Regional Variation in Residential Heat Pump Water Heater Performance in the U.S.

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Regional Variation in Residential Heat Pump Water Heater Performance in the U.S.

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ABSTRACT

Residential heat pump water heaters (HPWHs) have recently reemerged on the U.S. market. These units have the potential to provide homeowners significant cost and energy savings. However, actual in-use performance of an HPWH will vary significantly with climate, installation location, HVAC equipment, and hot water use. In conditioned space, the cooling provided by the HPWH can be either a net benefit or a penalty depending on climate; in unconditioned space the ambient air temperature has a significant impact on its performance. To determine the in-use energy consumption of an HPWH in different regions, annual simulations of 50 and 80 gallon HPWHs as well as a standard electric resistance water heater installed in conditioned and unconditioned spaces were performed for more than 900 locations across the U.S. The simulations included a benchmark home to account for interactions between the space conditioning equipment and the HPWH and a realistic hot water draw profile that varied between 45 and 60 gallons per day with local mains water temperature. Results showed that the HPWH will always save some source energy compared to a standard electric water heater, although savings vary widely with location. In addition to source energy savings, the breakeven cost (the net installed cost an HPWH would have to have to be a cost neutral replacement for a standard water heater) was also examined. The highest breakeven costs were seen in cases with high energy savings, such as the Southeast, or high energy rates, such as New England and California. Although the breakeven cost is higher for the 80 gallon HPWH than for the 50 gallon HPWH, the 80 gallon unit's higher net installed costs makes it likely that the 50 gallon HPWH will be more cost effective.

INTRODUCTION

U.S. homes use significant energy for water heating, accounting for about 18% of the total energy consumed, or 1.8 quads annually (EIA, 2009). Conventional gas and electric storage water heaters dominate the market and in 2009 comprised about 94% of residential shipments (U.S. DOE, 2010a). However, many more efficient options, including integrated heat pump water heaters (HPWHs), are available. The HPWH takes heat from the ambient air and adds it to a hot water storage tank via a vapor compression cycle. These units have a rated efficiency (energy factor [EF]) of 2–2.5; typical electric water heaters have an EF of ~0.9.

HPWHs have been sporadically available in the U.S. for many years, although they have historically had poor market penetration. These systems are more expensive than traditional electric storage water heaters and earlier generations of HPWHs had reliability issues (Dubay, Ayee, & Gereffi, 2009). Although HPWHs have been niche products, several large manufacturers have recently entered the market and have ENERGY STAR®-qualified HPWHs available. Additionally, new residential water heater efficiency standards that go into effect in 2015 will effectively require all new electric water heaters larger than 55 gallons (208 L) to be HPWHs, which should increase market penetration significantly (U.S. DOE, 2010b).

HPWH efficiency is highly variable and depends on the temperature of water adjacent to the condenser, ambient air conditions, hot water draw profile, and controls. The actual efficiency of these units will thus vary regionally. They also cool and dehumidify the spaces they occupy, which may be either a net benefit or a detriment depending on the installation location, climate, and the efficiency of the space conditioning equipment. Some HPWHs on the market today can be ducted

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to mitigate space conditioning impacts; however, the potential of ducting is not considered here.

This work uses annual simulations to evaluate the efficiency, energy savings, and economic potential of HPWHs across the U.S. with a focus on regional variations. It presents selected results from—and expands on—a previous study of HPWHs (Maguire, Burch, Merrigan, & Ong, 2013). This work focuses on HPWHs used as replacements for traditional electric storage water heaters in homes with air source heat pumps (ASHPs) for heating and cooling. Although an HPWH could replace a gas water heater, it is generally not cost effective. Natural gas on average costs roughly 1/3 of what electricity costs per unit of site energy (EIA, 2012a), so for such a replacement to be cost effective the HPWH would have to save more energy than the current technology does in most of the country. A more detailed look at the potential of HPWHs as a replacement for natural gas water heaters is provided in the aforementioned study.

METHODOLOGY

The savings potential of an HPWH as a replacement for a traditional water heater depends on whether a gas or electric water heater is being replaced. Fifty-two percent of U.S. homes use natural gas as the primary water heating fuel and 41% use electricity (EIA, 2009). The rest use other fuel sources such as fuel oil, propane, wood, and solar. However, the distribution of water heating fuel types varies regionally. While all regions have some electric water heaters, they are most common in the Southeast and the Pacific Northwest.

