on the HPWH.

[8] The water heater in Lab Home B had no ducting capability.
[9] Soler & Palau. Mixed Flow Duct Fan, 8-3/8 In. L, Ball. Specs are available through Grainger at: http://www.grainger.com/Grainger/SOLER-PALAU-Mixed-Flow-Duct-Fan-3CGA6

Occupancy Simulation

Occupancy was simulated identically in both homes via a programmable breaker panel employing motorized breakers to simulate sensible loads associated with occupancy, lighting, and equipment and appliance loads. The basis for occupancy simulation was data and analysis developed in previous residential simulation activities (Hendron and Engebrecht 2010; Christian et al. 2010). The occupancy simulations and schedules developed here were derived specific to the home style, square footage, and an assumed occupancy of three adults.

Hot Water Draw Profile

To simulate hot water draws, a modulating solenoid valve was installed at the kitchen sink hot water supply and controlled via the Campbell data acquisition system. PNNL selected a hot water draw profile that was representative of a typical daily draw pattern and was feasible to implement reliably and consistently using existing equipment in the PNNL Lab Homes. Specifically, these experiments implemented the draw profile based on the Building America House Simulation Protocols, which specify typical daily draw volumes for different appliances, based on the number of bedrooms, and an hourly draw pattern, based on fraction of total daily load (Hendron and Engebrecht 2010).[10] For this comparison of HPWH performance, PNNL elected to simulate a "high" usage profile to create a worst-case scenario to exaggerate the impact of the HPWH on the space conditioning system in each ducting experiment. Thus, for the HPWH experiment, a daily draw volume of 130 gal/day was used, drawn at 2 gallons per minute (gpm) of hot water at the tap. This draw profile was deemed a "worst case scenario" regarding the impact of HPWH space conditioning impacts and homeowner comfort, but was within the range of the daily hot water use data reported in the LBNL meta-analysis (Lutz et al. 2012). PNNL determined the hot-only portion of the 110°F water draws based on an energy balance, to define the daily flow rate of hot water only. A 125°F set point was selected for the water heaters because it is typical for a default set point of water based on the Lawrence Berkeley National Laboratory (LBNL) evaluation of field hot water use data (Lutz et al. 2012). No seasonal variation in hot water draws was implemented, although season differences in water heater energy use due to varying mains temperature was observed.

HVAC Operation

Throughout the experiment, the HVAC systems were operated identically in the two homes. In the cooling season, the 2.5-ton SEER 13 heat pumps maintain an interior set point of 76°F with no setback, as per Building America House Simulation Protocols (Hendron and Engebrecht 2010). In the heating season, the heat pumps are set to "emergency heat," to operate like electric resistance furnaces and maintain an interior set point of 71°F with no setback (Hendron and Engebrecht 2010). Operation of as an electric furnace in the heating season allows for more precise quantification of the incremental thermal load on the HVAC system resulting from the HPWH, since the efficiency of the electric resistance elements is 100% and is not a function of environmental conditions.

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[10] PNNL determined the hot-only portion of the 110°F water draws based on an energy balance, to define the daily flow rate of hot water only.

Results and Discussion

The HPWHs were baselined in March, April, and May 2013. Some difficulties were encountered maintaining equivalent water draws in both homes, resulting in a longer than expected baseline period. The cooling season data were collected between June and August 2013. Heating season performance data were collected in December 2013 and January 2014. In each season, the impact of exhaust ducting or supply and exhaust ducting (i.e., full ducting) was evaluated on HPWH energy use, HVAC energy use, and interior temperatures. The performance of the ducted water heater in Lab Home A (both exhaust ducting and fully ducted) was compared to the unducted HPWH in Lab Home B. Detailed baseline, space conditioning energy use, water heating energy use, and thermal comfort results are presented in the subsequent sections.

Baseline

Prior to initiating the experiments, the homes were extensively baselined with the water heaters operating in electric resistance and heat pump modes. The baseline is essential to providing quality data, since any variability between the homes in the baseline would be retained and possibly magnified in the experimental phase, confounding any comparative results between the homes. Fundamental home construction characteristics were verified as part of previous work, which was not repeated here (Widder et al. 2012). However, due to the potential for changes in the homes, the experiment blower door measurements were taken on both homes as part of the baseline period. Following blower door measurements, the homes went through an active null testing period, with full occupancy simulated to verify equivalent performance.

