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ABSTRACT

Electric resistance storage water heaters were replaced with heat pump water heaters (HPWH) in eight Central Florida homes in 2013. Comparison of one year pre and post-retrofit hot water energy showed 68.5% (5.3 kWh/day) sub-metered savings. Beyond heating water efficiently, HPWH create cool air as a byproduct, which could be used to supplement space cooling. However, common practice in Florida is to locate water heaters in attached garages.

A lab test was undertaken to investigate the effect of coupling a garage located HPWH to the conditioned space with ductwork. With the HPWH ducted to and from the interior, cooling energy dropped by 3.5% or 0.8 kWh/day. Effect on space heating energy for this configuration could not be determined. Experiments also investigated using an outdoor air source for the HPWH, to supplement ventilation. During the cooling season, the HPWH tempered the outdoor air with only a minimal impact on cooling energy. Space heating energy increased by 17.5% or 1.4 kWh/d. The space coupling of the HPWH had a minimal impact on water heating efficiency.

In later field evaluation, eight occupied homes were retrofitted with a HPWH coupled to the conditioned space. Two configurations were evaluated: interior location (3 homes) and garage with ducting to and from conditioned space (5 homes). Results were more pronounced than the lab evaluation: cooling energy savings averaged 8% (1.1 kWh/day). Space heating energy use increased by 24.1%, although with considerable variation.

The cost of coupling the garage located HPWH to the conditioned space was $620. Average cooling savings for ducted sites was $49/year, for a 12.6 year simple payback. However, the space heating energy penalty cut savings by one third. This penalty could be largely eliminated in winter with a damper system to divert cold exhaust air from the conditioned space.

Introduction

The Building America Partnership for Improved Residential Construction (BAPIRC), led by the Florida Solar Energy Center (FSEC), investigated the effect of ducted and interior located heat pump water heaters (HPWH) on space conditioning energy use and water heating energy use. A growing volume of research is revealing how HPWH have potential to save significant amounts of site and source energy over alternative electric storage water heating options. In a recent study by the Florida Solar Energy Center, eight Central Florida homes had electric resistance water heaters replaced with HPWH. Comparison of one year pre and post-retrofit water heating energy showed 68.5% (5.27 kWh/day) sub-metered savings (Parker 2014). Other studies have utilized modeling and simulation to show that even when considering the impact of the cold air byproduct of HPWH on space conditioning energy use, interior installation in most climates still results in significant energy savings (Maguire 2014, Sparn 2012). Cooling dominated climates stand to benefit the most from this space coupled cooling effect. A few studies have evaluated this impact experimentally, in select climates, with monitored data (Munk 2010). One study looked at the impact of ducted and unducted HPWH in conditioned attics in five homes in Georgia and South Carolina spanning climate zones 2-4 (Roberts 2016). There remains a need to experimentally quantify impact on space conditioning in hot humid climates.

Common practice for new construction in Florida is to locate the water heater in an attached garage. Also, much of the existing housing stock also has the water heater located in the garage. This report describes results from experiments that ducted the exhaust air from a garage located HPWH to the conditioned living space. Experiments were conducted in a residential laboratory building at the Florida Solar Energy Center in Cocoa, FL[1]. In addition, data is presented from eight occupied homes located throughout Brevard County, FL. Five homes had an electric resistance (ER) water heater replaced with a garage located HPWH ducted to the living space. Three homes had an ER water heater replaced by and interior HPWH.

Evaluation Methods

Laboratory Experiments

Laboratory experiments were conducted in a 1,536-ft^2 single-story building (volume = 14,208 ft^3) constructed to mimic typical existing Florida housing stock, with uninsulated concrete block walls, single pane windows, R-19 ceiling insulation, and SEER 13 cooling system with electric resistance heat. The enclosure is moderately leaky (8 ACH50), and the building has no forced mechanical ventilation. To maintain a well-mixed, single zone, full height interior walls for the 3 bedroom, 2 bathroom design were never constructed. Instead, half-height, moveable wall modules were built and installed in order to simulate the moisture capacitance of a fully constructed building, while maintaining excellent air circulation throughout the space.

Occupancy is simulated through creation of sensible and latent gains (15.5 kWh/d and 11 lbs/day respectively). The rate of heat generation varies hourly, according to a family realistic schedule (Fang 2011). The hot water schedule was derived using a hot water random event generator developed by the National Renewable Energy Laboratory (NREL) (Hendron 2008). These values were averaged by month to create the monthly average gallons per day of hot water used for the experiment (Figure 1).

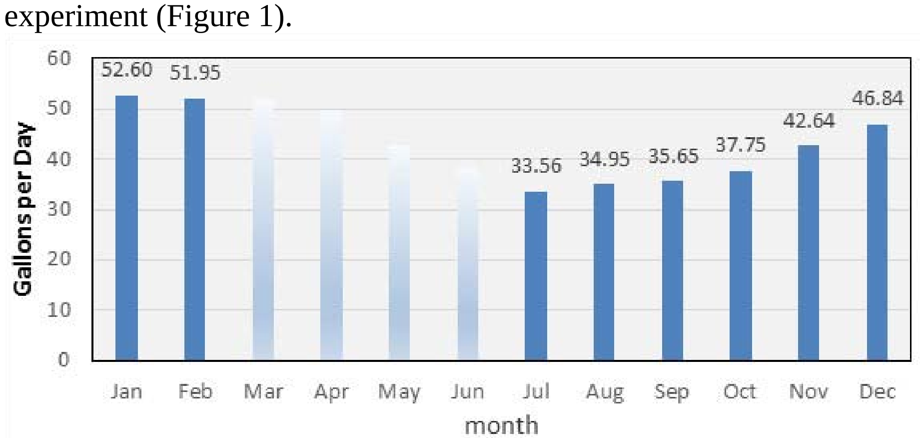

Figure 1. Daily volume of hot water utilized for the eight month testing period.

