The HPWH Handbook: Optimum Installation Practices and Answers to Lingering Research Questions

Sarah Widder, PhD, Cadeo Group LLC
Ben Larson, Ecotope, Inc.

ABSTRACT

Residential heat pump water heaters (HPWHs) have the potential to reduce electric water heating loads by up to 63% in the United States. HPWHs are, however, inherently more complex devices than electric resistance tanks and raise new questions about the interaction of the water heater with the space conditioning system, performance of the HPWH in all climates, and occupant comfort and acceptance. Recent research has evaluated the performance of HPWHs in a variety of installation locations, ducting configurations, and climates, which provides the data necessary to answer many of these lingering questions surrounding the proper installation of HPWHs in a variety of climates. This paper provides a comprehensive summary of the collective findings of these studies and, based on these research results, summarizes the relative performance of currently available HPWH models, the energy implications of different installation locations (garage, basement, or conditioned space) and ducting configurations (exhaust ducting, full ducting, or no ducting), as well as other criteria that may impact the optimal installation and operation of HPWHs in new and existing homes. The collective findings suggest that HPWHs save energy in almost any location, including interior conditioned space, but the energy savings potential is affected by the HVAC system efficiency in those situations. The optimal installation location is also influenced by climate, where interior installs are favored in warm climates and basement or garage installs are best in cool climates. Ducting HPWHs is never recommended for energy reasons, although it could be considered to address comfort concerns.

Introduction

Water heating is the second largest energy use in houses, after space conditioning, representing approximately 18% of residential energy consumption (EIA 2009). Heat pump water heaters (HPWHs) offer an efficient option for residential water heating with the potential to reduce energy consumption by up to 63%.[1] Previous research has demonstrated savings of 43 to 62% in water heating energy consumption are possible, based on field tests (Ecotope 2015). If 25% of consumers with electric resistance storage water heaters (ERWHs) replaced their existing tanks with HPWHs, the United States would save approximately 17 terawatt hours annually, enough electricity to power almost a million houses for a year (all electric, including space heat).[2]

---

[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).
[2] Calculations based on U.S. Energy Information Administration 2009 Residential Energy Consumption Survey Data (EIA 2009). Available at: https://www.eia.gov/consumption/residential/data/2009/, assuming a typical all-electric house consumes approximately 17,000 kWh/yr

The current generation of residential-scale HPWH products, brought to market starting in 2009, are typically integrated, hybrid water heaters – that is, they integrate all heat pump components with the tank – and have a similar form factor as conventional electric resistance storage water heaters. They commonly retain both an upper and lower electric resistance heating element, which may run in conjunction with, or in place of, the heat pump cycle. The products are designed to overcome performance issues experienced with earlier HPWHs while still offering a compelling price proposition for consumers (Kresta 2012; CEE 2018; Cadeo 2016; NEEA 2016).

Despite the significant energy savings available from HPWHs, several real and perceived technical barriers have stood in the way of widespread market penetration of the technology. Remaining concerns include the performance, installation, and customer acceptance of HPWHs that have led to confusion regarding the likely energy and associated cost savings that can be expected under different scenarios. Recently, research has evaluated and addressed many of these concerns. The primary issues and the findings of recent research, often debunking the concerns, are summarized in Table 1 and subsequently described in further detail. While nuanced questions remain, the majority of the lingering questions have been answered by this research. We can now operationalize this body of knowledge through a comprehensive analysis comparing the performance of HPWHs across a range of installation scenarios and climates. The output supports actionable recommendations regarding HPWH performance and installation under different scenarios. This article builds on those previous studies to synthesize and summarize their findings in this fashion.

Table 1. Summary of Recent Research Addressing Perceived Performance Issues of Current-Generation Integrated HPWH Models

Issue	Concern	Findings	Resources
Hot Water Capacity	HPWHs will not recover as quickly as ERWHs	HPWHs have sufficient capacity to meet even large loads and in heat pump only mode	Widder et al. 2014; Ecotope 2015
Noise	HPWH fans and compressors are noisy and disruptive	HPWHs are generally less than 55 decibels A-weighted (dBA). When on the other side of a wall, sound drops to 35-40 dBA.[3]	Ecotope 2015; Larson 2013; Kvaltine 2015; Larson 2015
Comfort	HPWHs installed in conditioned space will cause uncomfortable cold drafts	Any cooling is typically localized to the isolated room where the HPWH is installed (typically infrequently occupied rooms) and temporary in nature.	Widder et al. 2014; Ecotope 2015
Space Conditioning Interaction	HPWHs installed in conditioned space will increase the space heating load, negating useful energy savings	HPWHs increase the heating system load much less than originally thought. In mild weather, there is no heating system penalty and, in the summer, the added cooling is beneficial.	Widder et al. 2014; Widder et al. 2017

The majority of the issues listed in Table 1 are primarily focused on customer acceptance of HPWHs. First, an obvious concern with the decreased output capacity of heat pumps is

[3] 35-40dbA is approximately the same sound level as a refrigerator (CDC, 2017)

limited tank recovery and an increase in hot water run out events. However, laboratory and field research conducted in the Pacific Northwest has shown that HPWHs have sufficient capacity to keep up with high hot water loads (>100 gallons per day), even when using the heat pump alone (Larson 2013; Kvaltine 2015a; Kvaltine 2015b; Larson 2015; Widder et al. 2014; Ecotope 2015). In addition, manufacturers have further mitigated this concern by installing back-up electric resistance elements in the HPWH tank and employing conservative control strategies that use those elements to heat the water more quickly when there is a risk that hot water might run out. This finding has been corroborated by conversation with HPWH owners who express satisfaction with the HPWH hot water delivery (Cadeo 2017).