The blower door results found both the baseline home and the experimental home to have test leakage rates of 0.18 ± 0.01 air changes per hour natural (ACH_n). Null testing with full occupancy (lighting, occupant-related, appliance, and equipment sensible loads) and simulated hot water draws showed exceptionally similar whole-house energy use between the two homes, within 2.3% with a standard deviation of 3.3% (2.3 ± 3.3%) over the 7-day period of full baseline testing.

Space Conditioning Impacts of the HPWH

Regarding space conditioning impacts, the heating season and the cooling season exhibited different trends, as one would expect.

In the cooling season, both exhaust only and fully ducted scenarios led to increased HVAC energy usage as compared to the HVAC energy use with an unducted HPWH, since the supplemental space cooling from the HPWH exhaust cannot be taken advantage of. The unducted HPWH provides a space cooling benefit equivalent of approximately 1.5 kilowatt-hours per day (kWh/day) compared to both the exhaust only and fully ducted scenarios, which results in space conditioning energy savings of 9.3 ± 1.0% over exhaust only and 9.3 ± 2.2% over fully ducted scenarios, as shown in Figure 3.

In Figure 3, the HVAC energy use of Lab Home B with a HPWH in an unducted configuration is presented in blue; the HVAC energy use of the Lab Home A with a HPWH in an exhaust only ducted configuration is presented in green; and the HVAC energy use of Lab Home A with a HPWH in a fully ducted configuration is presented in red. Note in each case, the duct treatment is compared directly to an unducted control case (Lab Home B). The average difference in HVAC energy use during each experimental period is represented by the yellow diamonds, where positive values indicate increased energy use resulting from ducting (Lab Home A - Lab Home B). The difference in the HVAC energy use in Lab Home B with the unducted HPWH between exhaust only ducted comparison and the fully ducted comparison periods is due to weather differences during the two experimental periods.

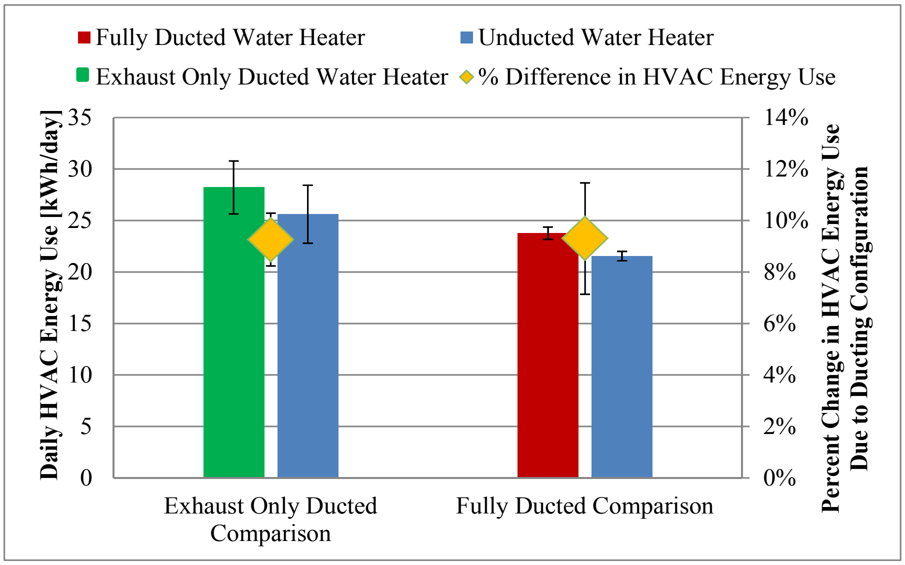

Figure 3. Daily HVAC energy use (kWh/day) and difference in HVAC energy use (%) for the exhaust only ducted comparison and the fully ducted comparison periods in the cooling season.

In the heating season, HVAC energy use in Lab Home A in the exhaust only ducted configuration increased as compared to the unducted HPWH in Lab Home B. Conversely, HVAC energy use in Lab Home A with the fully ducted HPWH decreased as compared to the unducted HPWH in Lab Home B, as shown in Figure 4. Figure 4 uses the same formatting as Figure 3.