[1] Lab results represented are the average of two identical HPWH installed in two, side-by-side labs, each 1,536 sqft. Labs were identical with the exception that one lab was carpeted and one had an exposed slab.

The hourly schedule for hot water draw events on June 6 (Figure 2) was chosen to represent a family-typical daily schedule. This profile was maintained throughout the experiment, with event magnitudes adjusted proportionally to varying monthly gallons per day.

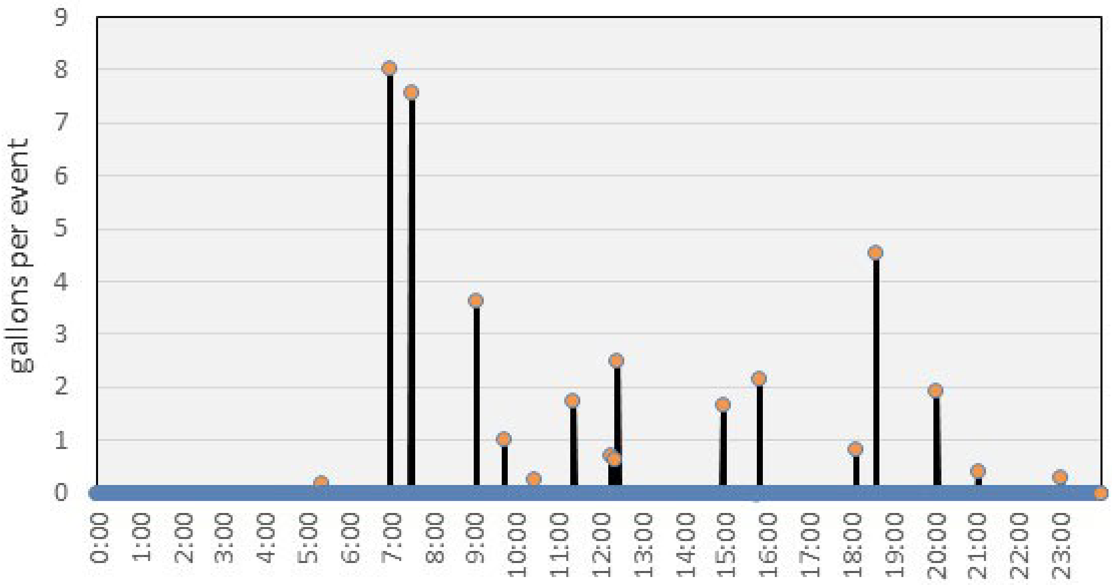

Figure 2. Daily schedule of hot water draws from the NREL hot water event generator.

An A.O. Smith 60 gallon Voltex model PHPT-60 water heater was installed in the garage of the lab building. This unit was selected because of the availability of a ducting kit, and relevance to other ongoing research. The unit was set to run in hybrid mode, allowing both heat pump and electric resistance operation, and water temperature was set to 125 ^{o}F. A dampered ducting scheme was developed allowing for flexibility of locations from which to draw intake air, and to discharge exhaust air (Figure 3). Grey lines indicate actual duct runs which utilized 8” smooth wall, insulated metal duct. Colored lines indicate intake/exhaust air pathways. Figure 3 also shows the initial duct installation before wrapped with R-6 insulation. The HPWH discharge duct terminated into a directional grill to divert airflow towards the center of the indoor space. The separation between the discharge to the indoor space and the intake from the indoor space is 62” apart. The HPWH manufacturer recommends that a total duct length of 10 feet on the combined intake and exhaust sides is not exceeded. However, to accommodate the experiment, total duct run generally exceeded that depending on the configuration utilized. This measured 6’11” for the Garage to Garage, 15’11” for the Indoor to Indoor, and 18’8” for the Outdoor to Indoor flow paths, as measured from the installed 8-inch duct collars.

The baseline, or reference configuration against which all experimental configurations are tested is the purple garage to garage path in Figure 3, which represents a typical, non-ducted, garage HPWH installation in Florida in terms of air source and air discharge location. During the experimental period of July 2014 – February 2015, dampers were adjusted about every 10-days to switch among this reference path and:

- The red outdoor to indoor path, pulling in outdoor air as a high temperature heat source to maximize water heating efficiency, and discharging cooler, dryer exhaust air to the conditioned space. Because this acts as supply ventilation to the conditioned space, air cannot be pulled from the garage due to indoor air quality reasons.

- The green indoor to indoor path, which would also represent an interior HPWH installation, except for reduced tank losses afforded by the relatively warm garage location.