Second, HPWHs include a fan and compressor that some worried would be unacceptably loud when installed inside a house, leading to unsatisfied occupants and contractor call backs. Most HPWH models available on the market today have sound levels near 55 dBA, which is quieter than a portable air conditioner (Larson 2013; Kvaltine 2015a; Kvaltine 2015b; Larson 2015; CDC 2017). Designs have continued to improve and newer models have sound ratings as low as 50 dBA (NEEA 2016). Further, HPWH installations generally have a wall or closed door between the water heater and the house occupants. Field measurements show this reduces the noise level by 15+ dBA effectively rendering the water heater quieter than most refrigerators (Ecotope 2015). Recent market research has found these levels to be acceptable to consumers (Cadeo 2017).

Third, the HPWH refrigeration cycle generates cool exhaust air (10–20 ºF below the intake air) and some have noted this exhaust air could cause uncomfortable, cold drafts. Previous research has evaluated the extent and latency of cool exhaust air and has shown that only the immediate surroundings are cooled a perceptible amount (i.e., exceeding 6 °F after 60 minutes of HPWH runtime) (Widder et al. 2014; Ecotope 2015). The effect of the immediate, localized cooling is largely mitigated, however, by the fact that water heaters are typically located in locations that are infrequently occupied. Due to transient occupancy, it is unlikely that temporary cooler temperatures would be a significant issue.

Finally, when HPWHs are installed in conditioned space, they remove heat from the conditioned air, which can increase the heating load during the heating season (and decrease the cooling load during the cooling season). As such, some have worried that this “heating system penalty” will meaningfully decrease or even negate the energy savings available from the water heater in heating dominated climates. Recent research and analysis, however, has suggested that this heating, ventilation, and air-conditioning (HVAC) system interaction may not be as significant as previously thought, as the HVAC system thermostat may sense only a portion of the overall energy removed from the space by the HPWH (Widder et al. 2017; Ecotope 2015; Shapiro and Puttaguntha 2016). Evaluations of the net, whole-house energy savings from HPWHs have found HPWHs to achieve savings in all cases, and be cost-effective in most cases (Widder et al. 2014; Colon et al. 2016a and 2016b; RTF 2018).

To mitigate both the impact of the HPWH on the space conditioning system, and the perceived barriers related to noise and thermal comfort described above, some have considered ducting HPWHs. Most studies and programs have considered either: (a) exhaust-only ducting or (b) full (i.e., supply and exhaust) ducting. Exhaust ducting can mitigate the concern of localized cooling, since it will expel the exhaust air stream out of the house, however it will increase infiltration potentially leading to increased heating and cooling energy use in some climates (Widder et al. 2014). In the case of full ducting, Widder et al. (2014) found that, in the PNNL Lab Homes in Richland, Washington, full ducting was the energy optimal configuration for a heat pump-only water heater. It mitigates any heating system interaction and, thus, in this climate, maximizes energy savings from the HWPH. However, the incremental energy savings associated with full ducting (compared to an unducted HPWH) have been shown to be modest at best, are dependent on the control strategy of the HPWH, and may not be justified due to the incremental cost and complication associated with installing ducting on HPWHs.

As the body of work described above illustrates, substantial progress has been made in understanding and resolving questions related to HPWH performance in different installation configurations. The work to date provides a substantial basis for concrete information and recommendations regarding HPWH performance and installation. Nevertheless, none of these sources have summarized this body of work or synthesized it into actionable recommendations for programs and installers on the optimal location to install HPWHs under different scenarios. This article operationalizes the existing research using national simulations that compare the performance of HPWHs across a range of installation scenarios and climates to answer the following questions:

- What is the optimal installation location and configuration for HPWHs?
- In existing homes, given an existing water heater location, how should a HPWH be installed?

Theory

The main variables that impact the selection of the optimal[4] installation location for a HPWH are the existing water heater (if any) location and fuel; the existing HVAC system and fuel, if any; and climate. These variables will affect the installation cost and energy savings of the water heater.

The existing water heater location and fuel is important because there is significant expense associated with changing the water heater location, including re-piping and running electrical connections to the new location. As such, wherever the existing water heater is currently installed is typically the best location to leave it. However, in new homes, the selection of water heater location is not constrained by any existing plumbing system.

The HVAC system is important because, as previously described, when HPWHs are installed in conditioned space, they remove heat from the conditioned air. During cold outdoor temperatures, the additional cooling increases the load on the heating system. During hot weather, the additional cooling is beneficial and decreases the cooling load. In mild weather conditions, when no heating or cooling is needed, any heat extracted from the space by the HPWH is essentially free heat. The relative extent and magnitude of these differing impacts (penalty, benefit, free) on the net annual HVAC load depends on the climate, as well as the efficiency of the HVAC system. That is, the HPWH will remove the same amount of heat from the air, but the HVAC system will use different amounts of energy to make up that loss (or gain) depending its efficiency.