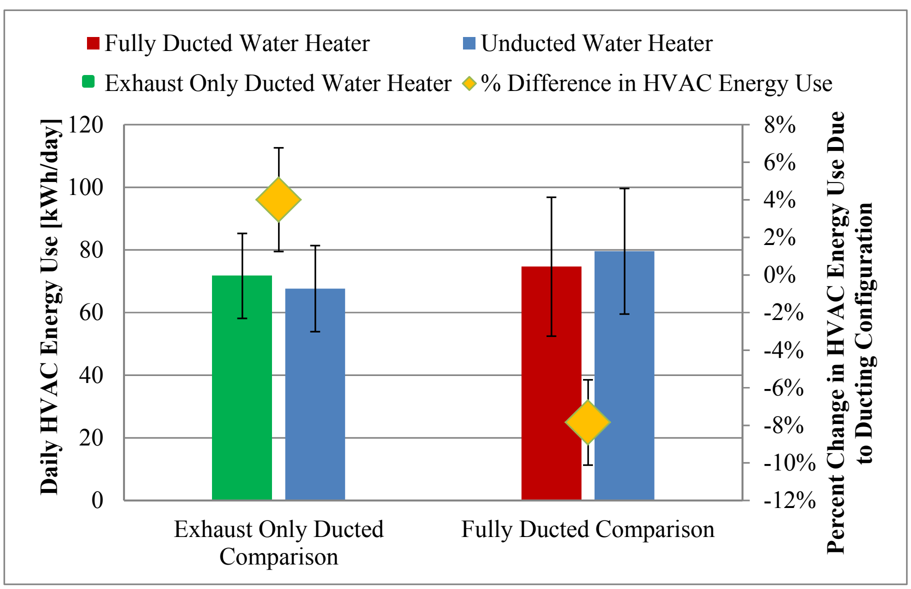

Figure 4. Daily HVAC energy use (kWh/day) and difference in HVAC energy use (%) in for the exhaust only ducted comparison and the fully ducted comparison periods in the heating season.

In Lab Home A in the exhaust only ducted configuration, the HVAC energy use increased 3.244 ± 2.5 kWh/day, or 4.0 ± 2.8%, which is converse to the expected impact of exhaust ducting. With regard to Lab Home A in the fully ducted configuration, the HVAC energy use was observed to decrease 7.8 ± 2.3% as compared to Lab Home B with an unducted HPWH, reducing HVAC space conditioning loads by 5.7 ± 1.6 kWh/day.

Models have suggested that HPWHs installed in conditioned space will increase HVAC energy use in the heating season due to the use of air that has been initially heated by the HVAC system to heat water and the introduction of cool exhaust air into the space (Larson, Hadley, and Harris 2012; Winkler and Christiansen 2012). Therefore, models assume, any heat that has been extracted from the space must be made up by the HVAC system in order to maintain interior thermostat set points. These models also have shown that exhaust ducting will mitigate the impact of HPWHs on space conditioning systems by preventing cool exhaust air from being introduced into the conditioned space (Larson, Hadley, and Harris 2012; Winkler and Christiansen 2012). However, the data collected in this experiment suggest that exhaust-only ducting did not decrease space conditioning energy use, as compared to Lab Home B with an unducted HPWH.

It is hypothesized that the exhaust-only ducting did not help mitigate the space heating penalty the home for two reasons. First, exhaust-only ducting may depressurize the conditioned space with respect to the outside, increasing infiltration and thus resulting in increased HVAC energy use to heat the outside air. In addition, the outdoor air introduced through infiltration was colder than the HPWH exhaust air temperature by, on average, 20 °F. Therefore, in the exhaust only ducting case, the HVAC system had to make up more than the thermal energy removed by the space to heat the water. This is demonstrated by the fact that exhaust only ducting, which will increase depressurization of the interior space, was observed to increase HVAC energy use. Whereas full ducting, where the HPWH is completely isolated from the conditioned space and does not impact the pressurization of the home with respect to the outdoors, showed a decrease in HVAC energy use during the heating season. This suggests that depressurization of the interior space and its resultant impacts on infiltration-related space conditioning energy use may be a significant factor when determining the space conditioning interaction of HPWHs, especially in cold climates where the outdoor air temperature is below the exhaust temperature of the HPWH for considerable portions of the year.