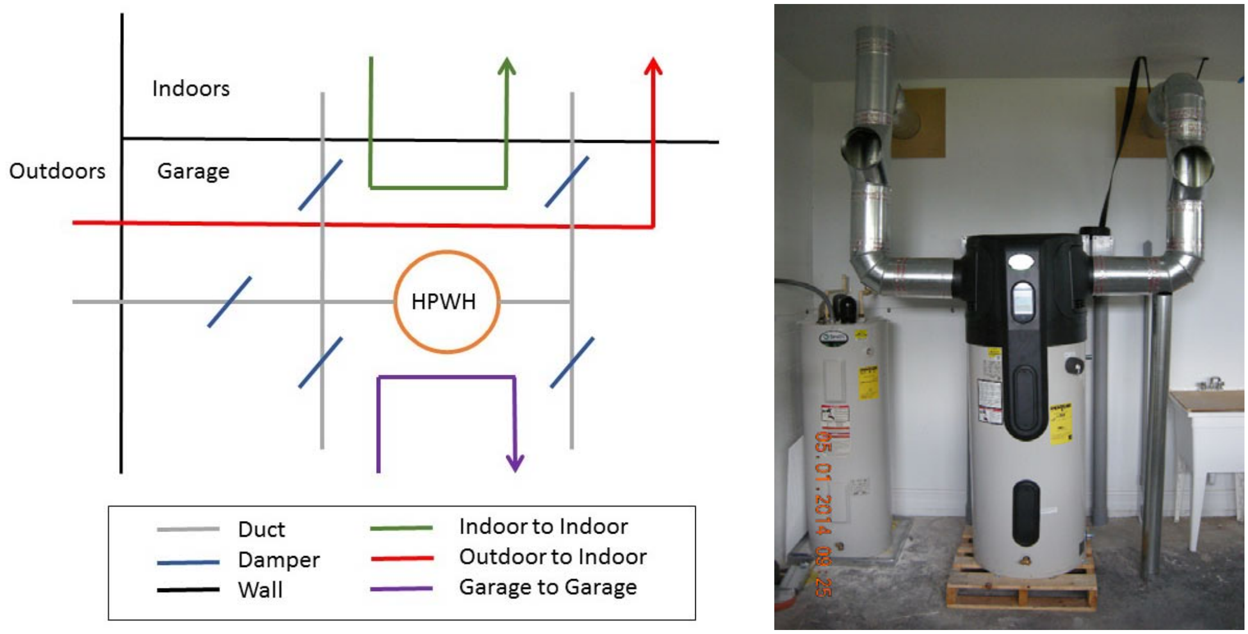

Figure 3. Dampered HPWH ducting scheme (left). Grey lines: duct runs, colored lines: air pathways. Dampers allow directional switching of air flow (blue). Ducting of intake and exhaust air using 8” smooth metal duct (right).

Table 1 summarizes the measurements and equipment used to conduct laboratory testing and data acquisition for the project.

Table 1. Equipment used for laboratory monitoring

Category	Measurement	Location	Type	Accuracy
HPWH Performance	Intake/Exhaust Air Temperature and RH	duct	volts	0.5ºC / 3%RH
	Airflow	Duct termination (register)	powered flow hood	5%
	Inlet/Outlet Water Temperature	pipe	type T thermocouple	
	Water Flow	outlet	positive displacement	1.5%
Interior Room Conditions	Temperature and RH	thermostat	volts	0.5ºC / 3%RH
Power Use	Air handler	panel	pulse watt hours	0.5%
	Condenser	panel	pulse watt hours	0.5%
	HPWH	panel	pulse watt hours	0.5%
Weather	Outdoor T/RH	tower	volts	0.5ºC / 3%RH

Measured airflow varies based on duct length and damper settings as shown in Table 2. Compared to the manufacturer stated non-ducted airflow of 450 cfm, airflows are reduced about 64% with ducted installation. Also shown in Table 2 is the measured water heating COP. The

COP was calculated using the daily sum of hot water energy output by the sum of electric energy input. Results indicate very little difference in COP as a function of source of intake air, which varied from a high of 97 °F in the garage to a low of 31 °F outdoors. In other research performed at FSEC, similar efficiency (COP=2.2) was obtained for a non-ducted version of this HPWH with greater hot water loads imposed (Colon 2016).

Table 2. Ducted HPWH airflow and water heating COP for each flow path.

Airflow Configuration	Measured Airflow (cfm)	Building Pressure Impact During HPWH Operation	Measured HPWH COP
Garage to Garage	160	None	2.1 ± 3.4%
Indoor to Indoor	157	Balanced pressure	2.1 ± 3.4%
Outdoor to Indoor	148	Positive pressure	2.2 ± 3.4%

Field Experiments

Electric resistance water heaters were replaced with HPWH in 8 homes from FSEC's Phased Deep Retrofit (PDR). In the PDR project, BAPIRC collaborated with Florida Power & Light (FPL) utility to conduct a phased residential energy-efficiency retrofit program (Parker 2014). Site characteristics for the 8 homes are provided in Table 3.

Table 3. Heat pump water heater retrofit site characteristics

Site #	City	Year Built	Living Area (ft^2)	House Airtightness (ACH50)	AC SEER	Space Heating
1	Merritt Island	1961	2,028	13.7	13.0	Heat Pump
5	Rockledge	2006	2,328	5.6	13.0	Heat Pump
9	Melbourne	1984	1,013	12.9	< 13	Resistance
13	Merritt Island	1963	1,052	16.4	15.5	Heat Pump
26	Palm Bay	1999	1,502	4.7	17.0	Heat Pump
50	Melbourne	1958	2,168	5.5	17.0	Resistance
51	Cocoa	1994	2,233	8.3	16.0	Heat Pump
56	Merritt Island	1963	1,000	13.5	10.0	Resistance

Three different HPWH were evaluated—the GE 50-Gallon GeoSpring, Airgenerate 66-gallon model ATI66DV[2], and A.O. Smith Voltex model PHPT-60. FSEC has previously reported on the performance of these units in a laboratory setting at its Hot Water Systems Laboratory (Colon 2013 and Colon 2016).