Previous modeling has demonstrated these impacts and observed the benefits/penalties of installing HPWHs in conditioned spaces in different climates (Larson, Logsdon, and Baylon 2011; Maguire, Fang, and Wilson 2013). These modeling efforts accounted for the increased sensible thermal load introduced by the HPWH with varying degrees of granularity, relying on the best available data to describe latent heat removal of HPWHs and the interaction of HPWHs

[4] "Optimal" location is defined, primarily, on the most cost-effective location (based on energy savings and estimated incremental installed cost). For further description see the Methods section.

with the space conditioning system, including the utilization of "free" solar heat gains. However, this work did not account for the fact that, even when installed in conditioned space, the thermostat may not fully "sense" all of the HPWH thermal load due to the distance between the HPWH exhaust air and the space conditioning system thermostat (*Ibid.*; Widder et al. 2014). That is, these models assume that all the conditioned space within a home acts as a single well-mixed-zone, when, in reality, homes experience significant variability in temperature.

Recent research in the PNNL Lab Homes has provided primary data to better describe how HPWHs interact with space conditioning systems and confirmed that the HVAC system does not make up 100% of the load imparted to the space (Widder et al. 2017). The PNNL study measured the space conditioning system interaction for several HPWH locations throughout the Lab Homes, quantified in terms of a HPWH "interaction factor." The interaction factor is defined as the ratio of the amount of heat replaced by the heating system to the amount of heat (sensible and latent) extracted from the air by the HPWH. Values less than one mean the thermostat sensed less than the total heat removed. The results showed the incremental energy use of the space conditioning system varies depending on the "thermal distance" between the HPWH and the thermostat in the house. For example, as shown in Table 2, the study found, for thermally "far" locations, the HVAC system only makes up about half of the theoretical cooling load imparted to the space. For thermally "near" locations, the incremental space conditioning system energy use increased and the interaction was closer to 100%. Researchers also observed the degree of sustained local temperature depression was correlated with the thermal distance where thermally "far" locations were associated with greater sustained depressions. This is referred to as localized cooling in the table, where localized cooling describes the average daily temperature difference caused by the HPWH immediately adjacent to the water heater (Widder et al. 2017).

Table 2. Summary of PNNL Lab Homes Study (Widder et al. 2017) Findings; Mean Values and Standard Error.

Thermal Location	**Far**		**Near**	
Actual Location	Master Bathroom	Water Heater Closet (no direct supply or return air duct)	Living Room	Utility Room (where air handler is located)
Interaction Factor	0.6 ± 0.2	0.5 ± 0.1	0.8 ± 0.2	1.4 ± 0.4
Localized Cooling	13.8 ± 2.1 °F	9.9 ± 2.8 °F	1.7 ± 1.9 °F	2.1 ± 1.9 °F
Notes	Greatest "thermal distance" from thermostat	Representative of semi-conditioned space	Small "thermal distance" (minimal localized cooling)	Greatest interaction (thermostat influenced by localized cooling); Interaction >1.0 due to overheating of house

The PNNL study describes how interaction factors less than one result, primarily, from the fact that houses are a complex, multi-zone airflow network and not all the heat added or removed to a given space will influence the temperature measured by the thermostat. This concept is referred to in the study as "thermal distance" and is influenced both by physical distance from the thermostat and thermal buffers or barriers that impede heat transfer and air flow between the location and the thermostat, such as walls and doors (*Ibid.*). Other contributing factors, described by Widder et al. (2017), which previous modeling work variously included or excluded with differing levels of accuracy, are (1) latent heat removal (dehumidification) that does not affect the dry bulb temperature and is, therefore not "sensed" by the thermostat; and (2) free solar heat that is available even in the winter on days when the sun provides a majority of the heating load for the house.

The authors recently synthesized the findings to understand how they apply to the population of potential water heater installations in single family homes in the PNW. The observed, localized cooling was used to connect the Lab Home findings to those of HPWHs in various installation locations observed in the field (Ecotope 2015). The amount of persistent cooling was used as a proxy to provide a categorization scheme for thermal distances of "near," "far," or "buffer." The number of field installations of each category was then tallied to give a relative weight for typical HPWH installation locations (RTF 2018). Using these weights and the average "near[5]" and "far" interaction factor values observed in the PNNL Lab Homes study (Widder et al. 2017), the authors determined the average interaction factor was approximately $^{2}/_{3}$ for HPWHs installed inside conditioned spaces in single-family homes (RTF 2018). The remaining $^{1}/_{3}$ appears as "free" because it comes from persistent temperature depressions in the water heater install space, making use of excess solar gains, and benefiting from latent heat removal.

Methods

To operationalize the findings of previous research and provide recommendations regarding the optimal installation location of HPWHs, this article uses simulations to evaluate the energy savings of HPWHs compared to an ERWH baseline in a variety of installation locations and under several installation scenarios. The simulations provide a quick and effective way to compare multiple different HPWH installation scenarios against a common baseline. The selected simulation tool, described below, has been extensively calibrated to existing HPWH laboratory and field measurements and incorporates the average interaction factor,[6] presented previously, to account for the reduced space conditioning system interaction observed in the Lab Homes (Widder et al. 2017).

Simulation Tools

The primary tool used in this analysis is HPWHsim,[7] which was designed to model electric storage tank water heaters, specifically HPWHs. As inputs, the simulation takes a hot water set-point, inlet water temperature, and ambient space temperature and steps through a draw schedule at one-minute increments, tracking tank temperature and activating heating components accordingly. HPWHsim simulates all currently available HPWH models in the U.S. market with unique parameters to describe the number and position of electric resistance elements, the

---

[5] The "near" value ignored the interaction factor of 1.4 observed in the utility room, as those findings are unrealistic in actual houses because water heaters are not installed with their exhaust directed at, or near, the thermostat.

[6] The average interaction factor is used for all locations in conditioned space because more granular data on the precise installation location of HPWHs and the thermal distance of those locations from thermostats is extremely variable and, more importantly, not typically known with sufficient fidelity to warrant modeling specific locations in the conditioned space.

