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CO_2 Heat Pump Water Heater Field Evaluation in a School Cafeteria Application

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Abstract

Heat pump water heaters have been demonstrated to provide significant energy savings compared with electric-resistance water heaters. They have been adopted in the residential market, albeit slowly. Adoption has been limited in commercial applications because of high cost, complexity, and uncertainty. There is particularly little uptake in small commercial applications, where few heat pump options are available—heating water with gas is far more common. However, heat pump water heaters using CO_2 as the refrigerant, which are now available in the United States, may overcome some of the barriers for small commercial applications. This report describes a field test of a CO_2 heat pump water heater at a school cafeteria in Mobile, Alabama. The system was instrumented to capture performance and hot water delivery and monitored for over one year. The results show good efficiency, with a coefficient of performance (COP) of 2.9. The water heater delivered supply water with a setpoint of 149°F (65°C) and provided the full hot water demand on all monitored days.

Keywords

CO_2 refrigerant
Energy efficiency
Field demonstration
Heat pump water heaters
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PRIMARY AUDIENCE: Utility engineers interested in efficient electric water heating

KEY RESEARCH QUESTION

Heat pump water heaters have been established to be efficient for many residential and commercial applications, but uptake—particularly in the commercial market—has been slow. In particular, there are few options for small commercial applications. This field study monitors a CO_2 heat pump water heater in a small school cafeteria, and the results provide real-world data on performance and efficiency for this application.

RESEARCH OVERVIEW

This report describes a field demonstration of a split-configuration CO_2 heat pump water heater in a small commercial application. A single, 4.5-kW nominal-capacity heat pump was installed with two 83-gallon (314-liter) storage tanks, outside the cafeteria of a school in Mobile, Alabama. The heat pump water heater uses CO_2 refrigerant, and the manufacturer is the first to sell such products in the U.S. market. These systems were initially targeted toward residential applications but are potentially applicable for small commercial applications. The system was equipped with an instrumentation package to collect data for over one year of operation.

KEY FINDINGS

- The average coefficient of performance (COP) on days with normal hot water usage was 2.9, and the average energy consumption on those days was 8.6 kWh. On those days, the average hot water draw was 163.8 gallons (620 liters). The school reports 750–1,000 meals per day. The end uses include sinks, dishwashing, and a small laundry machine (residential-style equipment).
- The water usage was much lower or zero on weekends, holidays, and during school vacation periods. On 45% of all of the days monitored, the water usage was less than or equal to 15 gallons (57 liters) per day. This should be considered when evaluating potential applications for this technology.
- The heat pump water heater was installed outdoors in Mobile, Alabama. It operated efficiently in all weather conditions to which it was exposed (generally in the range of 40–90°F [4.4–32°C]).
- The total capacity of the heat pump and two tanks was more than sufficient to maintain the hot water temperatures required, and in fact the heat pump was sometimes triggered to run by a 24-hour timer rather than by cumulative water draws. The ability to provide hot water with such wide time gaps between reheats suggests good potential for load shifting or scheduled run times. Each day, the water heater typically ran one time for a duration of several hours.

WHY THIS MATTERS

CO_2 heat pump water heaters may offer a potential path toward efficient, electric water heating in small commercial applications. With the flexibility to be installed indoors or outdoors and operate without electric-resistance backup heat in a wide temperature range, along with high-temperature supply water, they have some key advantages over other technologies that have been considered for this market.

HOW TO APPLY RESULTS

This effort showed a successful deployment of a single CO_2 heat pump water heater in a small commercial application. The usage profile and climate of this application are relatively favorable for heat pump water heaters. Utilities should consider future demonstration efforts to further identify potential barriers or risks to adoption and quantify the potential savings in a variety of small commercial applications.

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PROGRAM: End-Use Energy Efficiency and Demand Response, P170

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Section 1: Background

Heat pump water heaters (HPWHs) have yet to make major headway into the small commercial market in the United States; most residential-style systems lack the heating capacity, storage volume, or both, whereas most commercial-style systems are costly and require engineering planning as well as considerable space. One possible alternative is the use of CO_2 HPWH systems, which are currently emerging in the U.S. market. These systems, initially designed with residential applications in mind, are split-configuration systems that deliver single-pass heating of water to high temperatures (in the system tested, 149°F) and can be installed indoors or outdoors, nominally running in conditions from -15°F to +110°F. They use an external, pumped, single-pass heat pump heating approach, which means that the system can be installed with one or more tanks, allowing flexibility in the amount of storage. The tanks are also stratified, which enables superior maintenance of the supply temperature during draw-down and re-heat. These factors could potentially make CO_2 HPWHs a good fit for the small commercial market, in applications such as restaurants and kitchens.

