What Does the Future of Space and Water Heating Look Like?
Field Test Results of Combined Space and Water Heating in Low-Load Homes Using CO_2 Refrigerant Air-to-Water Heat Pump

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ABSTRACT

Heat pump water heaters (HPWHs), based on CO_2 refrigerant, have the potential to operate efficiently while introducing negligible amounts of global warming gases from the refrigerant system to the atmosphere. Their wide ambient temperature operating range also allows them to provide heat at cold outdoor conditions. This paper reports on field tests using air-source, split-system CO_2 HPWHs to provide both space and water heating needs in low-load houses with hydronic distribution heating systems using off-the-shelf components. The distribution systems studied include radiant floors, radiators, and fan coils, which each operate at different temperatures with unique impacts on system performance. Test sites are located in the Pacific Northwest, in diverse climates with low temperatures ranging from -16°F to 26°F. The field tests recorded: domestic hot water flow and temperature; space heating loop load, temperature, and water flow; outdoor and interior temperatures; and equipment power consumption. The data were collected at one-minute intervals. The results include total system efficiency for combined space and water heating, plus lessons learned on optimal design and installation. Additionally, the project delivered insights that will be leveraged to more accurately monitor space and water heating systems that are studied in future research projects.

Introduction

Beginning in October 2012, Washington State University (WSU) and its partner Ecotope have been researching the performance and operation of CO_2 refrigerant hydronic heat pump systems in applications ranging from water heating only, to operation for demand response (DR) and to combined space and water heating. Funding has been provided by the Bonneville Power Administration's (BPA) Technology Innovation Program (TIP). The Northwest Energy Efficiency Alliance and Sanden International USA have been key partners through all of this research together with utilities throughout the Pacific Northwest. The research in the first two project stages revealed the potential for adding another load to the heat pump beyond just water heating. In October 2014, research began on the performance of CO_2 refrigerant HPWHs for both space heating and domestic hot water (DHW) in new, low-load homes.

Research Questions:

a. What is the total space and water heating energy use for each site?
b. What is the modeled performance of the space heat function?
c. What is the modeled performance of the water heat function?

Site Selection and Characterization

Sites were recruited from builders participating in high-efficiency construction programs who were interested in innovative space and water heating equipment. The goal of the project was to sample three primary heating climate zones International Energy Conservation Code (IECC) Zones 4C, 5, and 6. Data from these sites is provided in Table 1.

Table 1 Site data

Site #	1	2	3	4	5	6	7	8	9	10
HDD	5,622	6,239	8,851	8,851	5,655	4,461	4,867	4,867	4,867	4,696
Design T	19	-1	-16	-16	23	24	27	27	27	24
Heating load Btu/hr	13,098	11,760	28,864	21,061	12,430	6,226	10,285	8,516	10,853	11,007
Dist. system*	RF	RF	RF	RF	RP	RP	RF	RF	RF	RFF+FC
Set point	67	73	67	63	70	60	71	73	68	73
DHW T°F	120	120	122	120	120	130	120	130	120	120
# Occ.	4	2	2	0	2	0	3	2	4	5

*RF = radiant floor, RP = radiant panel, and RFF+FC = radiant first floor and fan coils on second floor

Space and Water Heating System Design

The main source of space and water heating at the experimental sites is a Sanden GAUS-315EQTD CO_2 refrigerant split system HPWH equipped with an 84-gallon storage tank. An inverter-driven, variable-speed compressor, gas cooler (heat exchange from refrigerant to water), evaporator, and pump are located in the outdoor unit. Plumbing lines transport water between the tank and the outdoor unit, as shown in the basic schematic in Figure 1.