[7] HPWHsim https://github.com/EcotopeResearch/HPWHsim

arrangement of the condensing coils, the performance of the vapor-compression system, and criteria on when to engage or disengage various heat sources for each model. The parameters are calibrated to laboratory and field measurements (Kvaltine 2016) and the output validated and verified (Horowitz 2016; RTF 2018). The simulation is used to calculate energy savings for utility programs in Washington, Oregon, Idaho, and Montana, and is incorporated in California's residential new construction code compliance software, CBECC-Res.[8]

The secondary tool used is SEEM[9] which serves to calculate the water heater's impact on the space conditioning system. Designed as a residential building simulation, SEEM consists of a sub-hourly thermal and moisture simulation that interacts with weather, duct specifications, and equipment parameters to calculate the annual heating and cooling energy requirements of the house. At every time step, the simulation calculates a house heating or cooling load, of which the HPWH energy flows (standby losses and exhaust air) are a part. In this study, SEEM serves as a wrapper for HPWHsim and an accounting repository for when the house is in heating, cooling, or neither so the impact of running the HPWH can be tallied over the course of the year.

Combined, the tools are able to accurately calculate changing refrigeration cycle efficiency as both the water temperature and the source air temperature change due to localized cooling, or indoor or outdoor air temperature changes, whichever is relevant to the simulated scenario.[10]

Scenarios

With the simulation tools in hand, we set out to explore the savings potential for various installations across the United States. The important parameters, presented in Table 3, include: climate, installation location, ducting, and HVAC system.

Table 3. Parameters Explored in Energy Simulations

Parameter	Possible Values
Water Heater	Baseline: 50-gallon Electric Resistance (UEF 0.95), Efficient Case: 50-gallon HPWH (AWHS Tier 3 performance)
Climate Zone	1A – Miami, 2A – Houston, 2B – Phoenix, 3A – Atlanta, 3B - Los Angeles, 3B - Las Vegas, 3C - San Francisco, 4A – Baltimore, 4B – Albuquerque, 4C – Seattle, 5A – Chicago, 5B – Denver, 6A – Minneapolis, 6B – Helena, 7 – Duluth
Installation Location	Basement (unconditioned), Garage, Interior Conditioned Space (main house and conditioned basements)
Ducting	Interior Conditioned Spaces Only: No Ducting, Exhaust Only, Full Supply and Exhaust
HVAC Types	Electric Furnace with Central A/C (SEER 13), Gas Furnace (AFUE 80) with Central Cooling (SEER 13), Central Heat Pump (HSPF 7.9 / SEER 13). Duct system located in attic and basement spaces has ~20% combined conductive and air leakage energy loss some of which is regained by the house or HPWH.

The baseline case simulated an ERWH while the experimental case included a HPWH. TMY files representative of the familiar International Energy Conservation Code zones were

[8] CBECC-Res http://www.bwilcox.com/BEES/cbecc2019.html
[9] SEEM https://rtf.nwcouncil.org/simplified-energy-enthalpy-model-seem
[10] A comparable modeling suite is available in BEopt, https://beopt.nrel.gov/home, which, like the tools here, also has a variable user input for setting the interaction.

used as weather input files (NREL 2011). The climate influences energy use in two ways: (1) variation in inlet water temperature, which dictates the amount of energy necessary to heat water to the tank set point temperature, and (2) the outside air temperature, which determines the magnitude of the space conditioning load and/or the temperature of air available to the HPWH as an energy source (in unconditioned locations or fully ducted scenarios).

The simulation considered three installation locations: (1) unconditioned basements, (2) garages, and (3) interior conditioned space, comprising main house and conditioned basements installs. Garages are taken to be unconditioned across all climates and the temperatures behave like a buffer spaces staying between the house and a lagging average of the outside temperature. The unconditioned basement is modeled assuming no intentional conditioning; mechanical equipment is in the space but no heating (or cooling) is supplied to the space and it is occupied only transiently. Based on their extreme thermal distance, HPWHs installed in the buffer spaces of garages and unconditioned basements have no interaction with HVAC system.[11] The third location assumes the water heater is installed in conditioned space, which comprises all inside locations including conditioned basements. For HPWH installations within the conditioned space, we considered three ducting scenarios: none, exhaust only, and full. In all cases, the ducts were installed from the HPWH exhaust and/or supply to the outside. This research did not explore the option of installing ducting on a HPWH installed in an unconditioned space with the ducting routed to and from the conditioned space, which may be beneficial in cooling-dominated climates.[12]

The five installation scenarios simultaneously explore the effects of the HPWH ambient air temperature on water heater energy use and the impact on the space conditioning system. In garage and unheated basement installations, the ambient space air temperature, which is largely a function of climate, determines the HPWH energy use. HPWH exhaust air also influences the basement temperature, which in turn affects HPWH performance, and this is accounted for in the model. In the winter time, these temperatures are often unfavorable for HPWHs.[13] In conditioned space installations, the temperatures are generally favorable, but maintained at the expense of incremental heating system energy consumption. In these unducted conditioned space installations, localized cooling may also have a slight impact on HPWH performance, which is accounted for in the simulation results. With the addition of exhaust ducting, the impact of localized cooling on HPWH performance is mitigated and the incremental cooling load from the HPWH exhaust is replaced by an increased infiltration load. However, in some climates, the cold outside air introduced through increased infiltration may exact a larger penalty on the heating system than the unducted HPWH exhaust, which typically far outweighs any impact of localized cooling on HPWH performance. That is, the space conditioning penalty is typically much larger than the incremental energy consumption of the HPWH based on the temporary temperature

[11] There is a possibility of the HPWH removing heat from the air in an unconditioned basement where ducts and heating equipment is located. This could theoretically lower the buffer space temperature, slightly increasing heat loss from the house. However, the theoretical change is only a small fraction of the heating load and empirical results showed a diminishing interaction factor for increasing thermal distance which would only be exaggerated by buffer space HPWH locations (Widder et al. 2017). Therefore, we assume little to no interaction with the HVAC system for these cases.