Second, the impact of an unducted HPWH on space conditioning loads may not be as large as models suggest. Specifically, many models assume a single, well-mixed zone such that any heat transferred to the water by the HPWH must be mostly made up by the HVAC system to return to the same thermal condition in the conditioned space. However, these experiments suggest that the relative amount of energy that must be made up by the HVAC system may be substantially less than 100%. The increased space conditioning energy use resulting from the unducted HPWH in conditioned space is determined based on the difference in HVAC energy use between Lab Home A in the fully ducted configuration and Lab Home B with the unducted HPWH. Assuming that fully ducted scenario perfectly mitigates the effects of using air heated by the HVAC system and exhausting cool air into the space, the experimental data show that approximately 43.4 ± 12.2% of the expected thermal energy contribution from the space is made up by the space in the heating season and a thermal benefit[11] of approximately 37.2 ± 4.7% is observed in the cooling season, as shown in Figure 5 (comparing the bars on the right).

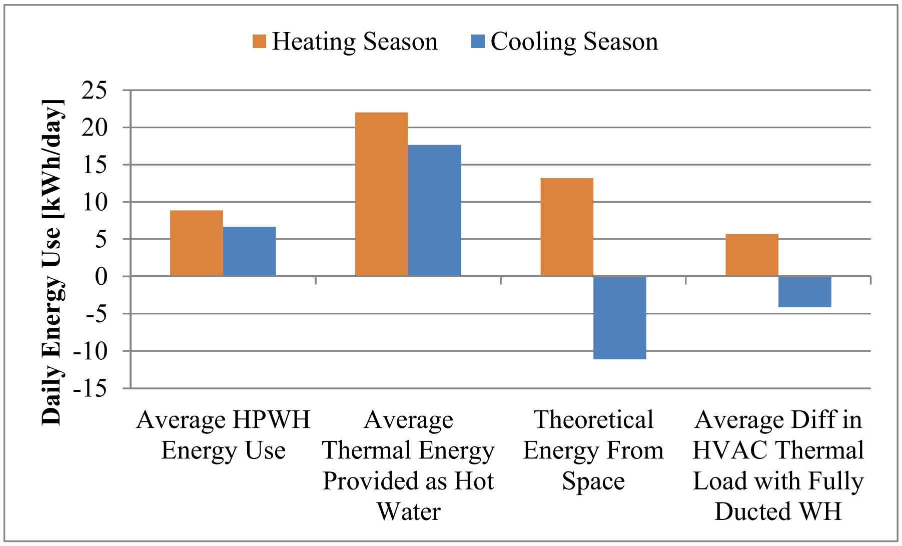

Figure 5. Comparison of: (a) average HPWH energy usage (as electricity provided to the HPWH), (b) average daily thermal energy provided as hot water, (c) average theoretical contribution to hot water thermal energy provided by the space (determined based on the difference between (a) and (b)), and (d) the average difference in (kWh/day) compared to the average increased daily HVAC energy use in Lab Home B with an unducted HPWH compared to Lab Home A with a fully ducted HPWH in the Heating Season (orange) and Cooling Season (blue). Note, the "average difference in HVAC energy use with fully ducted WH" represents an increase in HVAC energy use for the HPWH without ducting the Heating Season and a decrease in HVAC energy use associated with the unducted HPWH in the cooling season, as compared to the unducted case (Lab Home B - Lab Homes A in both cases).

The thermal energy provided as hot water is determined using the following equation:

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

Where, Q_{water} represents the energy provided to the water in kWh; V_{water} represents that the measured average daily hot water volume drawn in gallons; ρ is the density of water in pounds per gallon (8.34 lb/gal); $C_{p,water}$ is the specific heat capacity of water (1 Btu/lb °F or 0.2931 Wh/lb °F); T_{out} represents the measured outlet water temperature in °F; T_{in} represents the measured inlet water temperature in °F. This calculation was corroborated by comparing the energy provided as hot water by the HPWH to that calculated based on the measured HPWH electrical energy use and system COP and the values agreed within 2%.

It hypothesized that the measured difference in HVAC energy use is less than theoretical energy provided by the space to heat water due to buffering of the HPWH space conditioning impacts by the interior walls and the overall thermal mass of the home. For example, while the installation of exhaust ducting or full ducting did not appear to have a measurable impact on average interior temperatures in the main body of the house, the temperatures in the water heater closet were affected by approximately 5 to 8 °F (e.g. the unducted HPWH cooled the air in the closet), as shown in Table 2. However, the impact of different ducting configurations on the

[11] Note, the COP of the HPWH and the HVAC system have been accounted for in these calculations.

temperatures in other spaces in both homes was not significant. This suggests that the water heater closet may have experienced localized cooling. Since the closet is located on the perimeter, localized lower temperatures will result in a reduction in building shell losses during the heating season. It is not clear however if this is sufficient to make up for the full difference in expected heating load observed.