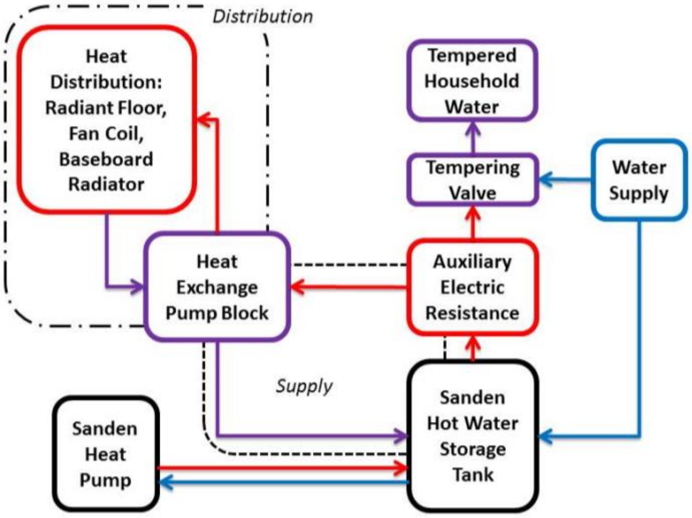

Figure 1 Schematic of space and water heating system design

Because the Sanden produces water at 149°F, the domestic hot water is delivered through a tempering valve. The delivery temperature is set by the occupant. Hot water for space heating moves from the tank through the backup electric resistance (ER) system – a modulating demand water heater manufactured by Seisco that adds energy to the water if it is not at the setpoint as it enters the unit. Space heat is provided by hot water pumped by a TACO X-Block through its integral heat exchanger. The heat is transferred to the load side and distributed by a hydronic system. Seven sites have radiant floors; one has a radiant floor plus fan coils, and two have radiant panels.

The output capacity of the heat pump ranges from 4 kW at cold temperatures to 4.5 kW at 30°F and above. The systems were designed to meet the design loads of the homes with the combined capacities of the heat pump and auxiliary heat system.

Data Collection

The main monitoring collection device is a SiteSage Energy Monitor with Internet connection so data can be downloaded daily and settings on the logger can be controlled remotely. This ensures that issues are identified and corrected as soon as possible. Temperature and flow information as well as electrical use data were collected. All data was taken at one-minute intervals. A schematic of this monitoring system is provided in Figure 2.

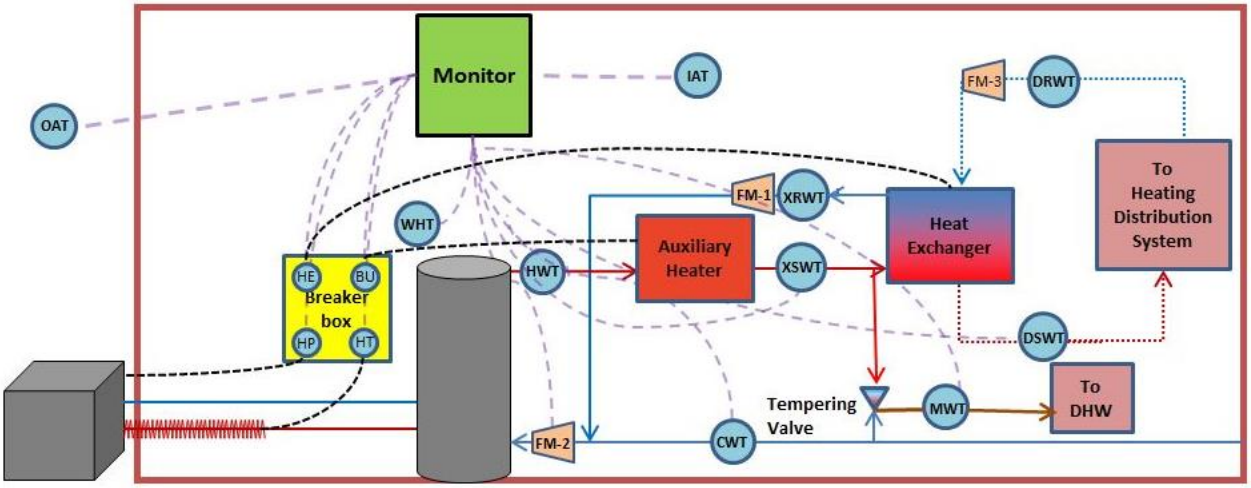

Figure 2 Schematic of monitoring system

Water flow:

- Through hot water tank measured at the cold water inlet (FM-2) (FM=Flow Meter)
- Through space heating supply loop measured on return to tank (FM-1)
- Through space heat distribution loop measured on return to heat exchanger (FM-3)

Temperatures:

- Cold water supply (CWT)
- Hot water to tempering valve (HWT)
- Tempered water to house (MWT)
- Outside air temperature (OAT)
- Inside air temperature near the hot water tank (WHT)
- Inside air temperature in conditioned space (IAT)
- Hot water supply to heat exchanger (XSWT)
- Return water from heat exchanger to hot water tank (XRWT)

- Hot water to heating distribution system (DSWT)
- Return water from heating distribution to heat exchanger (DRWT)

Power measurements:

- Time and amperage of compressor, fan, and pump electricity use (HP)
- Time and amperage of pipe freeze protection (heat tape) electricity use (HT)
- Time and amperage of auxiliary heating loop electricity use (HA)
- Time and amperage of heat exchange supply and distribution pumps and controllers (HX)

The period of data collection analyzed for this report varied from almost a year at a site in Bellingham, Washington, to only several weeks at other sites. Data acquisition was limited by the length of time it took to complete construction at some sites, monitoring equipment issues and heat pump issues. Data is available showing cold weather operation for most sites.