The market for small commercial HPWHs is diverse, but it includes loads like school cafeterias, restaurants and fast food establishments, and others similar end uses. The U.S. Department of Energy's Commercial Reference Building Models provides an estimate for hot-water usage in commercial buildings [1]. The estimates for water usage for typical examples of several buildings are shown in Table 1-1. The usage varies significantly by specific site. These values show a range of hot-water consumption from about 300 to 1,200 gallons per day, with a peak from 24 to 123 gallons in an hour. The lowest usage in this estimate is quick-service restaurants, and the highest is hospital kitchens.

Table 1-1
Commercial kitchen hot-water usage for typical example buildings

Building	Meals per Day	Max. Gallons per Hour	Typical Weekday Total Gallons
Primary School	400	83	691
Secondary School	600	110	919
Quick-Service Restaurant	800	24	310
Full-Service Restaurant	780	80	1031
Large Hotel	780	80	1197
Hospital	800	123	1175

Overview of the CO_2 Heat Pump Water Heater

Heat pump water heaters using CO_2 refrigerant differ in several ways from the conventional hydrofluorocarbon (HFC)-refrigerant options that have become relatively common in the United States. The following highlights some of the main differences.

There are three main configurations of heat pump water heater in the United States, shown in simplified schematics in Figure 1-1. Three configurations are shown:

- Single-pass heating: Water is removed from the lower part of the tank, at a variable flow rate heated by the full temperature lift (such as 68°F to 140°F), and returned to the top of the tank. In this approach, the tank remains strongly stratified, with water at the top at or very near the set-point temperature unless the tank has been completely depleted.
- Multi-pass heating: Water is removed from the lower part of the tank, at a fixed flow rate, and heated by a varying temperature lift. The tank is partly or mostly mixed, with the temperature increasing gradually.
- Integrated or wrap-around-condenser heating: The heat pump condenser is wrapped around the outside of the tank (between the tank body and the insulation layer) and transfers heat through the wall of the tank. In this approach, the lower portion of the tank is heated through the wall of the tank.

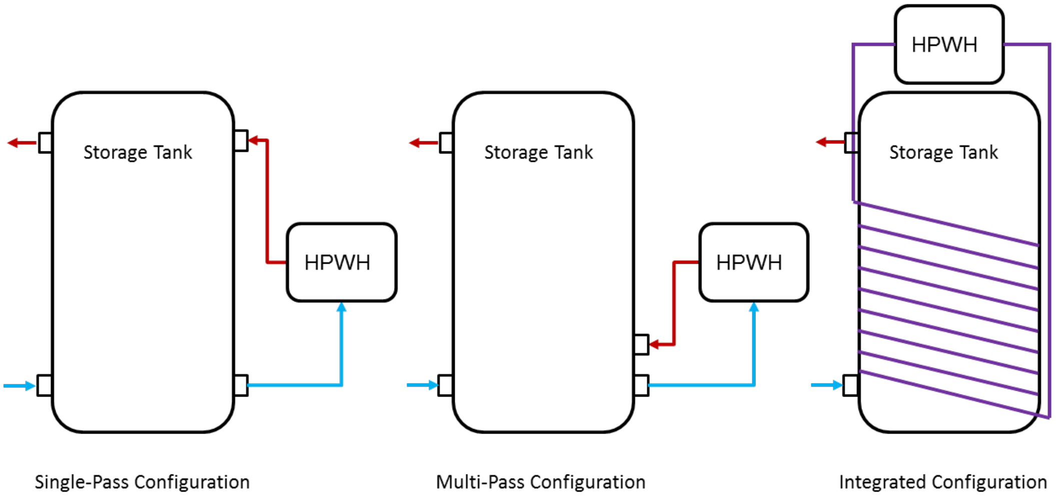

Figure 1-1
Simplified schematic of existing heat pump water heater configurations, showing single-pass, multi-pass, and wrap-around-condenser configurations

The integrated configuration is the typical configuration of "conventional" residential heat pump water heaters in the United States. Each of the single-pass and multi-pass configurations are available in the U.S. market for commercial applications [1, 2, 3].

CO_2 transcritical refrigeration systems are most often designed to use the single-pass configuration. The reason is clear after a review of the transcritical cycle. Figure 1-2 shows two refrigerant pressure-enthalpy diagrams, with CO_2 on the left and R134a on the right. Both are approximations for illustration purposes. In both cases, a 60°F evaporator temperature with 10°F of superheat is assumed. With R134a, a 145°F saturated condensing is used, and 5°F of subcooling is assumed. With the CO_2 cycle, the condensing process is replaced by a process referred to as *gas cooling*, because the cycle is operating in a transcritical mode, and the high-side refrigerant does not actually condense. This process has a continuously-varying refrigerant temperature along the length of the heat exchanger, as opposed to the process of a conventional heat pump with phase change.