Table 2. Average and standard deviation of interior temperatures measured in the main body of the house and the HPWH closet temperature in the heating season and cooling season for the exhaust only ducted and fully ducted comparisons, in °F

	Exhaust Only Ducted Comparison			Fully Ducted Comparison		
Cooling Season	Exhaust Only	Unducted	Difference	Fully Ducted	Unducted	Difference
Average Interior Temperature (°F)	75.9 ± 2.1	75.5 ± 2.3	0.3 ± 3.1	74.7 ± 0.4	74.6 ± 1.0	0.1 ± 1.1
HPWH Closet Temperature (°F)	73.7 ± 1.2	68.3 ± 5.4	5.4 ± 5.5	72.4 ± 1.0	67.7 ± 5.8	4.7 ± 5.9
Heating Season	Exhaust Only	Unducted	Difference	Fully Ducted	Unducted	Difference
Average Interior Temperature (°F)	71.76 ± 1.6	71.8 ± 1.65	-0.1 ± 2.3 ± 2.2	71.3 ± 1.5	72.871.7 ± 1.05	-0.4 ± 2.1.5 ± 1.7
HPWH Closet Temperature (°F)	64.3 ± 2.6	56.3 ± 3.1	8.0 ± 4.1	63.1 ± 4.7	56.0 ± 2.7	7.1 ± 5.4

Water Heating Energy Use

Ducting can also impact the energy consumed by the water heater itself, as the efficiency of the HPWH will be affected by the temperature of the inlet air. For example, while full ducting may most effectively mitigate space conditioning interactions, such a configuration may increase water heating energy use due to the cold inlet air causing decreased HPWH efficiency. In the cooling season, both exhaust only ducted and fully ducted configurations (Lab Home A) led to decreased water heater energy usage, 8.2 ± 0.7% and 8.5 ± 0.5% respectively, due to the ducting effectively mitigating localized cooling in the water heater closet. In the cooling season, crawlspace temperatures were not substantially different from interior temperatures due to ground coupling, shading, and heat transfer between the crawl and the conditioned space through the floor. The crawlspace experienced an average temperature of 73.0 ± 1.3 °F and the interior conditioned space observed an average temperature of 74.7 ± 0.4°F during the fully ducted comparison period in the cooling season.

In the heating season, the water heater energy use also was affected by the HPWH closet temperature and the extent to which localized cooling was mitigated by the ducting configuration. Exhaust only ducting led to a 7.0 ± 2.3% decrease in water heating energy use, due to mitigation of localized cooling. However, as expected, the fully ducted scenario led to a 4.3 ±1.8% increase in water heating energy use due to cooler crawlspace temperatures providing inlet air to the water heater, as shown in Figure 6. Crawlspace temperatures were 44.2 ± 2.2 °F throughout the heating season due to ground coupling, several degrees warmer than the average outdoor temperature of 40.0 ± 9.0 °F.