The biggest monitoring challenges were flow meter accuracy and data gaps caused by the monitoring system. Calibration of flow meters using a micro-weir or an ultrasonic flow meter is recommended to test flow measurement and provide correction factors if needed. Loss of data by the monitoring system was not expected and it affected some sites more than others. Temperature sensors incorporated into the flow meters were also subject to failure; in some cases, system reconfiguration was not accompanied by monitoring adjustments. Notwithstanding these issues, usable data was available for over half the sites and the data analyzed in this report is carefully selected and filtered to provide accurate information representing all types of heat distribution systems in the study.

Data Analysis

The analysis examined the performance of the system for both space and water heating, and a number of its operating parameters, including: the temperature of the system cold water supply, heated water, and tempered water; and the calculated volume of water used to temper the hot water before use. The total volume of water used and daily use averages were also calculated for domestic hot water. In addition, the characteristics of the space heating loop were examined for temperatures, operating parameters, and energy used under representative conditions.

Protocols

Domestic Hot Water

Calculating domestic hot water use requires the following elements:

- Average temperatures by flow event or by day for cold water supply, hot water, and tempered water for the domestic hot water supply
- Thermal energy required to heat cold supply water for each flow event
- Volume of water added to temper hot water for each flow event
- Volume of total water for each flow event

To calculate accurate temperatures for cold supply water, hot water, and tempered water for DHW, at least three minutes of consecutive flow were required. Temperatures were then calculated by dropping the initial reading and averaging over the remaining readings for a given flow event (or draw). Daily averages were used as the representative temperatures for short-duration draws that were less than three consecutive minutes. When only short draws occurred during a given day, the daily average water temperatures from adjacent days were used.

Only water volume flowing into and out of the HPWH tank was metered via data loggers, so additional water added to temper the hot water was calculated for each flow event by using the known water flow (gallons) and the difference between the daily average tempered water flow and the daily average cold or hot water temperatures, respectively. Total tempered water flow for each flow event was the sum of the cold water flow and the added water.

Average water temperatures were used to calculate the thermal energy needed to heat the cold water for each draw. The energy is calculated via the familiar calorimetric equation shown below where p is the density and C_p is the heat capacity of water.

Equation 1: Energy = Volume x p x C_p x (Temperature 1 - Temperature 2)

In the specific case of domestic water use, the energy is defined as Qdhw, Temperature 1 is the tank outlet (HWT) and Temperature 2 is the tank inlet (CWT) temperature.

Space Heat

The relevant energy values for the space heating system were calculated using Equation 1 but with values substituted as shown in Table 2.

Table 2 Measured flow and average temperature values used to calculate system loads

Calculated variable	Flow volume	Temperature 1	Temperature 2
Qaux	Supply return after heat exchange (FM-1)	Auxiliary heat outlet (XSWT)	Hot water from tank (HWT)
Qsystem	Supply return after heat exchange (FM-1)	Hot water from tank (HWT)	Supply return after heat exchange (XRWT)
Qdistribution	Distribution return before heat exchange (FM-3)	Distribution after heat exchange (DSWT)	Distribution return before heat exchange (DRWT)

Overall System Efficiencies

Water heating is rated with Energy Factors; space heating is rated by Coefficient of Performance (COP) or Heating Season Performance Factor (HSPF). The combined system performance has been designated as a Field Energy Factor (FEF). This accounts for all system inefficiencies such as tank loss, pipe loss, pump energy, controls, defrost, and freeze protection. FEF efficiencies are calculated as:

Equation 2: FEF = (Qdhw + Qsystem) / Qinput

where Qinput is the sum of energy inputs to the HPWH (HP), auxiliary heat (HA), heat exchanger block (HX), and heat tape (HT).

When data was unavailable for the supply side of the heat exchanger, an FEF was calculated using data from the distribution side of the system:

Equation 3: FEFdis = (Qdhw + Qdistribution) / Qinput.

Space and Water Heating Efficiencies

Given that heat is simultaneously provided by one heat source through a single tank for both space and water heating, it is impossible to calculate a definitive efficiency for each end use. This is particularly true for a heat pump, because its efficiency varies with outdoor air temperature, supply water temperature, and load. Thus, a period of water heating only during the summer cannot be used to determine its portion of the load in winter.