Modeling for this work was done using TRNSYS, a modular energy simulation tool (Klein, et al. 2010). Two HPWHs were modeled here: a 50 gallon (189 L) unit (EF=2.35) and an 80 gallon (303 L) unit (EF=2.3). These models were based on extensive lab testing of several different HPWHs (Sparn, Hudon, & Christensen, 2011). The models use a detailed, stratified tank model and performance curves derived from the lab testing. In addition to differences in the tank volume, the two units have different control logics and heat pump performance maps. When the backup electric resistance element turns on for the 50 gallon HPWH, the element stays on until the tank fully recovers; the 80 gallon HPWH reverts to the heat pump once the tank has partially recovered. HPWH performance can vary significantly between units of the same volume because of differences in control logic, condenser design, and other factors; however, these units are roughly representative. In addition to modeling the HPWHs, a base case of a typical 50 gallon electric water heater (EF=0.9) was simulated. All water heaters had a setpoint of 120°F (49°C).

The hot water draw profile used here is a discrete, event-based profile created with the Building America Domestic Hot Water Event Schedule Generator (Hendron & Burch, 2007). This tool creates discrete hot water events based on probability distributions for each end use derived from field monitoring of domestic hot water use. It creates a full year of discrete events based on these distributions and takes into account clustering of events, vacations, and differences in weekday and weekend hot water use. For sinks, showers, and baths, a mixed use temperature of 105°F (40.6°C) is assumed to account for the tempering of hot water to a useful temperature. Dishwasher and clothes washer hot water use is assumed to be untempered. Hot water use varies depending on the mains water temperature, which is modeled using an algorithm based on annual weather (Burch & Christensen, 2007). The delivered energy is shown in Figure 1.

The building models are benchmark buildings based on the Building America House Simulation Protocol and represent current building practices (Hendron & Engelbrecht, 2010). Each home is a 2500-ft^2 (232-m^2), two-story, single-family structure with a 420-ft^2 (39-m^2) attached garage. Although the models are generally consistent with the House Simulation Protocol, they required some simplifications. A full list of simplifications is provided in (Maguire, 2012). The building envelope insulation levels are consistent with 2009 International Energy Compliance Code specifications and vary with climate (ICC, 2009). Foundations varied by state depending on common construction practices (Labs, et al., 1988). Basements dominate the northern U.S., while the southern U.S. is primarily slab on grade. If a home had a basement, that was assumed to be the unconditioned space location where the HPWH was installed. If there was no basement, the unconditioned space was assumed to be the garage. Each home had a reversible ASHP with a heating season performance factor of 7.9 and a seasonal energy efficiency ratio of 13.

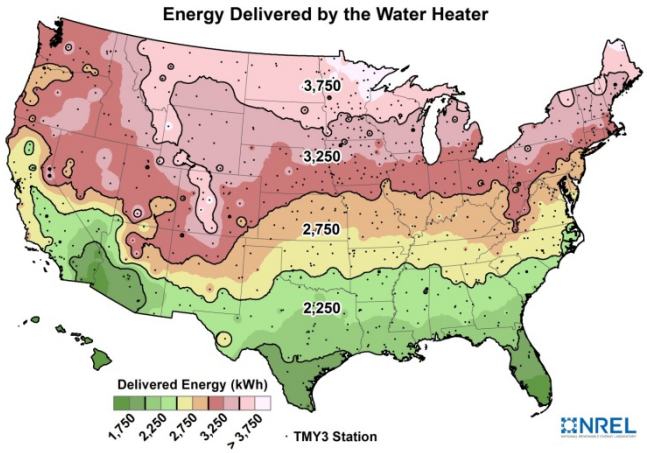

Figure 1: Simulated annual water heating loads for all locations

HPWH EFFICIENCY

The efficiency of the HPWHs is quantified using the system COP (COP_{sys}) metric. COP_{sys} is defined as:

$$COP_{sys} = \frac{E_{del}}{E_{cons}} \tag{1}$$

COP_{sys} is the delivered energy divided by the consumed energy and is calculated in the same way as the efficiency of other water heating systems. This metric takes into account the impact of heat pump COP, tank losses, and all electricity usage. However, it does not take into account any impact of the HPWH on the HVAC equipment or whether the HPWH is fully meeting the load. The COP_{sys} for both HPWHs in conditioned and unconditioned space is shown in Figure 2.