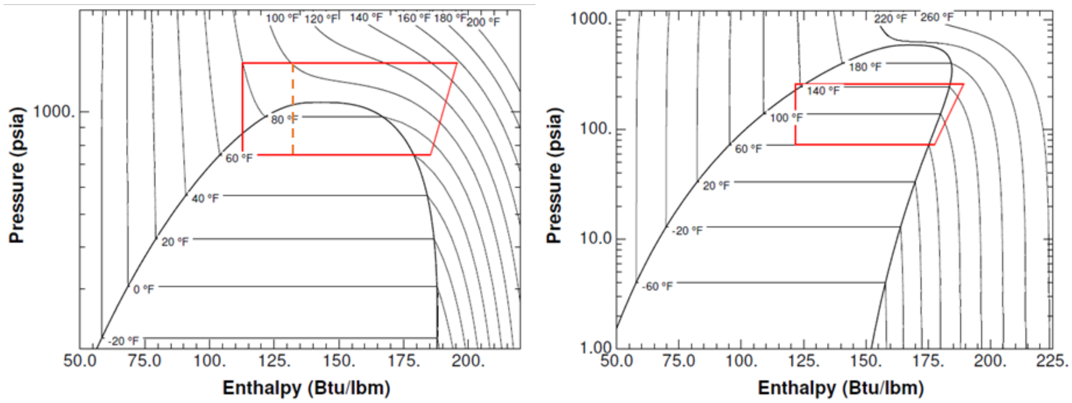

Figure 1-2
Pressure-enthalpy diagram of transcritical (left) and subcritical (right) ideal heat pump cycle

Note that the top-left point on the CO_2 cycle—the state of refrigerant leaving the gas cooler —depends highly on the temperature of the fluid being heated. In the example, 80°F is used. If the fluid to be heated enters at 100°F, then the cycle can reject less heat (shown with the dotted line); for a given compression process, the capacity and efficiency would be significantly less (in this simplified example, the COP is about 25% higher with 80°F refrigerant leaving the gas cooler than with 100°F refrigerant leaving the gas cooler). This explains why the CO_2 cycle is best deployed in a single-pass configuration, where the entering water is always cold water from the bottom of the tank.

Survey of Available Systems

The system evaluated in this study was a Sanden SanCO_2 heat pump water heater, shown in Figure 1-3. The system is a split configuration, with the entire heat pump housed in one unit, and a separate water tank, which has four water ports: inlet and outlet for the heat pump, cold-water inlet, and hot-water outlet. The energy factor was 3.35, the out-of-box water temperature setting was 149°F, the power supply was rated at 220-240 VAC single phase, 15 A. The ambient air operating temperature range was -15°F to +110°F. The manufacturer sold two tank sizes, 66 gallons and 83 gallons.

Figure 1-3
Sanden CO_2 HPWH from the manufacturer spec sheet

Heat pump water heaters using carbon dioxide as a refrigerant first became available in Japan in the early 2000s, sold by a number of manufacturers under the name EcoCute. A number of manufacturers sell these systems in Japan, Europe, Australia, and elsewhere, including Daikin, Sanden, Mitsubishi, Sanyo, and others. An example of an EcoCute configuration, in this case made by Sanden and evaluated by EPRI in a prior research effort [4], is shown in Figure 1-4. These systems are very similar to the unit tested here, except the storage tank is generally more complex. A mixing valve is typical, and some units have features such as a water re-heating circuit and a plate heat exchanger, which can be used to maintain bath water temperature, for example. Such EcoCute systems have not been sold in the United States through conventional avenues but have been evaluated under research efforts.

Figure 1-4
Japanese-Style EcoCute System

In addition to the residential EcoCute systems available in other countries, there are also commercial water-heating technologies. One example is Mayekawa’s CO_2 HPWH, available as a water-to-water or air-to-water heat pump. This system, built for large commercial and industrial applications, has a nominal heating capacity of 80 kW (air-to-water) or 100 kW (water-to-water) and provides single-pass heating, which may be set to an output temperature of 149°F or 194°F. Like other large-capacity commercial HPWHs, the system needs to be engineered to the specific needs of the site, including storage as appropriate. This system was evaluated by EPRI in 2013 [5] and is shown in Figure 1-5.

Figure 1-5
Mayekawa Commercial Water-to-Water CO_2 HPWH

Other efforts to develop CO_2 HPWHs for the United States have been undertaken. For example, researchers at Oak Ridge National Laboratory partnered with GE on a development project to test CO_2 heat pump water heaters with wrap-around condensers [6].

This report describes a field evaluation of a CO_2 HPWH made by Sanden. To the researchers' knowledge, it is the first such system to be commercially available in the United States, and although it is initially targeted for residential applications, it is also being considered for multifamily and small commercial end uses. The specifications for the heat pump and tank are shown in Table 1-2. The ratings, such as energy factor and first-hour rating, are residential standard tests and are shown with the tank specifications listed. The ratings are not directly applicable to the equipment in the field.