Results

The project began October 1, 2014, with the goal to conduct a field study on six new homes. Recruitment was successful and a total of nine new homes plus a major thermal remodel comprised the final cohort. These homes were completed over a period of a year and monitored as they were finished. A great deal was learned about system design and performance, which resulted in changes to the system plumbing at some sites during the monitoring period.

Auxiliary heat strategy: The first site had an ER tank for auxiliary heat. Monitoring showed that most of the minimal auxiliary energy was used to keep the tank warm. A demand electric water heater became the standard design. Eight sites now have this system and two sites have no auxiliary heat.

Heating supply water return location: Potable water is taken from the bottom of the 84-gallon tank to the outdoor unit, where it is heated and then returned to the top of the tank. Hot water is taken from the top of the tank for both domestic hot water and space heat. At the first site, the return water from the radiant floor averaging 83 °F was returned to the top of the tank. On cold days the home occupants had cool showers due to mixing of this return with the hot water.

An additional concern in determining return water location was the warning by the heat pump manufacturer that both efficiency and defrost function depended on cold water supply to the heat pump, making it vital to maintain tank stratification. The heating system return water was cooler than the 149°F water at the top of the tank, but hotter than the normal cold water supply. The ideal location for the return was in the central portion of the tank, but no port was available. A fitting to divert heating supply return water to the center of the tank was installed at Site 1, where it cured the cold showers. This strategy was adopted at the next six sites.

Subsequently, a lab test was conducted to compare the impact on tank temperature stratification of three different return strategies: top of the tank, top of the tank with diversion fitting, and bottom of the tank. The best location for maintaining tank stratification, which improved system efficiency, was found to be at the bottom of the tank; second best was the diversion fitting; and third was the top of the tank. The recommendation was that a tank designed for combined systems should have multiple ports to allow installers to match the return to the proper temperature level in the tank. The two sites constructed after this finding had return water from the heating system plumbed to the bottom of the tank, and the plumbing was revised at three existing sites to implement this design change.

It should be noted that the need for cold water supply to optimize performance of the heat pump is incompatible with strategies to preheat the supply water. Site 1 had such effective preheating strategies that its supply water was often hotter than the return water from the heating system. This is part of the reason for its reduced system performance.

Auxiliary heat for domestic hot water: The original system design provided auxiliary heat only to the space heating system. As sites in colder locations came online, home occupants experienced cool showers when space heat was operating. Five of the sites were re-plumbed to connect the DHW to the electric demand auxiliary heat source.

Monitoring combined systems is challenging: Several challenges in monitoring the systems limited the data set available for analysis. (1) This is the first time scientific monitoring has been done with the monitoring system used, and many days of data were lost due to data collection issues. (2) The system plumbing revisions resulted in loss of data and changed operation. Moving the heating return to the bottom of the tank caused the temperature sensor, which was integrated into the flow meter, to end up on the upstream side of the return entry point, resulting in loss of the incoming water temperature at three sites. (3) Some temperature sensors and flow meters malfunctioned, preventing calculation of key variables. (4) The monitoring required Internet service and the provider ceased service at Site 1 in October 2015.

The resulting analysis was conducted on sites that had complete data sets for the periods analyzed, and data were screened to ensure that periods with missing data were not used. Sites were excluded from the analysis because of failures in the systems. The sites used in the analysis are 1, 4, 5, 6, 7, and 10 which represent all distribution system types and two climate locations.

Daily Water Use by Site

Average daily hot water use in the Pacific Northwest is ~15 gallons per person per day (gpd). Several of the sites have water use lower than average. Site 10 used substantially more hot water than other sites. Sites 4 and 6 were unoccupied during monitoring, so any hot water use is related to construction cleanup.