The COP_{sys} of a 50 gallon HPWH in conditioned space is highest in hot and humid locations because the lower loads require less electric resistance element use. Additionally, the higher humidity leads to higher indoor wet bulb temperatures, which improve heat pump performance. In unconditioned space, the same general trend can be seen, although the efficiency is generally lower. The heat pump for the 50 gallon HPWH runs only if the ambient air temperature is 45–120°F (7.2-49°C). For the 80 gallon unit, the operating range is 45–110°F (7.2–43°C). If the ambient air temperature is outside that range the heat pump cannot run and the HPWH will use the electric resistance elements. In unconditioned space in cold or very hot climates this may occur for parts of the year. Even if the unconditioned space temperature stays within these bounds, the lower unconditioned space temperatures in colder climates lead to lower COP_{sys}.

Because the 80 gallon HPWH in conditioned space can run almost exclusively on the heat pump, COP_{sys} increases as the load increases. In a situation with a higher load, a higher proportion of the heat from the heat pump goes to meeting the load instead of making up for standby losses, increasing COP_{sys}. Humidity also impacts overall efficiencies, which are slightly higher in the more humid eastern U.S. The unconditioned space case shows the same general trend as the 50 gallon case, because the unconditioned space air temperature is the driving factor. However, in the 80 gallon case some sharp changes in COP_{sys} occur north of Oregon, Oklahoma, Arkansas, Tennessee, and North Carolina. This is due to a change in the foundation type: the unconditioned space installation location changes from a garage south of this line to a basement in the north. Because the basement temperature is buffered by the ground and conditioned space, it is significantly less variable than the garage temperature. This leads to less time below the 45°F (7.2°C) cutout temperature of the heat pump and a higher annual COP_{sys}. The 80 gallon unit's larger tank volume and control logic differences enable it to run more efficiently than the 50 gallon unit. To determine the impact of each factor, simulations were performed for a 50 gallon HPWH with the 80 gallon heat pump and control logic, as well as an 80 gallon HPWH with the 50 gallon control logic and