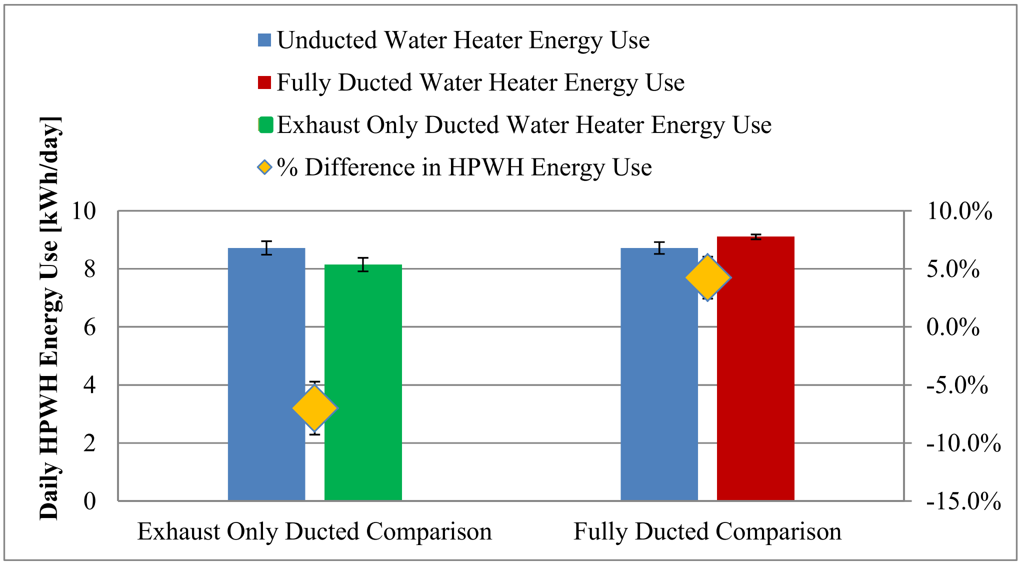

Figure 6. Average daily HPWH energy use (kWh/day) during exhaust only comparison and fully ducted comparison periods in the heating season.

Note that these comparisons do not include the auxiliary fan energy used by the supplementary exhaust ran. The fan energy was necessary, due to the ducting configuration, to provide sufficient airflow.[12] The measured airflow through the ducting during these experiments, with the supplemental exhaust fan running, was 166 cubic feet per minute (cfm) for the exhaust only ducting and 117 cfm for the full ducting, both of which are in accordance with installation recommendations (Kresta, Winer, and Vasquez 2012) for exhaust fan flow rates and GE's recommendations (S Schafer, Engineer, GE Appliances, pers. comm., Feb 2013). Fan energy, in this extreme case, would increase total HPWH energy use approximately 888 Wh/day, on average, or approximately 10%. However, this was not included in the comparison of water heater energy use since if the HPWH were manufactured to accommodate ducting, the fan could be integrated into the HPWH and fan energy significantly reduced.

Conclusions

HPWH are a promising technology for substantially reducing water heating-related energy use. However, concerns have been raised regarding the impact of HPWHs on space conditioning energy when installed in conditioned space in northern climates. Modeling studies have suggested that installing exhaust ducting on HPWHs may mitigate some of this impact. However, this field evaluation of two HPWHs in the PNNL Lab Homes suggests that this may not be the case. Conversely, the data from these experiments suggest that exhaust only ducting increased space conditioning energy use 4.0 ± 2.8% in the heating season experiments as compared to the unducted HPWH, potentially due to increased infiltration of colder outdoor air resulting from depressurization of the interior space. Full ducting was observed to substantially mitigate the impact of the HPWH on the HVAC system. The fully ducted HPWH decreased HVAC energy use 7.8 ± 2.3% as compared to the Lab Home with an unducted HPWH in the heating season.

[12] Note, the GE GeoSpring HPWH is not designed for exhaust or full ducting, as purchased.

In addition, the experimental data indicate that the penalty of installing a HPWH within the thermal envelope of the home may not always be as large as simplified modeling studies suggest. The interactions between the HPWH and the space conditioning system may be more complex, potentially due to the buffering of interior walls resulting in localized cooling in the water heater closet, with very little impact on surrounding interior temperatures. In this testing, only approximately 43.4 ± 12.2% to 37.2 ± 4.7% of the heat removed from the closet by the HPWH was made up by the HVAC system, in the heating and cooling seasons, respectively. The study also verified the benefit of HPWHs installed in conditioned space in providing supplemental cooling, decreasing HVAC energy use by 9.3% compared to an exhaust only or fully ducted HPWH.

Although fully ducting the HPWH was observed to be an effective strategy to mitigate space conditioning impacts of HPWHs installed in conditioned space, this ducting configuration may also increase water heater energy use due to cooler supply air temperatures. This study shows that using air from cooler crawlspace temperatures increased water heater energy use4.3 ±1.8%, however, this incremental difference is small compared to the difference in HVAC energy use accomplished by the different ducting configurations.

Additional modeling and economic analysis is necessary to assess the cost effectiveness of ducting and to make formal recommendations regarding appropriate installation of HPWHs under multiple scenarios. A number of variables will impact the optimal HPWH configuration in each home, including climate, water heater location, foundation type, HVAC system, and volume of hot water use. In addition, if exhaust ducting of HPWHs is required or otherwise installed, it will be important to understand the source of supply air and the implications for interior depressurization, particularly for tight homes, homes with non-sealed combustion appliances, and homes in high-radon areas.