[2] Airgenerate HPWH are no longer available.

Three homes received a GeoSpring unit as a replacement for an electric resistance tank. Two were the newer model GEH50DFEJSR, and one was the original model GEH50DNSRSA. The GE units were located in interior utility rooms in each home. Three additional homes each received an Airgenerate unit as a replacement for an electric resistance tank. The DV model came equipped for ducting air to and from the unit, and each unit was installed in an attached garage. Two homes had previously received Voltex models as replacements for electric resistance tanks as part of the PDR project. These two units, each located in attached garages, were modified with A.O. Smith's available ducting kits for the Voltex. The Voltex and Airgenerate units were then ducted such that air used for heat pump operation was pulled from, and returned to, the conditioned living environment. Insulated metal and flex duct was used for ducting, and air was pulled from and supplied to the same general location in each home (Figure 4).

Figure 4. HPWH configurations: Left, interior GE unit in utility room, Site 13; center, ducted Airgenerate unit at Site 5; right, ducted A.O. Smith unit at Site 26.

Table 4 summarizes the measurements and equipment used to conduct field testing:

Table 4. Equipment used for field monitoring

Measurement	Location	Type	Accuracy
Temperature and RH	thermostat	portable temperature & RH logger	±0.95°F ±3.5% RH
End use energy (space heating, cooling, water heating)	panel	pulse watt hours	±1%
Air Flow	grille	powered flow hood	5%

Airflow entering the conditioned space was measured during installation for all ducted units (Table 5). Airflow for the GE units was not measured as there is no ducting option. Ducted airflow was in the range of 113–130 CFM for three of the five ducted units. One unit had very low airflow (31 CFM), due to a long duct run. One unit had higher airflow (225 CFM) due to very short duct run.

Table 5. Retrofit heat pump water heater installation and commissioning summary

Site #	Model	Rated Efficiency in Hybrid Mode (EF)	Ducted Airflow (Tested CFM)	Location Receiving HPWH Air
1	GE	2.35	n/a	Utility room
5	Airgenerate	2.35	130	Dining Room
9	Airgenerate	2.35	113	Office
13	GE	3.25	n/a	Utility room
26	AO Smith	2.33	115	Bedroom
50	Airgenerate	2.35	225	Dining Room
51	AO Smith	2.33	31	Kitchen
56	GE	3.25	n/a	Utility room

Results and Discussion

Laboratory Experiments

Data was collected during the period of July 2014 – February 2015. The monthly cooling energy delivered by the HPWH to the building for each flow path is shown in Figure 5 and was determined by calculating a space enthalpy change as follows, with an estimated error range of 8%:

Q (Btu/day) = Sum [(space air enthalpy) – (HPWH exhaust air enthalpy)] * HPWH airflow

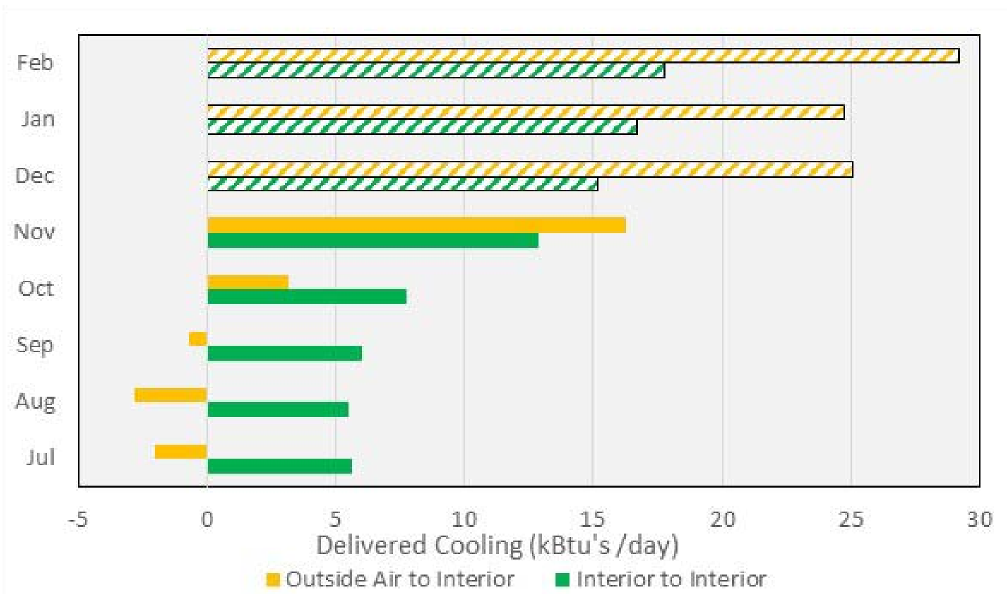

Figure 5. Average daily cooling energy delivered to the building by the HPWH. Hatched bars indicate heating season, solid bars indicate cooling season. Negative values indicate heat was added to the space.