Table 1-2
Specifications for HPWH under test

Heat Pump	
Energy Factor	3.35
First Hour Rating	97 gal
Supply Water Temperature Setting	149°F
Heating Capacity	4.5 kW
Heat Pump COP	4.5
Power Rating	208/230 V, 1 Ph, 60 Hz
Breaker Size	15 Amps
Pipe Size (Tank to Heat Pump)	1/2"
Tank	
Tank Volume	83 gallons
Tank Height	58–5/8"
Tank Diameter	26–3/4"
Heat Pump Inlet/Outlet Diameter	3/4"
Hot/Cold Water Inlet/Outlet Diameter	1/2"

A manufacturer image of the system is shown above in Figure 1-3, which also shows the four connection ports on the tank and one pressure-relief port. The two lower ports are the cold-water inlet and cold water out to the heat pump. Near the top are the hot-water, outlet hot-water return from the heat pump, and pressure-relief port. Also, the plastic covering shown on the upper-right hand side of the tank covers the temperature sensor.

Section 2: Overview of Field Testing

Site Overview

This study took place at the Faith Academy site, which has been host to a number of Southern Company/EPRI collaborative projects [7]. The water heaters at the site were an 80-gallon and a 120-gallon electric-resistance units. The 80-gallon unit was dated 1999 and was therefore flagged for removal, while the 120-gallon unit was kept as a backup in case of emergency. The two water heaters were installed on either side of a wall, adjacent to the kitchen space. One water heater was in a room with a washer/dryer. The kitchen included several sinks and a dishwasher, as well as the small residential-style washing machine. Photos of the site pre-retrofit are shown in Figure 2-1.

Figure 2-1
The two baseline water heaters (left, center) and the cafeteria's kitchen (right)

An HPWH system with two 80-gallon storage tanks was installed outside the cafeteria on an adjacent concrete slab to replace the two pre-retrofit units. The tanks were installed in parallel. The installation is shown in Figure 2-2.

Figure 2-2
HPWH and tanks during installation, showing parallel tank layout

The plan called for the existing 80-gallon water heater to be removed and the 120-gallon water heater to be left in place, but bypassed via the piping and de-energized. This configuration would leave the 120-gallon heater available to easily return to service in case of a problem with the heat pump equipment. However, this step was not taken during the installation of the new HPWH system. Instead, the remaining electric-resistance water heater was left in series with the new HPWHs. The instrumentation was all upstream of this water heater, so there was no corruption or loss of data. The measurements of hot water delivery were all upstream of the remaining water heater, and it was observed that the new HPWH could provide all of the hot water without issue. The electric-resistance water heater was therefore unnecessary. Over the winter break at the Academy in late 2016, this issue was corrected by turning off the valve on the 120-gallon water heater and de-energized it. Subsequent data confirmed that no change in the delivered water heating was observed. The design configuration, as well as the initial installed configuration, are shown in the simplified diagram in Figure 2-3.

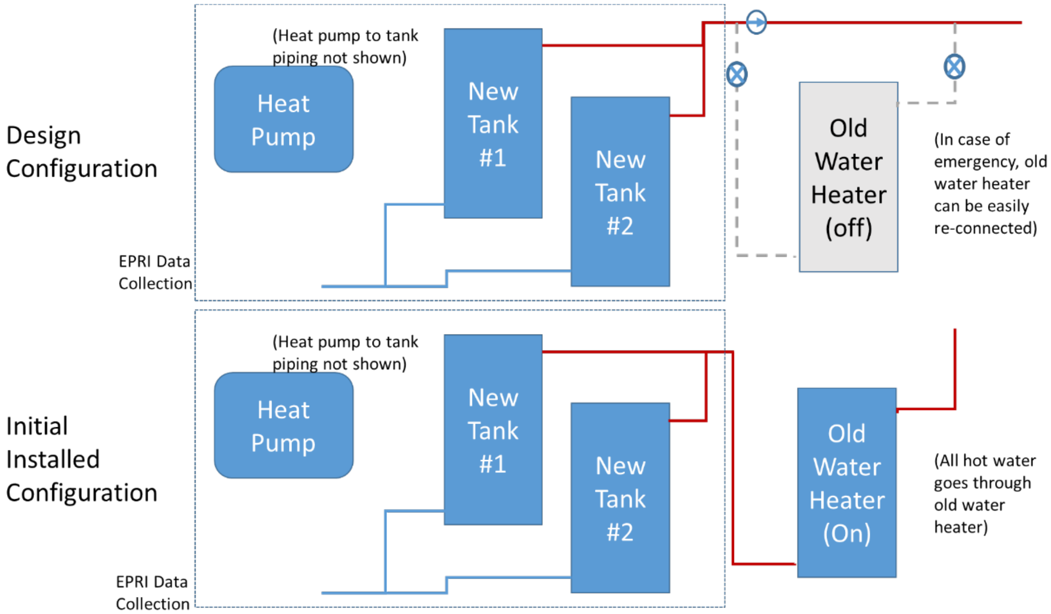

Figure 2-3
Designed Configuration and Initial Installed Configuration. The configuration was eventually corrected to the design configuration, with no impact on HPWH performance

Instrumentation was installed to monitor the performance of the HPWH. The monitoring package included:

- Power: Elkor WattsOn Power Meter (+/- 0.2% power)
- Water Flow: Seametrics MJNR-075-20P Pulse Meter (+/- 1.5% of reading)
- Water Temperature: Type 10K-3 Thermistor (+/- 0.4°F)
- Outdoor Air: Dwyer RHP-2R11 Temperature/Humidity Transmitter (2% RH from 10–90% RH @ 77°F; Temperature +/- 0.4°F)

Water flow was measured at the cold-water inlet to the entire water-heating system so that all hot water usage was measured. Temperature was measured at the cold-water inlet to the tank, at the inlet and outlet of the heat pump unit, and at the outlet of the tanks (supply to the building). Because there was no water-flow meter on the circulating water between the tanks and heat pump, the instantaneous heat pump capacity was not directly measured. However, the system-level COP can be calculated from the heating capacity of the delivered water from the tanks and energy from the water heater.

The power meter used in the research was capable of reading single-phase or three-phase power. Because the HPWH was a single-phase unit, an additional channel of the power meter was used to measure the current to the backup electric-resistance water heater; this was used as a simple check to observe operation of that water heater (initially intended to see if the staff ever had to turn it back on).

General Characteristics of Site Usage

The school has a routine usage of hot water during days when school is in session and little or no usage when school was not in session. Figure 2-3 shows a calendar with days colored by water usage; the lightest green is near-zero or zero water usage, and the darkest green corresponds to large water draw. Generally, weekdays have high usage, and weekends and holidays have low or no usage; in addition, there were a few extended breaks such as summer vacation, Thanksgiving, and winter breaks. Using this information, the days can be divided into days with draw and days without draw. Because the usage is generally either near zero or high, the data is sorted by days with and without usage with a threshold of 45 gallons per day.

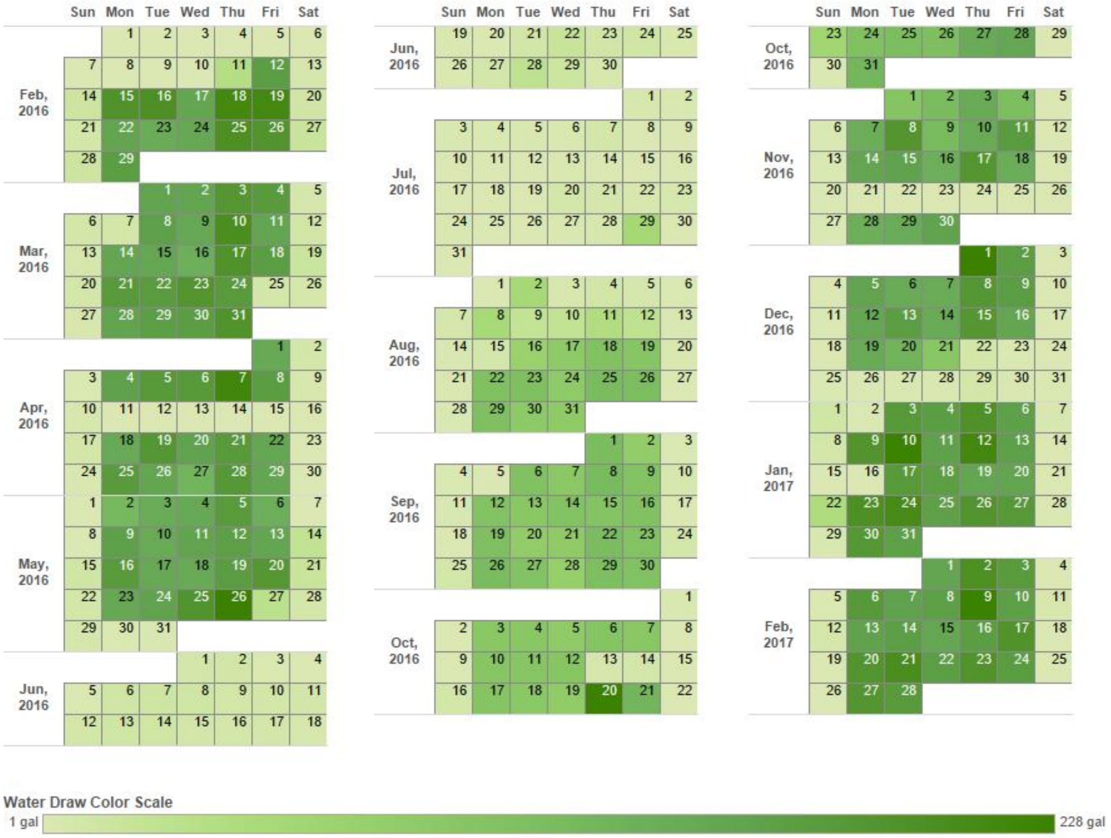

Figure 2-4
Calendar of test period, with color scale showing the range daily hot water used over 13 months

The average hourly water draw profile for all days with usage is shown in Figure 2-4. The hourly intervals are "hour beginning," meaning that the data at hour zero is from 12:00 AM to 1:00 AM, hour 1 is 1:00 AM to 2:00 AM, and so on. The value shown for each point is the average hourly power for all included days. The resulting load profile shows that there are typically three peaks, one early in the morning, one mid-morning and one in the early afternoon.