References

10 CFR 430.23(e). Test Procedures for the Measurement of Energy and Water Consumption – Water Heaters. Code of Federal Regulations, Washington, D.C. Available at: http://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3-sec430-23.pdf.

Christian J, T Gehl, P Boudreaux, J New, and R Dockery. 2010. "Tennessee Valley Authority's Campbell Creek Energy Efficiency Homes Project: 2010 First Year Performance Report July 1, 2009–August 31, 2010." Oak Ridge National Laboratory, Oak Ridge, Tennessee. ORNL/TM-2010/206. Accessed August 6, 2013, at http://info.ornl.gov/sites/publications/files/pub26374.pdf.

Ecotope, Inc. 2010. Residential Heat Pump Water Heater Evaluation Project Measurement & Verification Plan. Bonneville Power Administration, Portland, OR. Available at: http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_MV_Plan_Final_012610.pdf.

GE Appliances, Inc. 2014a. "GeoSpring™ Hybrid Electric Residential Water Heaters Owner's Manual & Installation Instructions." Knoxville, TN: General Electric Company. Accessed March 7, 2014. Available at: http://products.geappliances.com/MarketingObjectRetrieval/Dispatcher?RequestType=PDF&Name=49-50292.pdf

GE Appliances, Inc. 2014b. "GE GeoSpringTM Hybrid Water Heater Product Specification Page." Knoxville, TN: General Electric Company. Available at: http://products.geappliances.com/ApplProducts/Dispatcher?REQUEST=SpecPage&Sku=GEH50DEEDSR

Hendron, R and C Engebrecht. 2010. Building America House Simulation Protocols. National Renewable Energy Laboratory, Golden, CO. Available at: http://www.nrel.gov/docs/fy11osti/49246.pdf.

Kresta, D; A Winer; and S Vasquez. 2012. Heat Pump Water Heaters – They're here! (this time we mean it). Presentation at the 2012 BPA Efficiency Exchange Utility Summit, Portland, OR. Available at: http://www.bpa.gov/Energy/N/utilities_sharing_ee/Utility_Summit/Workshop2012/Heat_Pump_Water_Heaters.pdf.

Larson, B; A Hadley; and J Harris. 2012. "Heat Pump Water Heaters: Tier 2 - Ducted Interior Installations." Presented to the Pacific Northwest Regional Technical Forum February 14, 2012, by Adam Hadley and Jeff Harris, Portland, OR. Available at: http://rtf.nwcouncil.org/meetings/2012/02/HPWH_Ducted_Interior_Installations_Provisional_Proposal_021412_v5.pptx.

Larson, B; M Logsdon; and D Baylon. 2011. Residential Heat Pump Water Heater Evaluation: Lab Testing & Energy Use Estimates. Available at: http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_Lab_Evaluation_Final_Report_20111109.pdf.

Lutz, J; A Renaldi; A Lekov; Y Qin; and M Melody. 2012. Typical Hot Water Draw Patterns Based on Field Data. LBNL-4830E. Lawrence Berkeley National Laboratory, Berkeley, CA.

Northwest Energy Efficiency Alliance (NEEA). 2013. "Northern Climate Heat Pump Water Heater Specification – Version 5.0." Portland, OR: Northwest Energy Efficiency Alliance. Available at: http://neea.org/northernclimatespec.

Northwest Energy Efficiency Alliance (NEEA). 2014. Northern Climate Heat Pump Water Heaters Qualified Products List. Portland, OR: Northwest Energy Efficiency Alliance. Available at: http://neea.org/northernclimatespec.

Northwest Power and Conservation Council. 2010. Sixth Northwest Conservation and Electric Power Plan. Northwest Power and Conservation Council. Portland, OR. Available at: http://www.nwcouncil.org/energy/powerplan/6/plan/.

U.S. Energy Information Administration (EIA). 2009. Residential Energy Consumption Survey. Available at: http://www.eia.gov/consumption/residential/.

Widder, S; G Parker; M Baechler; and N Bauman. 2012. "Side-by-Side Field Evaluation of Highly Insulating Windows in the PNNL Lab Homes." PNNL-21678, Richland, WA: Pacific Northwest National Laboratory. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21678.pdf.

Winkler J and D Christensen. 2012. "Heat Pump Water Heater Modeling in EnergyPlus." NREL/PR-5500-54318, Golden, CO: National Renewable Energy Laboratory. Available at: http://www.nrel.gov/docs/fy12osti/54318.pdf .