[12] The benefit of installing ducting on HPWHs in garages and routing to conditioned space in cooling-dominated climates has been explored experimentally by the Florida Solar Energy Center (Colon et al. 2016a and b).

[13] Generally, HPWHs with R-134a refrigerant will not run the compressor when intake air is below 40 ºF. During this time, the resistance elements are used, which decreases the average operating efficiency of the system.

depression. With full ducting, the HPWH intake and exhaust is isolated from the HVAC system so outside air temperature again determines HPWH energy use.

The HVAC system efficiency was purposefully selected to represent minimally compliant equipment with typical duct leakage characteristics. This results in conservative (i.e., worst-case) estimates of the space conditioning system interaction impact for a given interaction factor and installation scenario.

Constants across all simulations were the hot water draw profiles and the house characteristics. For reference, the house heat loss rate was approximately 475 Btu/hr-ºF which includes an air leakage of seven air changes per hour at 50 Pascals. In practice, however, the house characteristics are secondary in the analysis of the primary parameters of climate, HVAC system, HPWH location, ducting, and interaction factor. While a super-insulated house is likely to have an interaction factor closer to one than a poorly insulated home, this analysis seeks to explore the primary influences of energy use in an average case. Fundamentally, all houses are heated and cooled and we are interested in the relative difference in energy use caused by installing the HPWH.

To capture the diversity of hot water use, simulations used a draw pattern that have been developed based on empirical data to adequately capture typical variations in daily hot water usage patterns based on behavior and seasonal factors (Ecotope 2015). They vary in daily hot water use from small (17 gallons) to large (105 gallons), with an average of 41 gallons/day. The patterns also vary throughout the year in response to changing incoming cold-water temperatures so there is more hot water use on winter days than summer days.

The scenarios are compared using three primary criteria to determine the "optimal" installation location in either new construction or retrofit scenarios: net site energy savings (in kWh equivalent units[14]), incremental cost effectiveness, and acceptability to the homeowner. The net energy savings from a HPWH compared to the ERWH baseline is the primary criteria and is assessed quantitatively. The incremental cost effectiveness, while potentially a quantitative metric, is difficult to assess reliably due to the significant variation in installation costs site-to-site and across the country. Therefore, this article evaluates the incremental value of energy savings compared to the typical incremental cost of the scenario on a semi-quantitative basis.[15] This semi-objective assessment allows users to make their own assessment regarding the cost-effectiveness of certain design choices based on their specific incremental costs. Homeowner acceptability is a subjective metric and considers many of the perceived nuisances (e.g. noise, cool air exhaust) described above.

Results and Discussion

The simulation results are presented in Figure 1, which shows the total net site energy savings relative to the same configuration with an ERWH, including all incremental changes in both water heating and space conditioning loads. Each installation scenario is represented by a different color and/or shape in the graph, across the breadth of IECC climate zones and for each HVAC type.

[14] The authors acknowledge that there are several metrics that can be used to compare energy savings, especially between electric and gas technology options, including source energy, site energy, equivalent cost, and carbon emissions, among others. This study presents the energy savings in terms of site kWh equivalent units due to the national, regional, and even local variability associated with the other listed metrics.

[15] That is, the relative magnitude of the values are compared, but strict cost-effectiveness metrics, such as payback periods or cost/benefit ratios are not computed.