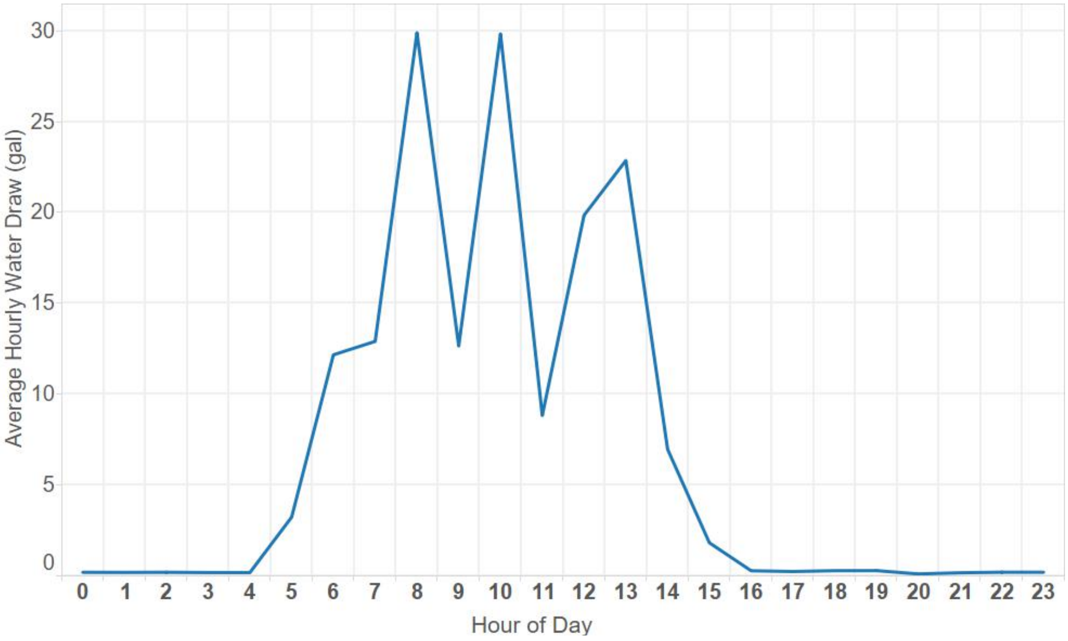

Figure 2-5
Water draw profile, February 2016 through February 2017, for days with at least 50 gallons of draw

In the figure above, each hourly average describes the average hourly average water draw during the 13-month period. For example, during the entire monitoring period, the average water draw during hours 0 through 4 was 0, while the average water draw during hour 8 was 30 gallons.

The three-peak trend occurs throughout the school year, with the main variation being how much hot water is drawn. In general, the amount of water drawn from the hot-water tanks is most during the coldest months; this is also typical of residential water heating, which occurs because of the decreasing temperature of the water entering the tank. To achieve a given water temperature at a tap, hot water leaving the tank is mixed with cold water. The hot water temperature is at the set-point temperature, but the cold water temperature changes seasonally. When the entering cold water temperature is lower, more hot water is used to reach the given temperature. This is why flow measured through the water heater is higher in winter.

The total water draw per day for all days (including when the school was not in session) is shown on a frequency chart in Figure 2-6 for the test duration. The bins show gallons up to the label amount; up to 15 gallons, 15 to 30 gallons, 30 to 45 gallons, and so on. A total of 384 days are included; 173 days, 45% of the total, have usage of 15 gallons or less, because of weekends or holidays. Similarly, 44% of the data falls in the range of 120 to 210 gallons per day. A range of 750 to 1,000 meals per school day was reported by the school.