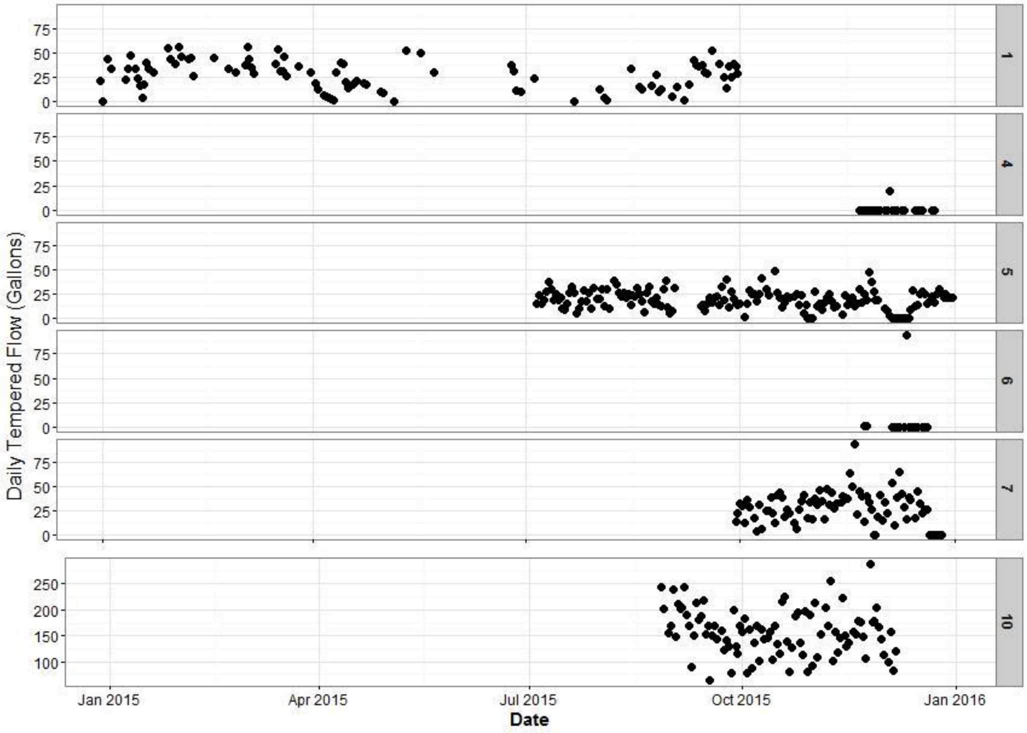

Figure 3 Daily tempered water flow

Daily Average Outside Air Temperature by Site

Sites 1, 5, 6, 7, and 10 are in the Maritime Northwest; Site 4 is in McCall, ID, a cold location and one of the last to come online. The longest-term location is Site 1 in Bellingham. Washington. Its data flow was interrupted when the Internet provider cut service. These findings are shown in Figure 4.