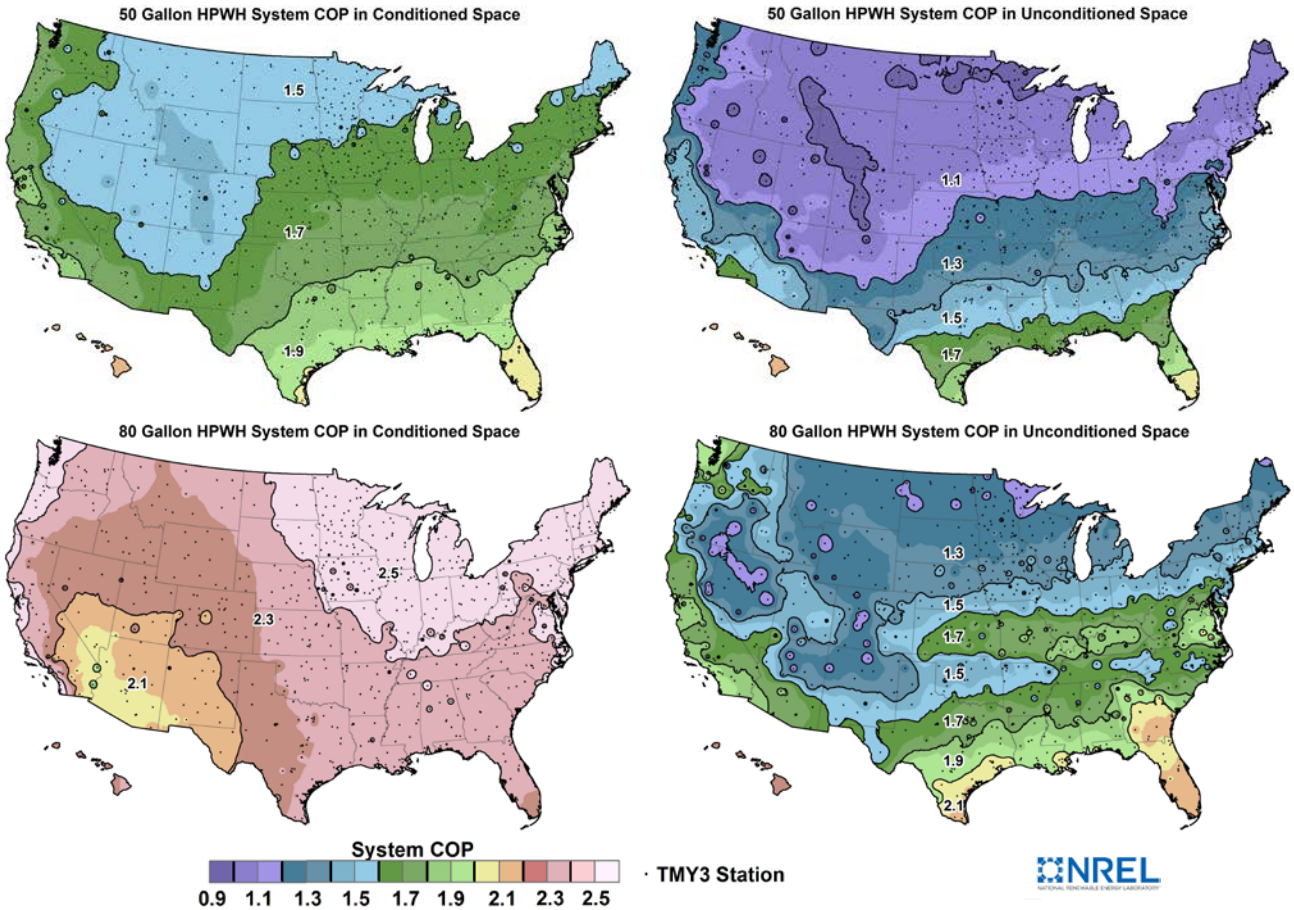

Figure 2: System COP of HPWHs

heat pump for Washington, D.C. Changing the heat pump and control logic increases COP_{sys} by 18%; using the same control logic with a larger tank increases COP_{sys} by 15%. Either change would likely increase COP_{sys} across the country.

ENERGY SAVINGS

The net energy savings of an HPWH is calculated as:

$$E_{saved,HPWH} = \Delta E_{WH} + \Delta E_{nrmlz} + \Delta E_{heat} + \Delta E_{cool} \tag{2}$$

This accounts for any changes in space heating (E_{heat}) and cooling (E_{cool}) as well as water heater energy consumption (E_{WH}). An additional term, the normalization energy (E_{nrmlz}), is added to ensure both water heaters meet the same load. HPWHs, particularly the 50-gal unit, tend to have a harder time meeting the load because the heat pump does not heat the tank as quickly as a typical electric water heater. The normalization energy is calculated as:

$$E_{nrmlz} = \frac{mc_p(T_{out} - T_{req})}{\eta} \tag{3}$$

The efficiency used in this equation is the instantaneous efficiency of the HPWH. The normalization energy calculated here is fictitious—it accounts for situations where the water heater does not meet the load. It can be thought of as having a tankless water heater with an infinite capacity on the outlet of the HPWH that heats water to a useful temperature when the