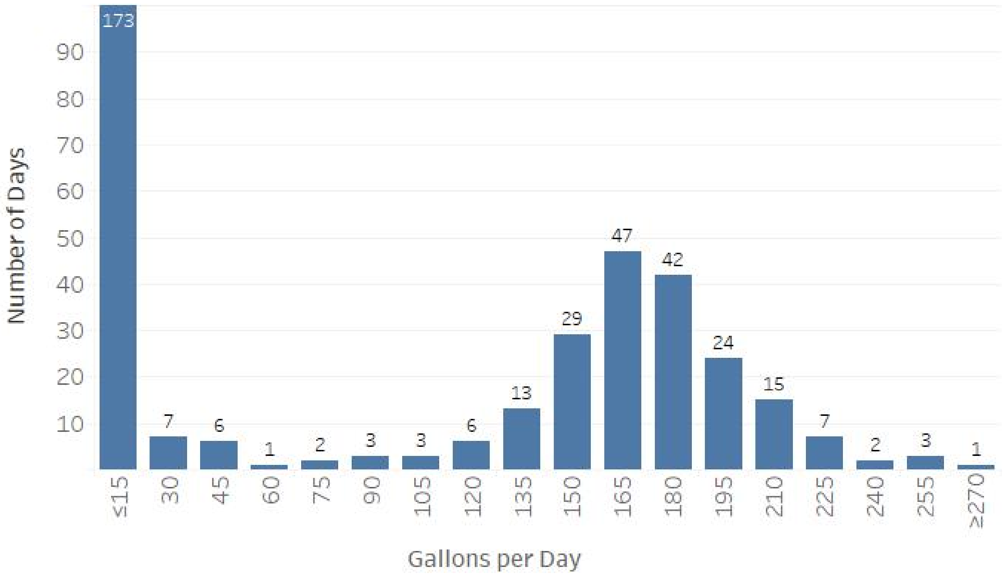

Figure 2-6
Frequency chart of daily water usage in gallons

The outdoor temperature and inlet-water temperature are also important to consider. Table 2-1 shows the measured average inlet-water temperature, as well as the average, minimum, and maximum outdoor temperature as recorded at the site for each month.

Table 2-1
Monthly average incoming water temperature and average, minimum, and maximum outdoor temperature measued on-site

		Avg. Water Inlet Temp	**Max. Outdoor Temp**	**Avg. Outdoor Temp.**	**Min. Outdoor Temp**
		°F	**°F**	**°F**	**°F**
2016	Feb	63.06	79.9	58.39	34.77
	Mar	66.16	89.4	65.39	36.39
	Apr	69.8	95.78	69.56	41.28
	May	73.97	98.68	75.98	49.65
	Jun	82.05	101.78	82.35	66.38
	Jul	82.95	102.19	86.16	72.2
	Aug	83.06	104.73	83.71	71.74
	Sep	82.87	101.07	80.78	54.05
	Oct	79.87	96.79	72.24	42.47
	Nov	75.54	95.03	63.27	31.72
	Dec	69.12	82.82	56.87	29.13
2017	Jan	66.34	88.24	58.72	21.05
	Feb	66.23	89.13	62.12	33.88

Section 3: Overview of Field Testing

The results of data collection are summarized in this chapter. An example of typical operation is shown in Figure 3-1, which shows outdoor temperature and heat pump power on the top graph and cumulative water draw and water supply temperature (only when water is flowing) on the bottom graph. This shows that heat pump operation is contained to one run cycle, which has a long duration: in this case, from approximately 11:30 AM to 9:10 PM. Prior to the re-heat, approximately 91 gallons were drawn. After the beginning of the re-heat, an additional 80 gallons were drawn.