For these experiments, the laboratory cooling set point was 77 ^{o}F and the heating set point was 73 ^{o}F[3]. The average day outdoor temperature profile for days the Outdoor to Indoor experiments were running is shown in Figure 6.

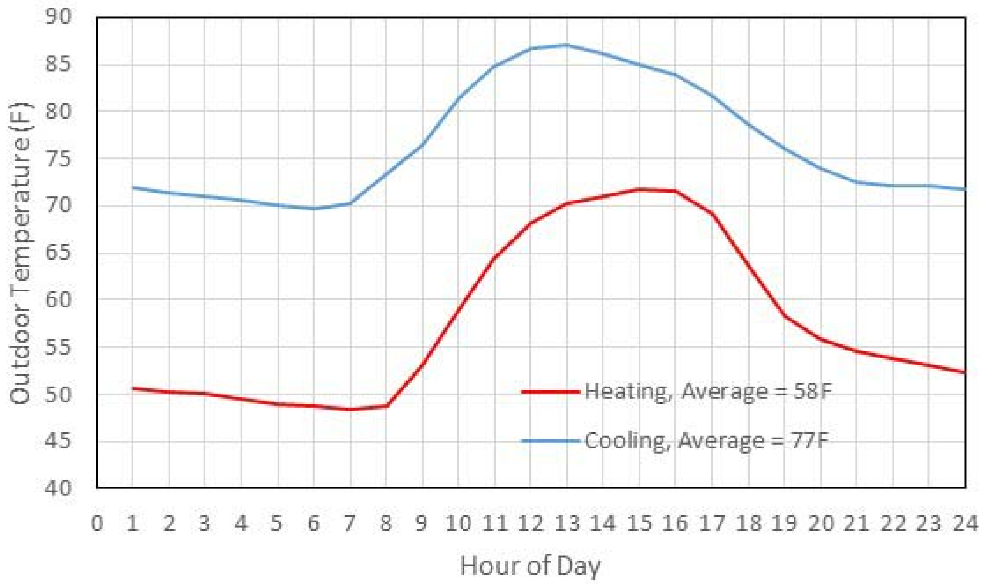

Figure 6. Average day outdoor temperature profile for Cocoa, FL for the days the Outdoor to Indoor flow path experiments were running.

During winter months, ducted HPWH configurations increased heating loads by approximately 16.5 kBtu/day for the indoor to indoor airflow configuration and approximately 26.3 kBtu/day for the outdoor to indoor airflow configuration. Regression analysis of daily space conditioning energy vs. daily average difference in outdoor and indoor temperature determined a heating energy increase of -0.2 kWh/d (-2.5%) and 1.4 kWh/d (17.5%) respectively. The decrease for the Indoor to Indoor flow path is likely from insufficient data for that configuration, resulting from a lack of days with sufficiently cold weather.

During summer months, average monthly auxiliary net cooling effect (Δh) provided by the HPWH increased from 5.6 kBtu/day (1.6 kWh) in July of 2014 to 12.9 kBtu/day (3.8 kWh) in November 2014 when utilizing the indoor to indoor airflow configuration (green bars in Figure 5). As seen in Table 6 this resulted in a savings of 0.8 kWh/day, or 3.5%. When using the outdoor to indoor airflow pathway (yellow bars in Figure 5), the HPWH was not able to completely mitigate the load imposed by the outdoor air, and a small net cooling load was added to the building during peak summer months. This resulted in a small (1%) cooling energy penalty which the authors consider to be very minor considering the outdoor air flow rate could constitute approximately 40% of the mechanical ventilation requirements of ASHRAE 62.2-2013[4]. Control of timing of outside air delivery would be required to comply with the standard.

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[3] A higher than typical heating set point is used to generate good signal given Florida's mild winter.
[4] At 8 ACH50, ASHRAE 62.2-2013 calls for 39 cfm of fan mechanical ventilation. Testing the Outdoor to Indoor flow path, the HPWH ran for 153 min/day on average during the testing period delivering 148 cfm of outdoor air.

Table 6. Space conditioning savings compared to baseline: two HPWH airflow configurations.

Flow Path	Average Space Heating Energy (kWh/day)	Space Heating Savings (kWh/d)	Average Cooling Energy (kWh/day)	Cooling Savings (kWh/d)
Garage to Garage	8.0	N/A	22.6	N/A
Indoor to Indoor	7.8	0.2 (2.5%)	21.8	0.8 (3.5%)
Outdoor to Indoor	9.4	-1.4 (-17.5%)	22.9	-0.3 (-1.3%)

Field Experiments

All the HPWH were installed and/or ducted between July and October 2014, and left in their default, hybrid operation modes. For most sites, data for the period of July 2013–July 2015 were analyzed. For Sites 1, 13, and 51, the pre-retrofit period was shorter due to other HVAC installation measures potentially confounding data, and space heating analysis had limited pre-retrofit data.

To identify heating and cooling days, heating and cooling balance point temperatures were determined for each site by plotting daily average space conditioning energy use vs. daily average outdoor temperature. Regression analysis was then performed to determine space conditioning energy savings using daily space conditioning energy vs. daily average temperature. Difference between average daily indoor and outdoor temperature was used in the cooling regressions as it normalized differences in average indoor temperature between pre- and post-retrofit periods, which exceeded 1°F in some houses. Also, operation of the ducted HPWH could alter the interior temperature profile. Cooling results are shown in Table 7, with average savings double that of the lab test.