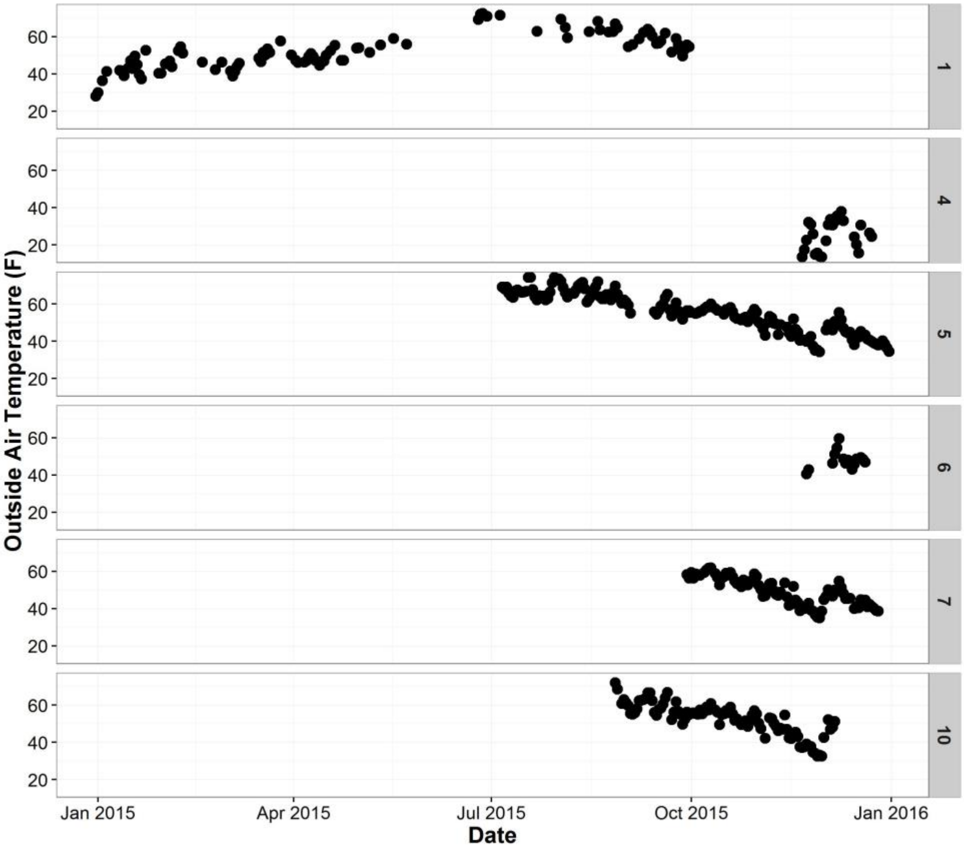

Figure 4 Daily average OAT

Daily Heat Pump Energy Use (kWh) by Site

Figure 5 shows the energy us by site. Site 4 in McCall, Idaho, the coldest location, shows the highest daily energy use in the 40 kWh per day range. Site 6 in Portland, OR, shows much lower energy use during the same period, with a high of 20 kWh per day (see Figure 5). These sites were both unoccupied during the monitoring period and therefore all heat pump energy use is for space heating. Regardless of the OAT, the systems were able to operate and produce heat. At all the sites in the coastal climates, the systems – including auxiliary heat – were able to provide space and water heating. At the very cold location for Sites 3 and 4, a larger-capacity heat pump would be an asset.

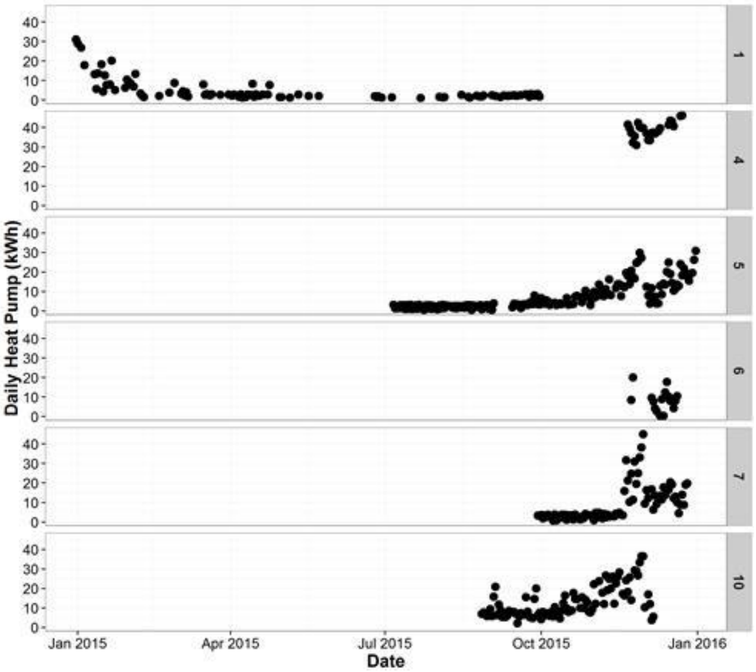

Figure 5 Daily heat pump energy use by site

Daily Auxiliary Heat Energy Use (kWh) by Site

The highest auxiliary use was at Site 4, the coldest site, and Site 10, which had the highest occupancy and a high-temperature fan coil system on the second floor. Sites 5 and 6 did not have auxiliary heat. These findings are shown in Figure 6.