outlet temperature sags. It ensures a fair comparison between the HPWH and the base case; however, in actual use the sag may be dealt with by raising the HPWH setpoint temperature, using a different HPWH operating mode, or changing daily hot water use patterns. Each method would have different impacts on annual energy consumption. The change in normalization energy accounts for about 10% of the total energy savings. All comparisons in this work were done on a source energy basis. To calculate source energy, the site electricity consumption in each case was multiplied by a national average source to site multiplier of 3.365 (Deru & Torcellini, 2007). The source energy savings of an HPWH for each case are provided in Figure 3.

Although source energy savings follows many of the same trends as the COP_{sys}, several other factors influence the savings. In the southern U.S. the water heating load is smaller, so the water heater energy savings are lower, but the space cooling from the heat pump is a net benefit. In colder locations these trends reverse, although the relatively efficient ASHP used for space heating (average annual heating COP≈2 across all locations) reduces the space heating penalty in colder locations. If less efficient space heating equipment were used (such as electric resistance heat), savings would be much lower in colder climates. In general, the 80 gallon HPWH outperforms the 50 gallon HPWH, although performance is comparable in some of the lower load situations. Savings are generally higher in conditioned space, because the increased water heater energy savings from a higher COP_{sys} outweighs any space conditioning impacts for this set of HVAC equipment.