Table 7. Cooling analysis results for space-coupled heat pump water heater retrofits

Site #	# of Occupants	HPWH Coupling	HPWH Energy Post (kWh/day)	Cooling Energy Pre (kWh/day)	Cooling Energy Post (kWh/day)	Cooling Savings (kWh/day)	Cooling Savings (%)
1	4	Interior	2.1	16.3	14.5	1.8	10.8
5	2	Ducted	2.7	44.7	43.0	1.7	3.8
9	2	Ducted	3.2	11.5	10.0	1.5	13.2
13	2	Interior	2.6	6.8	6.1	0.7	10.7
26	5	Ducted	3.5	11.5	10.1	1.4	12.3
50	4	Ducted	2.7	18.5	17.8	0.7	3.9
51	2	Ducted	1.3	15.0	14.2	0.8	5.6
56	3	Interior	3.1	18.9	18.7	0.2	2.7
Average	3	N/A	2.6	17.9	16.8	1.1	7.9
Median	2.5	N/A	2.7	15.6	14.3	1.1	8.2

Figure 7 shows the regressions for Site 9, clearly demonstrating reductions in space cooling energy after coupling the HPWH to the conditioned space.

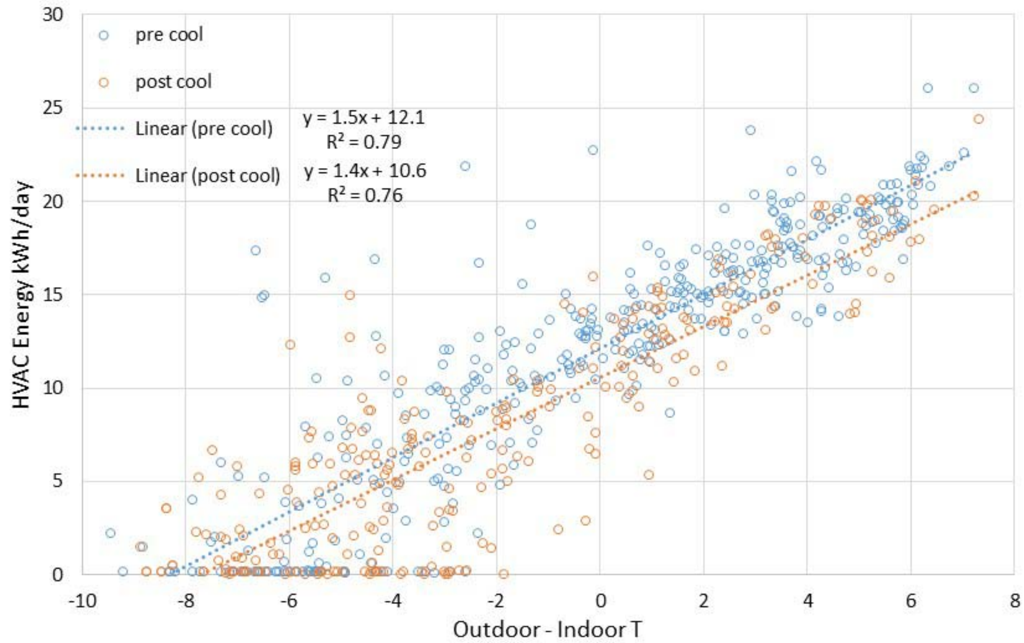

Figure 7. Daily HVAC energy vs. daily average temperature difference for Site 9.

Like Site 9, Sites 1, 13, and 26 also exhibit relatively parallel regression lines indicating cooling savings across a wide range of daily average outdoor temperatures. These sites also exhibit the largest percentage reductions in cooling energy use. Figure 8 is the post-retrofit composite average day's water heating power for these sites. Sites 9, 13, and 26 display both a morning and an evening hot water energy use peak (bi-modal), with the evening peak dominating for Sites 13 and 26. Site 1 peaks in the middle of the day, with some evening operation. It is possible late day HPWH operation provides cooling as the house recovers from load imposed during the hottest part of the day (summer peak demand) when it is needed most.