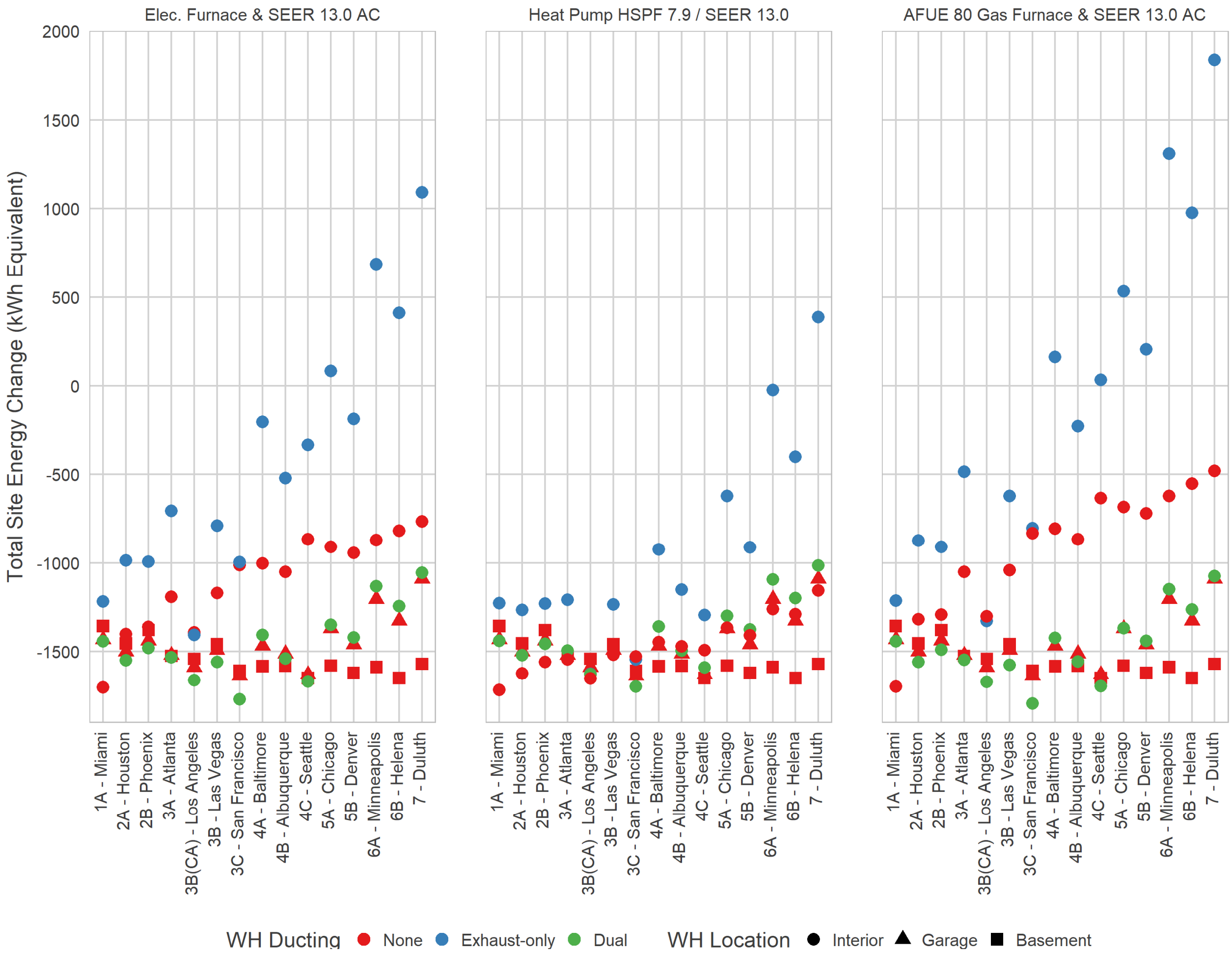

Figure 1. HPWH Installation Net Annual Site Energy Savings (kWh equivalent) Compared to ERWH Baseline for Each IECC Climate Zone and Across HVAC Types.

The first and most obvious trend illustrated in Figure 1 is how not to install a HPWH. In almost every case, installing exhaust only ducting (blue dots) on a HPWH results in the lowest energy savings and can even result in increased energy consumption (i.e., negative savings) in the extremely cold climates because of increased cold air infiltration. When considered against a conditioned space install, the simulation shows the cold air introduced to the house by the HPWH is still not nearly as cold, on average, as the outside air and results in significantly improved performance.

From the simulation results, presented in Figure 1, we can also evaluate the "optimal" installation location for a HPWH in the new construction case, where the builder is free to locate the HPWH anywhere in the house, as the existing water heater location does not impact the decision. Figure 1 shows that significant energy savings can be achieved with unducted interior (red circle), fully ducted interior (green circle), garage (red triangle), or basement (red square) locations. While full ducting appears the most beneficial in mild climates and can offer the greatest opportunity for energy reduction, any ducting option adds to the complexity and cost of the installation. In cases where the fully ducted option maximizes energy savings, the incremental energy savings between the fully ducted and next best option is generally on the order of 50-100 kWh/yr or less, which equates to approximately $5-$10/yr with a cost of electricity of $0.10/kWh. Given that the cost of fully ducting a HWPH can often exceed $400, the higher energy savings of full ducting do not justify the higher cost. Consequently, for general practice, we suggest avoiding any ducting in new construction. With that restriction, the resulting recommendations for optimal HPWH installation locations by climate and heating system type are presented in Table 4.

Table 4. Optimal HPWH Installation Locations

	Heating Type		
Climate Zone	**Electric Furnace**	**Heat Pump**	**Gas Furnace**
1	Interior Conditioned Space	Interior Conditioned Space	Interior Conditioned Space
2 and 3 (not Marine)	Garage	Interior Conditioned Space	Garage
3 and 4 Marine	Garage or Basement	Garage or Basement	Garage or Basement
4 and Colder	Basement	Basement	Basement

For the hottest climates, across all HVAC types, conditioned space installations offer the most benefits. With a significant cooling load and little heating system penalty, any cooling the water heater provides to the house is beneficial and interior conditioned space installations maximize that benefit. In addition, with regard to customer acceptance (our third criteria), research has shown that interior non-ducted installations are acceptable to homeowners and will not result in unacceptable noise or cold drafts (as described above). However, to further mitigate this concern, water heaters could be located in less frequently occupied spaces and buffered with doors or walls, as is typical construction practice.

In climate zones 2 and 3 (not Marine), garage installations allow the HPWH to take advantage of elevated summertime air temperatures not found in the house or the basement. However, for many of the climates, the garage, basement, and interior space options (red shapes) were tightly grouped and would result in nearly comparable performance, so any location would be a good location to install a HPWH. In cooler zone 3 climates, the interior unducted conditioned space installation begins to enact a slightly higher heating system penalty due to the higher heating load and, thus, results in slightly lower energy savings, especially for inefficient HVAC systems. When the house is conditioned by a heat pump, the difference is negligible.