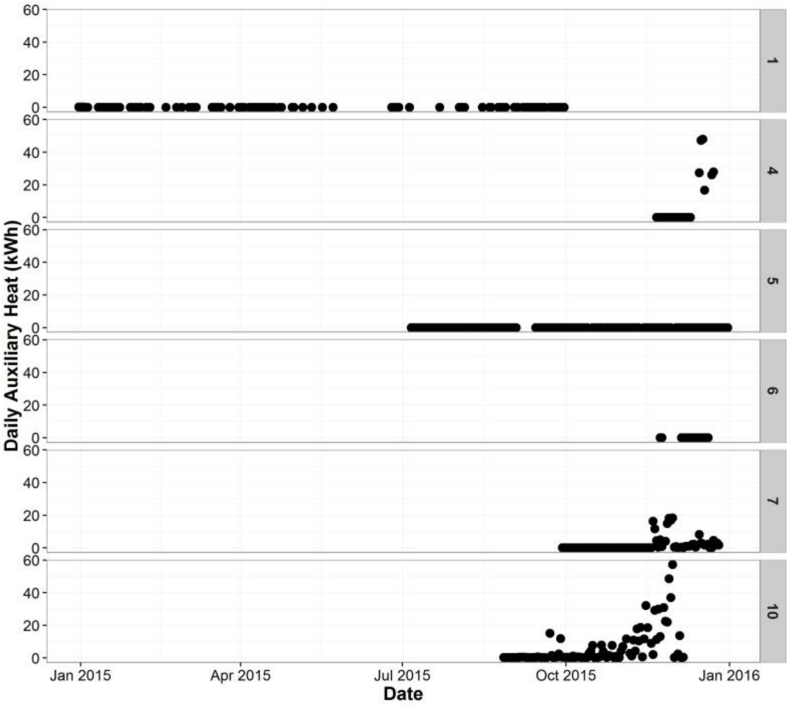

Figure 6 Daily auxiliary heat energy by site

Daily Field Energy Factor by Outside Air Temperature

Figure 7 shows the daily FEF for the analyzed sites arranged by OAT. Daily data for the heating season (October 1 to March 15) and non-heating season were averaged to examine seasonal differences for distinct system types (see Table 3 – "H" for heating and "NH" for non-heating). Select sites with more than 30 days of sampled data from a given season are presented. The combined space and water heating efficiencies vary according to temperature and other variables, such as DHW use. The most interesting comparison is between Site 5 and Sites 1 and 7. Site 5 has hydronic radiators for distribution, and Sites 1 and 7 have radiant floors. Note that Site 5 has a slower response to increasing OAT than the radiant floor sites.

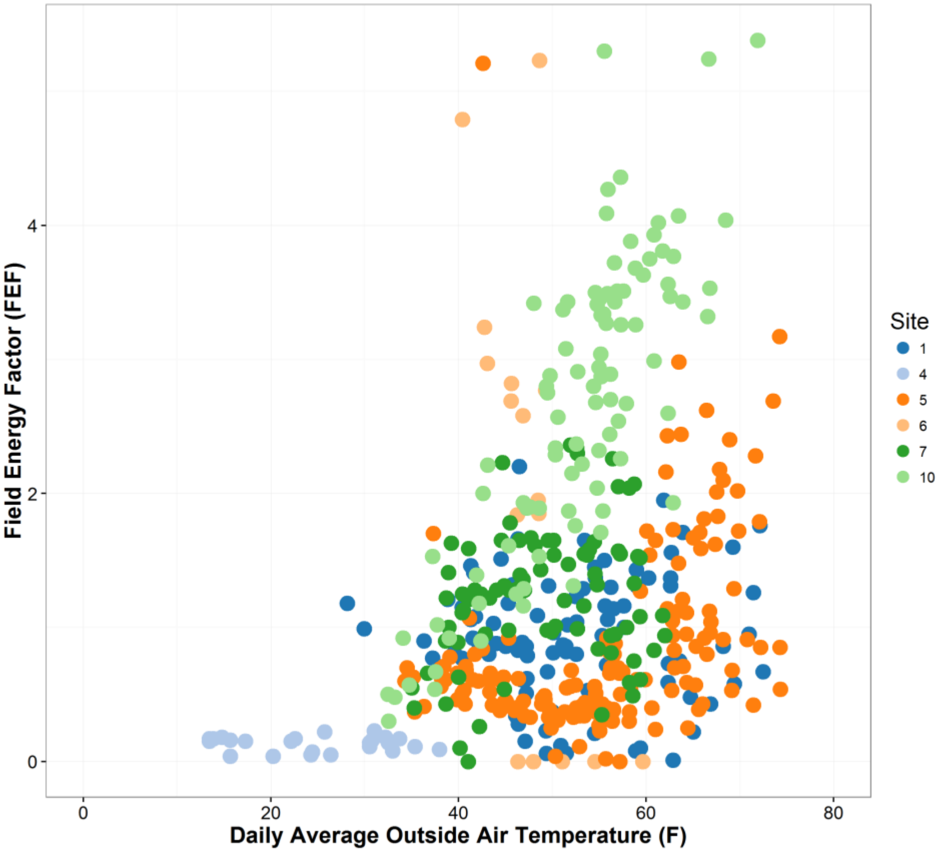

Figure 7 Daily field energy factor (including freeze protection)

Table 3 shows seasonal averages for key factors that impact performance. The systems with the high return loop temperatures (XRWT) have radiators (Site 5) or fan coils (Site 10).