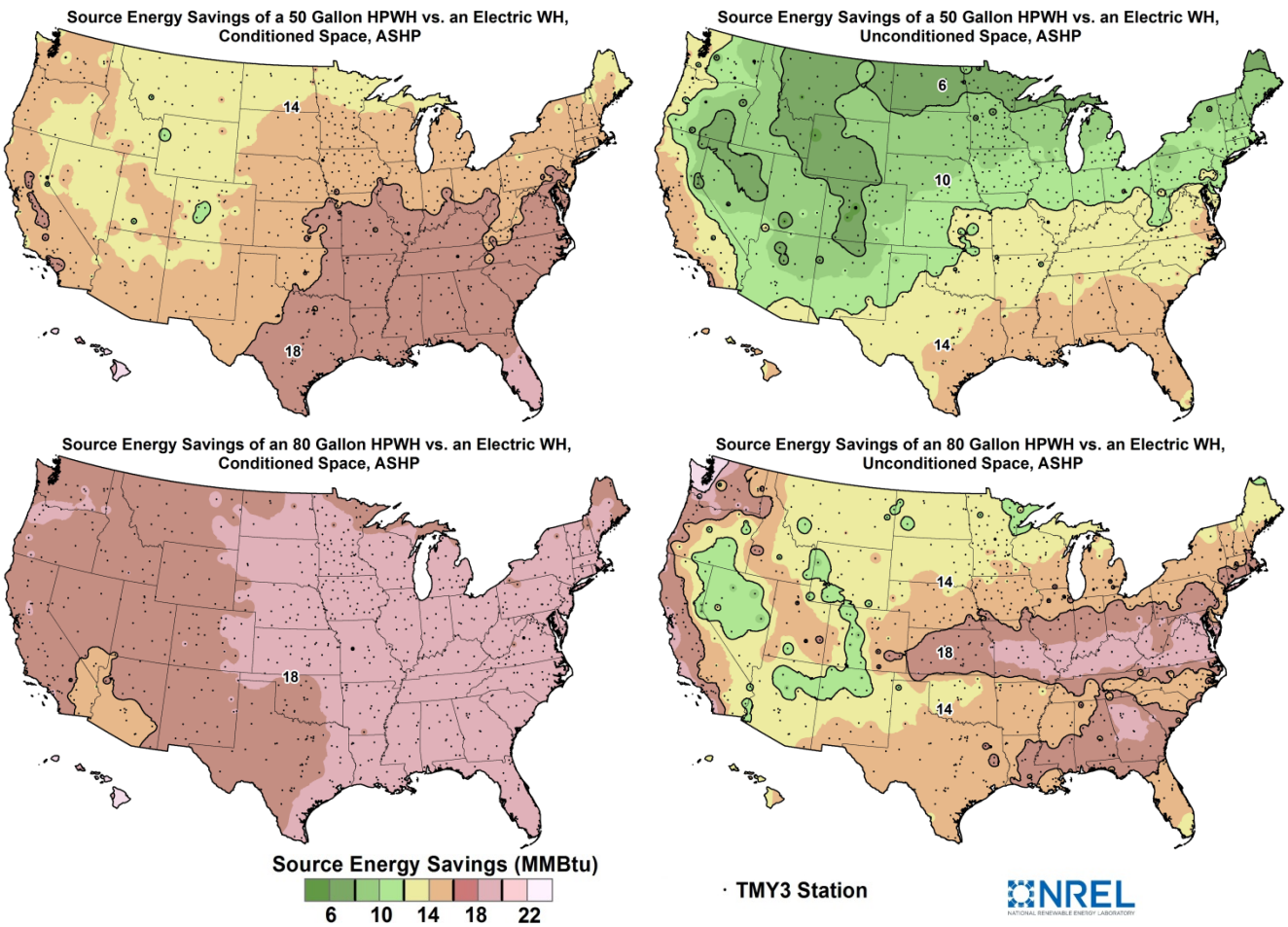

Figure 3: Source energy savings of HPWHs

BREAKEVEN COST

The breakeven cost is calculated to evaluate the economic potential of the HPWH. Breakeven cost is the net installed cost of the HPWH that achieves cost neutrality with a typical electric water heater over its lifetime. It is calculated as the point where all net present benefits of the HPWH (utility bill savings over the unit's lifetime) equal the net present costs (net installed cost and any maintenance costs). Any system with a net installed cost that is lower than the breakeven cost will provide net savings over its lifetime. Several economic assumptions must be made to calculate the breakeven cost of the HPWH. The HPWH would is assumed to be installed when a new water heater is required (either in new construction or after a water heater has failed). The HPWH is assumed to be purchased with cash (no financing) and all water heaters are assumed to have a life of 15 years. The HPWH has a maintenance cost of $100 every 5 years for the heat pump; the typical electric water heater has no maintenance cost. The electric resistance water heater has a net installed cost of $590. A discount rate of 5% and an electricity rate escalation of 0.5%/year are assumed. The HPWH net installed cost is not required for this calculation; however, it is needed to determine if a HPWH is a good investment. Recent estimates for the net installed cost of a 50 gallon HPWH range from $1300-$2200, with an average of $1500 (U.S. DOE, 2010b). An 80 gallon HPWH currently costs about $750 more than a 50 gallon unit and may have a higher installation cost.

The utility costs used here are based on utility specific rates for 2010 (EIA, 2012b). For locations with no utility information available, a state average rate was used. Incentives are not included in the breakeven costs shown here, although there is currently a $300 federal incentive and many local incentives for HPWHs, some as large as $1000 (IREC, 2012). The breakeven cost for the 50 gallon and 80 gallon HPWHs are given in Figure 4 and Figure 5, respectively. The two cases use different scales to empasize that the breakeven cost of 80 gallon HPWH would need to be higher than that of a 50 gallon HPWH to be cost effective.

Breakeven costs vary with utility rates and with energy consumption, so locations with high savings do not necessarily have the highest breakeven costs. The highest breakeven costs are seen in the locations with the highest utility rates, such as Hawaii, California, and New England. The lowest breakeven costs are seen in the Pacific Northwest and northern Mountain region, which have low savings and electricity rates. Breakeven costs generally drop when installing in unconditioned space due to lower energy savings. The breakeven cost of an 80 gallon HPWH increases in many locations due to higher energy savings. However, this increase is smaller than the expected premium that would be paid to install an 80 gallon unit with current prices. Thus, even though the 80 gallon HPWH saves more energy, it may not be cost effective.