In Marine climate zones 3 and 4, the moderate conditions show garages or basements to work equally well. Similar to the results for climate zones 2 and 3 (not Marine), the interior unducted scenario performs worse than the unconditioned installations for inefficient HVAC systems due to the increased heating system penalty. If the house is heated by a heat pump, an interior conditioned space installation is still a perfectly good location to install a HPWH.

In zones 4 and colder, unconditioned basements show the most energy savings. If these buffer spaces are not available, a similar effect can be achieved by locating the HPWH within the conditioned space but in less frequently occupied spaces like conditioned basements, utility closets, and laundry rooms. These both minimize the impact on the heating system and provide a barrier to sound and cold drafts. Garage and fully ducted installations are not recommended in cold climates because of the impact of the cold inlet air on HPWH performance, which will cause the HPWH to run entirely with resistance heat in the winter because the outside air is simply too cold for the R-134a refrigerant cycle.

In retrofit applications, there is often little choice in selecting the water heater installation location. The water pipes are set and can be prohibitively costly to relocate. Consequently, the HPWH is installed where the existing water heater is. In that case, Figure 1 shows the energy savings that can be expected. Most importantly, in every scenario (excluding exhaust ducting), there are energy savings. This spans all HVAC systems and climates, indicating every retrofit configuration offers real savings opportunities. This is especially true of houses with high-efficiency HVAC equipment, as illustrated by the heat pump results in Figure 1, where basement, garage, and unducted interior conditioned space installations all offer similar and significant energy savings in most climates (basements perform slightly better in extremely cold climates). Even in houses with less efficient HVAC equipment, unducted interior conditioned space installs offer significant savings opportunity due to fact that the heating system penalty is less than was initially thought.

In general, the primary question facing installers and homeowners when retrofitting a HPWH in conditioned space is whether or not to duct the water heater. As Figure 1 shows, exhaust ducting is not recommended in any situation and, while full ducting may be energy optimal, the incremental energy savings are not great enough to justify the additional cost and complication. Only in situations where the HPWH is in an unusual and/or highly trafficked area, where the cold air exhaust may pose a comfort concern, would full ducting be the recommended installation practice. To summarize, these results suggest that regardless of where the existing water heater is installed, and across all climates, the best way to retrofit a HPWH is just install it, with no ducting at all.

Conclusions

Research has demonstrated the potential of HPWHs to dramatically reduce electric water heating loads by up to 63% in the United States. However, several real and perceived technical barriers have stood in the way of widespread market penetration of the technology, especially related to installing HPWHs in conditioned space. Recent research has evaluated and addressed many of these concerns, including demonstrating that hot water capacity, noise, and comfort are not significant concerns in the majority of installations (Kresta 2012; CEE 2018; Cadeo 2017; NEEA 2016). Work by Widder et al. (2017) has also demonstrated that the space conditioning system interaction is much less than previously thought and HVAC systems will only “sense” approximately $^2/_3$ of the energy removed from the space. Still, the question of the optimal way to install a HPWH from an energy, cost effectiveness, and occupant acceptance perspective has remained.

This research question has different answers depending on whether it is being posed from a new construction or retrofit perspective. The results presented in this article, based on calibrated simulations of HPWH performance, suggest that in warm climates (climate zone 1), interior conditioned space presents the best opportunity for savings, while in colder climates (climate zones 4 and higher) the basement is the most optimal location. In mixed climates, the garage and basement both offer excellent energy savings, while the energy savings potential from interior conditioned space installation ultimately depends on the HVAC system efficiency. That is, in mixed climates, when the house is equipped with a heat pump, the interior conditioned space installation offers comparable energy performance, while houses with less efficient HVAC systems will result in slightly lower energy savings.

From a retrofit perspective, the best location to install the HPWH is almost always the same place as the existing water heater. The results of this research suggest that basements, garages, and interior space (unducted) all offer significant energy savings and are excellent locations to install a HPWH. When considering a conditioned space install, there is an additional question related to whether or not the water heater requires ducting. Based on these results, exhaust ducting is not recommended in any situation or climate. Fully ducting a HPWH can provide a marginal amount of additional energy savings in many situations, however it is our assessment that the improved performance is not justified compared to the additional cost and expense of installing full supply and exhaust ducting. This is especially true for homes with high-efficiency HVAC systems. Another reason to consider ducting is to mitigate any potential concern with noise or cool drafts induced by the HPWH when installed in a small and/or frequently occupied space. When there is a choice of installation location, these concerns can, of course, be entirely mitigated by installations in isolated and unfrequented spaces that are separated from common living spaces by walls or doors,[16] as is typical construction practice. Only in extreme situations (e.g., extremely small and well-insulated spaces like apartments or tiny houses), would full ducting be recommended to ensure homeowner comfort and acceptance. As previously mentioned, localized cooling does have a minor impact on HPWH performance and exhaust ducting can mitigate that penalty. However, our simulation results suggest that this benefit is small and is overwhelmed by the negative impact of increased infiltration load in the home. If significant localized cooling in a very small space is a concern, installation of louvered doors or full ducting could be considered, which would provide more favorable whole-house energy savings.

While many perceive the installation of HPWHs as complicated and only appropriate for particular installation locations, this research suggests that HPWHs are an appropriate and cost-effective solution in any location or climate and should never require complicated ducting except under extreme circumstances. We hope the results of this research help to further mitigate concerns related to HPWH installation locations and pave the way for wide-spread implementation and market penetration of this new, more efficient technology.