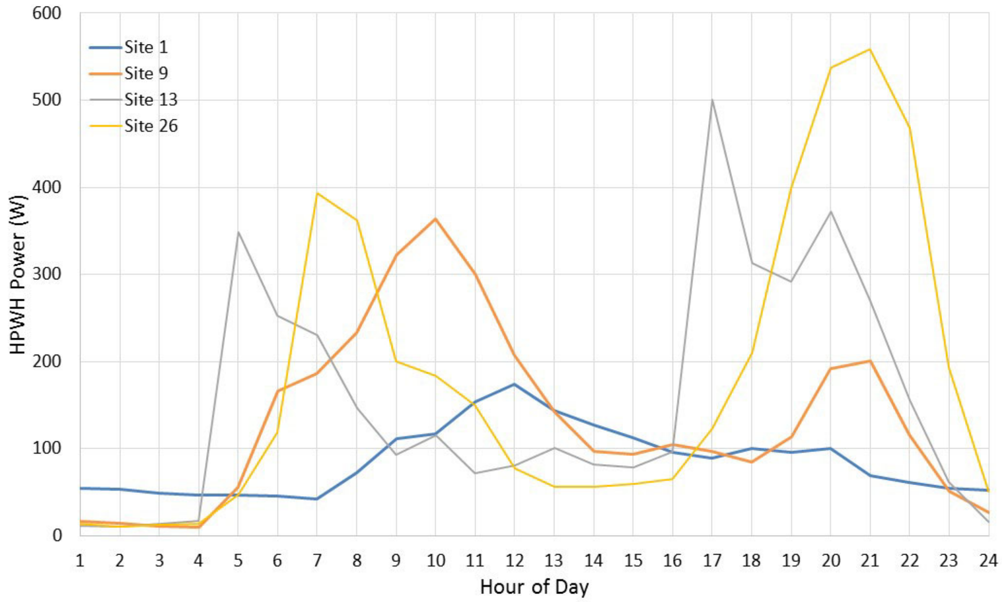

Figure 8. Post-retrofit composite average day's total water heating power for Sites 1, 9, 13, and 26

In Table 7, Sites 5, 50, 51, and 56 show lower cooling savings. Regression lines for these sites show savings at low Delta T, but converge at Delta Ts between 2°– 4°F. Examining hourly water heating power for these sites (not shown) reveals that sites 5, 50, and 51 exhibit peak HPWH power consumption in the early morning hours, with little daytime and evening operation. It is likely that during the morning, when outdoor temperatures are cooler and less demand is placed on the cooling system, extra cooling provided by a coupled HPWH is less beneficial. This is because the HPWH exhaust depresses space temperature below the thermostat set point, but without energy savings.

Space heating regressions were conducted using outdoor temperature, rather than Delta T and results are provided in Table 8. The need for space heating in Florida is sporadic, and changing occupant preferences and tolerances result in highly variable indoor temperatures. As expected, coupling the HPWH to the conditioned space increases space heating energy. However, the increase in space heating energy, with a median of 0.8 kWh/day (8.9%), is a more realistic result than that found in the lab experiments, with large increases in space heating energy obtained for sites 5 and 9.

Table 8. Space heating analysis results for space-coupled heat pump water heater retrofits

Site #	# of Occupants	Coupling	HPWH Energy Post (kWh/day)	Heating Energy Pre (kWh/day)	Heating Energy Post (kWh/day)	Heating Savings (kWh/day)	Heating Savings (%)
1	4	Interior	Insufficient Data				
5	2	Ducted	2.7	6.1	16.6	-10.5	-173.4
9	2	Ducted	3.2	4.9	9.2	-4.3	-88.8
13	2	Interior	Insufficient Data				
26	5	Ducted	3.5	3.7	4.0	-0.3	-8.9
50	4	Ducted	2.7	14.8	12.9	2.0	13.4

Site #	# of Occupants	Coupling	HPWH Energy Post (kWh/day)	Heating Energy Pre (kWh/day)	Heating Energy Post (kWh/day)	Heating Savings (kWh/day)	Heating Savings (%)
51	2	Ducted	Insufficient Data				
56	3	Interior	3.1	14.4	15.2	-0.8	-5.3
Average	3.2	N/A	2.6	8.8	11.6	-2.9	-24.1
Median	3	N/A	3.1	6.1	12.9	-0.8	-8.9

As expected, coupling a HPWH to the conditioned space has a negative effect on space heating. One way to counter this effect for a ducted HPWH is to install a damper system allowing cold HPWH exhaust air to be diverted from the conditioned space. Many of the ducted installations described in this report were installed with such a damper system, allowing the homeowner to take action if the cold HPWH exhaust air became a comfort problem (Figure 8), but findings indicate that none of the homeowners used the system.

Figure 8. Ducting arrangement at Site 5 allowing cold exhaust air to be diverted from the conditioned living environment if comfort became an issue during winter.

It is important to note that without a corresponding damper on the HPWH intake allowing air to be drawn from outside of the conditioned space (like that used in the lab experiment), some amount of space depressurization could occur during HPWH operation. The impact of that space depressurization and possible increase in infiltration on space-conditioning energy is not known.

The effect of HPWH retrofits on domestic hot water (DHW) energy use was also investigated, again using data for the period of July 2013–July 2015, inclusive of both heating and cooling seasons. As seen in Table 9, the six sites receiving coupled HPWH as replacements to electric resistance tanks had a median savings of 53.3% in DHW energy.

Table 9. Heat pump water heater electrical energy savings

Case	Site #	# of Occupants	DHW Energy Pre (kWh/day)	DHW Energy Post (kWh/day)	DHW Savings (kWh/day)	DHW Savings (%)
Electric Resistance Replaced with Space- Coupled HPWH	1	4	3.6	2.1	1.5	42.1
	5	2	7.0	2.7	4.3	61.3
	9	2	7.0	3.2	3.8	54.3
	13	2	6.2	2.6	3.6	57.4
	50	4	5.5	2.7	2.9	52.2
	56	3	5.9	3.1	2.8	47.6
Average		2.8	5.9	2.7	3.1	53.6
Median		2.5	6.1	2.7	3.2	53.3
Existing HPWH Ducted	26	5	2.9	3.5	-0.6	-21.7
	51	2	1.1	1.3	-0.1	-11.7
Average		3.5	2.0	2.4	-0.4	-15.9

As expected, the two sites that had HPWH for more than 1 year prior to ducting them showed slight increases in DHW energy use after the HPWH were coupled to the conditioned space (0.4 kWh/day). This study estimates that the coupling reduced potential DHW energy savings from a garage-located HPWH by 10.6% (0.4/3.6 kWh/day, where 3.6 = 3.2 kWh/day saving for electric resistance replacements + 0.4 kWh/day loss for existing ducting). In Florida, using garage air as a heat source is beneficial for HPWH water heating operation because garage temperatures are high for much of the year. Changing to a room temperature heat source can be expected to impact water heating efficiency. The lab experiments did not show this to effect COP (Table 2), but a reduction in COP may result from the airflow reduction caused by the ducting itself.