Table 3 Average daily values for heating (H) and non-heating (NH) seasons for select sites

Site	OAT (F)		CWT (F)		XRWT (F)	DHW (GPD)		FEF		Days sampled	
	H	NH	H	NH	H	H	NH	H	NH	H	NH
1	43.1	56.3	76.34	77.51	82.93	34.28	23.46	1.04	0.88	31	65
5	47.47	64.11	60.21	69.93	111.4	17.87	21.02	0.58	1.18	83	75

7	48.94	57.25	60.37	67.06	89.7	28.57	18.3	1.24	0.76	80	2
10	49.12	59.64	58.12	58.99	101.43	151.91	167.31	2.28	3.35	60	33

The system with the lowest average heating season performance in Table 3 is Site 5 which has the highest return water temperature. Its FEF doubled during the non-heating season—due in large part to the reduction in supply water temperature going to the outdoor unit. The non-heating season average FEF for Sites 1 and 7 are lower than those for the heating season. This appears to be related to the drop in daily water use at these sites. (Although there are only two non-heating season days in this sample for Site 7, it is considered instructive on this point.) The reason is that tank and pipe losses continue while there is less energy production from the heat pump to allocate it to. At sites 5 and 10, daily hot water use and FEF increased during the non-heating season. The large daily water use at Site 10 appears to coincide with the only outstanding performance in this sample; this performance was irrespective of the fact that its system operated at a higher return loop temperature than sites with only radiant floors. Hot water use brings cold water into the storage tank, which results in colder water going to the heat exchange with the refrigerant in the outdoor unit resulting in higher heat transfer.

The main implication is that the technology is promising, but these systems require significant development to increase average overall performance.

Modeled Space and Water Heating Efficiencies

The lab test done as part of this research measured the operation of combined space and water heating systems configured as they were in the field study under controlled conditions. With the data collected, annual system efficiency was estimated by applying the measured performance to different climate temperature profiles using a standard temperature-bin weighted calculation and TMY3 data to provide the number of hours for each temperature bin. Average hot water use by an average family (46 gpd) was used in this model.

Table 4 shows the results of the annual efficiency analysis for water heating only, space heating only, and combined water and space heating. Space heating always happens at cold temperatures and the heater returns water to the tank at temperatures higher than normal supply temperature, so its efficiency is less than water heating alone. Summer water heating sees a significant efficiency boost from warmer, outdoor temperatures and colder input water temperatures. Since most of the system energy output goes to space heating, the combined efficiency closely resembles the space heating-only efficiency. All cases include standby losses.

The modeled combined efficiencies are analogous to the FEF shown in Figure 7 and Table 3. Field studies show the natural variation that occurs when factors such as occupancy, weather, water use, and thermostat settings are involved. If extrapolated to a full year, the field data would correspond more closely to the modeled results shown in Table 4, especially those sites that best represent the modeled average.

Table 4 Modeled water, space heat, and combined annual efficiencies in different climates

Climate	Water heating	Space heating	Combined
Boise	2.9	2.3	2.5
Kalispell	2.6	2.1	2.2
Portland	3.0	2.6	2.7
Seattle	2.9	2.6	2.7
Spokane	2.8	2.2	2.4

Climate	Water heating	Space heating	Combined
Zone 4C	2.9	2.5	2.6
Zone 5	2.8	2.2	2.4
Zone 6	2.6	2.1	2.2

Conclusions

The most important variables in system performance shown by this research are volume of hot water use by the household, OAT, temperature of water returned to the heat pump, and thermostat temperature and hot water use temperature.

Combined space and water heating based on split system CO_2 refrigerant HPWHs in low-load homes works in field installations where they can operate within the capacity of the heat pump unit (4.5 kW) as determined by design heating load. A better question than “What is the total space and water heating energy use for each site?” is “What is the efficiency of the system under the conditions it actually experienced?” Each field site presents a unique set of factors; Figure 7 and Table 3 show how the system responds to similar climate conditions in different ways depending on these factors.

The systems overall used very little auxiliary heat. At most sites, the heat pump carried almost all of the space and water heating load. Two of the sites, including Site 5, have no auxiliary heat for either space or hot water. Larger-capacity heat pumps should be used for bigger loads, including space heating in cold climates, so the systems can meet the loads caused by low OAT without resorting to auxiliary heat.

Measures to maintain tank stratification are recommended, including a larger, 120-gallon tank and fitting the tank with multiple entry ports to accommodate systems with different operation temperatures so supply water can be returned to the optimum height in the tank to maintain stratification.

The development of combined space and water CO_2 heat pump systems is in the early stages. There is opportunity for significant development in system components for use with split system heat pumps designed for water heating like those studied. Another research possibility is CO_2 refrigerant heat pumps designed specifically for space heating with indirect water heating to optimize systems for the largest loads. Ultimately, systems designed specifically for combined space conditioning and water heating is the goal.

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