References

Cadeo. 2017. *Northwest Heat Pump Water Heater Initiative Market Progress Evaluation Report #3*. Northwest Energy Efficiency Alliance. Report #E17-362. Portland, OR. neea.org/docs/default-source/reports/2016-evaluation-findings-for-the-heat-pump-water-heater-initiative.pdf?sfvrsn=7

CDC (Center for Disease Control and Prevention). 2017. *What Noises Cause Hearing Loss?* Atlanta, GA. Last updated 6 February 2017. www.cdc.gov/nceh/hearing_loss/what_noises_cause_hearing_loss.html.

Colon, C, Martin, E, and Parker, D. 2016a. *Effect of Ducted HPWH on Space-Conditioning and Water Heating Energy Use--Central Florida Lab Home.* FSEC-CR-2050-16. Florida Solar Energy Center; Building America Partnership for Improved Residential Construction, Cocoa, Florida.

[16] Note, some door may need to be louvered to comply with manufacturer installation instructions. These louvers will allow sufficient air the be exchanged with the space, but will still damp temperature and sound impacts.

Colon, C, Martin, E, Parker, D, and Sutherland, K. 2016b. *Measured Performance of Ducted and Space-Coupled Heat Pump Water Heaters in a Cooling Dominated Climate.* FSEC-RR-644-16, Florida Solar Energy Center, Cocoa, Florida.

CEE (Consortium for Energy Efficiency). 2018. *Residential Water Heating Initiative*. Boston, MA.library.cee1.org/system/files/library/13557/CEE_ResWaterHeating_Initiative_16Mar2018.pdf

Ecotope. 2015. *Heat Pump Water Heater Model Validation Study*. NEEA Report #E15-306, Portland, OR. http://neea.org/docs/default-source/reports/heat-pump-water-heater-saving-validation-study.pdf?sfvrsn=8

EIA (U.S. Energy Information Administration). 2009. Residential Energy Consumption Survey. U.S. Department of Energy. Washington, D.C.

Horowitz, S., J. Maguire, P. Tabares-Velasco, J. Winkler, and C. Christensen. 2016. *EnergyPlus and SEEM Modeling Enhancements via Software-to-Software Comparison Using NREL's BEopt Test Suite*. National Renewable Energy Laboratory. TP-5500-61489. Golden, CO.

Kresta, D. 2012. *Heat Pump Water Heater Market Transformation Update*. Northwest Energy Efficiency Alliance. Portland, OR.

Kvaltine, N. and B. Larson. 2015a. *Laboratory Assessment of A. O. Smith HPTU Series Heat Pump Water Heaters*. NEEA Report #E15-306. Portland, OR. neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_ao-smith_hptu_12-09-2015.pdf?sfvrsn=2

Kvaltine, N. and B. Larson. 2015b. *Laboratory Assessment of Stiebel-Eltron Accelera 220 E Heat Pump Water Heater.* NEEA Report #E15-014. Portland, OR. neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_stiebel_220e_07-15-2015.pdf?sfvrsn=4

Kvaltine, N., M. Logsdon, and B. Larson. 2016. *HPWHsim Project Report.* Seattle, WA. Ecotope. www.bwilcox.com/BEES/docs/Ecotope%20-%20HPWHsim%20Project%20Report.docx

Larson B, M Logsdon, and D Baylon. 2011. *Residential Heat Pump Water Heater Evaluation: Lab Testing & Energy Use Estimates.* Bonneville Power Administration, Portland, Oregon.

Larson, B. 2013 *Laboratory Assessment of Rheem HB50RH Heat Pump Water Heater*. NEEA Report #06282013. Portland, OR. neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_rheem_hb50_06-28-2013.pdf?sfvrsn=2

Larson B., and N. Kvaltine. 2015. *Laboratory Assessment of GE GEH50DFEJSRA Heat Pump Water Heater*. NEEA Report # E15-013. Portland, OR. neea.org/docs/default-source/lab-test-reports/hpwh-lab-report_ge_h50dfejsra_04-09-2015.pdf?sfvrsn=2

Maguire J., X. Fang, and E. Wilson. 2013. *Comparison of Advanced Residential Water Heating Technologies in the United States.* NREL/TP-5500-55475, National Renewable Energy Laboratory, Golden, Colorado.

NEEA (Northwest Energy Efficiency Alliance). 2016. *Advanced Water Heater Specification*. Portland, OR. neea.org/docs/default-source/advanced-water-heater-specification/advanced-water-heater-specification.pdf?sfvrsn=22

NREL (National Renewable Energy Laboratory). 2011. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. Technical Report NREL/TP-5500-46861. Boulder, CO. https://www.nrel.gov/docs/fy11osti/46861.pdf

RTF (Regional Technical Forum). 2018. *Residential Heat Pump Water Heater UES Update*. 30 January 2018. Portland, OR. Northwest Power & Conservation Council. nwcouncil.app.box.com/v/20180130ResHPWHPres

Shapiro, C and S Puttagunta. 2016. "Field Performance of Heat Pump Water Heaters in the Northeast." Norwalk, CT. Consortium for Advanced Residential Buildings.

Widder S., J. Petersen, G. Parker, and M. Baechler. 2014. *Impact of Ducting on Heat Pump Water Heater Space Conditioning Energy Use and Comfort*. PNNL-23526. Richland, WA. Pacific Northwest National Laboratory.

Widder, S., C. Metzger, J. Petersen, and J. McIntosh. 2017. *Interaction between Heat Pump Water Heaters or Other Internal Point Source Loads and a Central Heating System*. Report #E17-302. Portland, OR. NEEA. neea.org/docs/default-source/reports/interaction-between-heat-pump-water-heaters-and-heating-system.pdf?sfvrsn=4