Analysis of seven other PDR sites that were retrofitted under an earlier phase of the study (Phase I) with unducted HPWH was conducted to act as a control group for analysis, to normalize for factors affecting water heating energy other than ducting. While the results varied among sites ranging from a 13% reduction in water heating energy to a 26% increase, an average of a 6.5% increase in DHW energy for this control group is less than the 16% found for the two ducted sites. Therefore, DHW energy savings when replacing an ER tank with a HPWH is expected to be greater if the unit is coupled to the garage rather than the conditioned space. In Phase I of PDR research (Parker 2014) DHW energy savings from replacing an ER water heater with an uncoupled HPWH in seven sites averaged 68.5% (5.3 kWh/day). Phase I percent savings for uncoupled HPWH matches well with the results presented here if the 15.9% savings loss from coupling (Table 9) is added to the observed 53.3% savings for the coupled units (53.3% + 15.9% = 69.2%). Absolute savings from uncoupled units in Phase I (5.3 kWh/day) are greater than what can be extracted here (3.2 kWh/day newly installed HPWH + negative 0.4 kWh/day existing HPWH = 3.6 kWh/day), because Phase I targeted households with the highest DHW energy consumption and had a mix of 60- and 80-gallon HPWH retrofits. Homes described in this paper used less DHW on average, and retrofits only included 60-gallon HPWH.

The cost to install the ducting to couple the HPWH to the conditioned space, inclusive of duct kit, other materials and labor, was $620. While details of each installation varied, the contractor charged a flat rate for each job. Median annual cooling savings for the ducted sites was $49/year, assuming $0.12/kWh, yielding a simple payback of 12.6 years. A median space heating energy penalty of $16 cut these savings by a third, yielding a simple payback of 18.4 years, nearly the ducting's 20-year expected life. Therefore, due to the cost of ducting, it is not cost-effective to couple a HPWH installed in a garage to the conditioned space. However, there is a small benefit to installing a HPWH in a location inside the conditioned space versus a garage location. One could expect a small (~$17/year) penalty on water heating energy savings due to the relatively cooler indoor air versus garage air, but the overall savings on space-conditioning energy (~$34/year) outweighs this penalty. These savings, however, may not adequately cover cost of rerouting plumbing to an interior location if the water heater was originally designed to be located elsewhere.

Conclusions

To determine if coupling a HPWH to the conditioned space can have a net positive effect on space conditioning and water heating energy, lab and field tests were done. For the lab test, a garage located HPWH was ducted to and from the conditioned space. Average monthly auxiliary net cooling energy provided by the HPWH increased from 5.6 kBtu/day (1.6 kWh) in July of 2014 to 12.9 kBtu/day (3.8 kWh) in November 2014. This resulted in an approximate cooling energy savings of 0.8 kWh/day, or 3.5%. When instead using outdoor air as a source, the HPWH was not able to completely mitigate the load imposed by the outdoor air, and a small net cooling load was added to the building during peak summer months. This resulted in a small (1%) cooling energy penalty which the authors consider minor considering the outdoor air could constitute approximately 40% of the mechanical ventilation air flow requirements of ASHRAE 62.2-2013. The space coupling configurations had minimal impact on water heating efficiency.

During winter months the indoor air source resulted in addition of 16.5 kBtu/day of space heating load on average and the outdoor air source added approximately 26.3 kBtu/day of space heating load on average. Due to a lack of data for the indoor air source configuration, regression analysis did not quantify a reasonable impact on space heating energy. However the outdoor air source was determined to increase space heating energy by -1.4 kWh/d (-17.5%).

In later field evaluation, eight occupied homes were each retrofitted with a HPWH coupled to the conditioned space. Two configurations were evaluated: interior location (3 homes) and garage with ducting to and from conditioned space (5 homes). Results were more pronounced than the lab evaluation. Cooling energy savings averaged 8% (1.1 kWh/day), and sites benefiting the most appeared to have more water use in the early evening, close to the summer space conditioning peak load, than sites that used most hot water in the morning, when supplemental cooling is less beneficial. Space heating energy use increased by 3 kWh/d (24.1%) on average with considerable variation. With relatively few heating days, the effect on annual energy use is relatively minor in Central Florida.

This study estimates that the coupling increases HPWH energy use by 16% (0.4 kWh/d), and replacing a garage located electric resistance tank with a coupled HPWH would generate 10.6% less DHW savings than if the electric resistance tank was replaced with an uncoupled HPWH.

The cost to install all ducting to couple a HPWH to the conditioned space was $620. Due to this cost relative to net savings, it is not cost-effective to couple an HPWH installed in a garage to the conditioned space. Economics may be different if a damper system diverting cold exhaust air from the conditioned space during winter mitigates the space heating energy penalty. There is a small net benefit to installing an HPWH in a location inside the conditioned space.

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