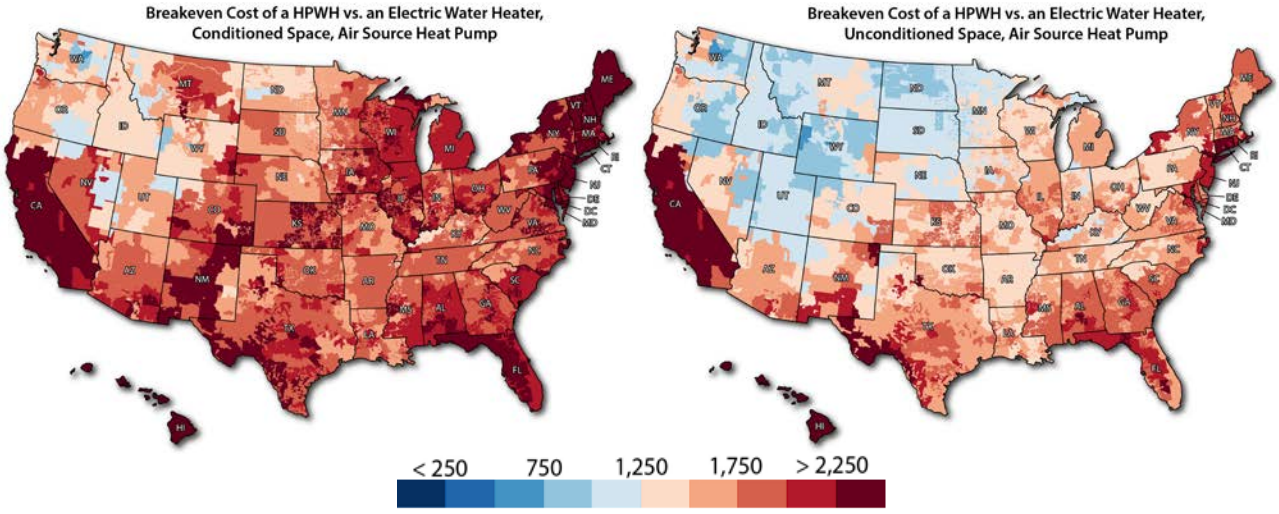

Figure 4: Breakeven cost for 50 gallon HPWHs

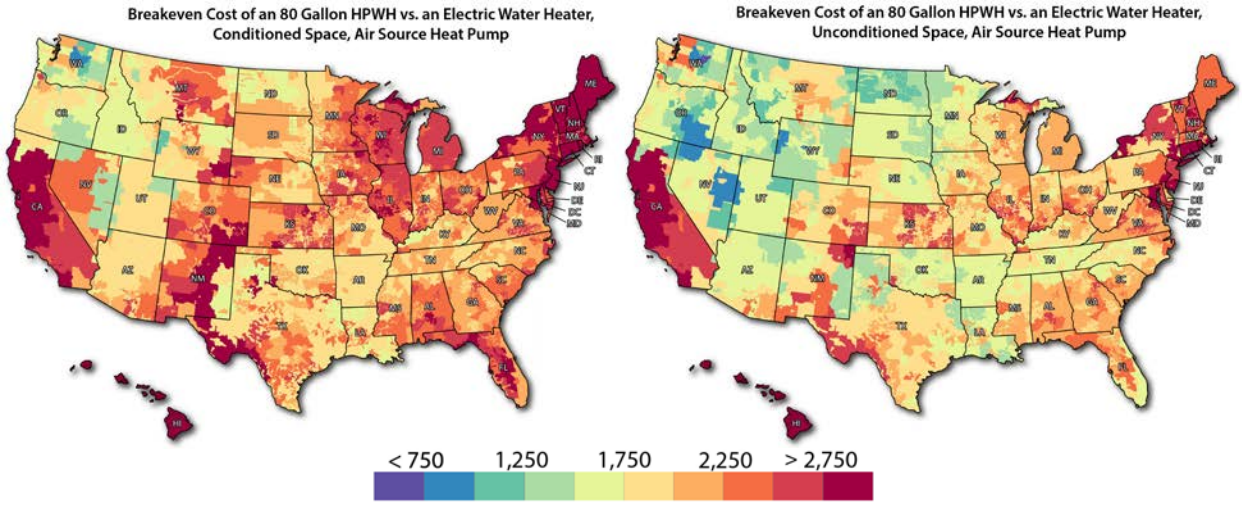

Figure 5: Breakeven cost for 80 gallon HPWHs

CONCLUSIONS

The performance of an HPWH is highly variable across the country. Source energy savings potential varies significantly depending on climate, installation location, and the specific HPWH installed. However, in all locations an HPWH has the potential to save energy over a typical electric water heater. Hot and humid locations have the highest source energy savings potential for units in unconditioned space. Installing in conditioned space saves more energy in most locations because the space conditioning penalty for homes with an ASHP in colder climates is smaller than the decrease in water heater energy savings from lower ambient air temperatures. HPWHs are also likely to be economically viable in many locations. However, many regions with the highest breakeven costs are not areas where electric water heaters are common.

The impacts of several factors have been explored here; however, other important variables such as the fuel used by the water heater being replaced, differences between HPWHs of the same volume, space conditioning equipment, building size and vintage, and hot water draw profile are not considered. Other types of space conditioning equipment and cases where gas water heaters are replaced are explored in (Maguire, Burch, Merrigan, & Ong, 2013), but other factors must be considered. Therefore, care must be taken in extrapolating these results to any particular home.

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NOMENCLATURE

ASHP	= air source heat pump
c_p	= specific heat at constant pressure
COP	= coefficient of performance
E	= energy
EF	= energy factor
HPWH	= heat pump water heater
m	= mass of water drawn

T = temperature

η = efficiency

Subscripts

cool = cooling

cons = consumed

del = delivered

heat = heating

nrmlz = normalization

out = outlet

req = required

sys = system

WH = water heater

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