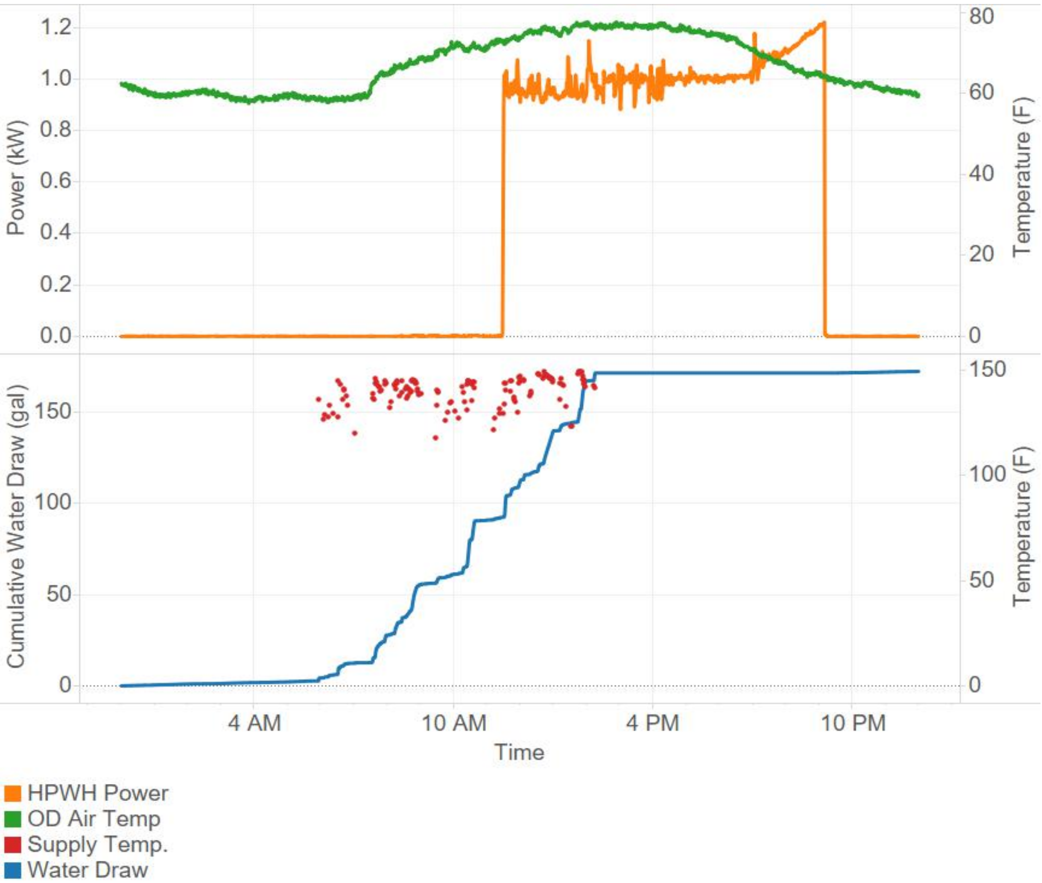

Figure 3-1
One-minute data from April 8, 2016, showing HPWH power, outdoor temperature, supply water temperature (during water draws), and cumulative water draw total

Data from the same time window is shown in Figure 3-2, in this case including the heat pump power and the water temperatures into and out of the heat pump itself. This shows part of the mechanism of single-pass heating: The water drawn from the bottom of the storage tanks is between 69°F and 71°F for most of the re-heat until the tank stratification reaches the lower part of the tank, at which point the temperature increases. Because the two tanks are in parallel, the thermal gradients (and likely flow rates) are different. Water leaving Tank 2 reaches 127°F. Water leaving Tank 1 reaches 108°F. The temperature of the water leaving the heat pump is between 150°F and 155°F during the re-heat. The temperature oscillates during the re-heat, as does the power of the system. This is probably due to oscillations of the flow control through the heat pump, as the system attempts to regulate the temperature of the water leaving the heat pump to its temperature set-point.

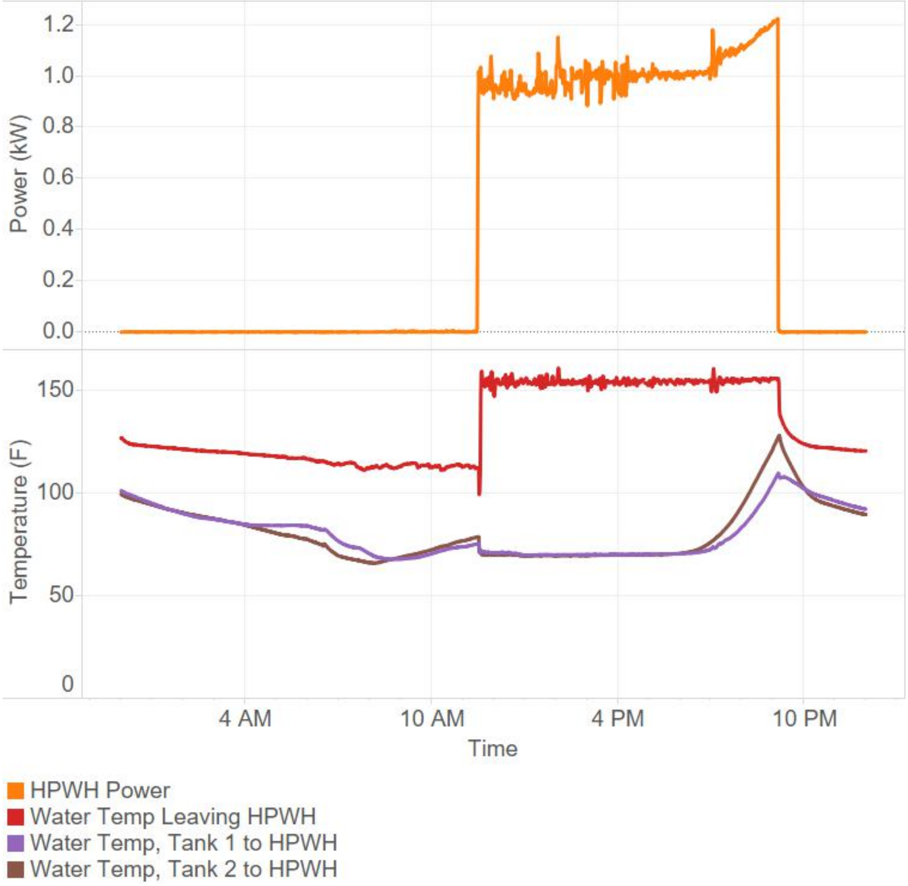

Figure 3-2
One-minute data from April 8, 2016, showing HPWH power, HPWH water outlet (to tanks) temperature, and HPWH inlet temperature (from tanks)

The hourly average power of the heat pump is shown, broken out by month, in Figure 3-3. This shows the average power in each one-hour interval for all days with hot water usage, for each month (June is not shown because there were no days with significant hot water usage). This graph reveals an interesting phenomenon that was observed at the site. The power profile is, in many months, consistent, with a long, pronounced run period and near-zero or zero power during all other hours. However, the power profile shifts over time. It would be expected to shift in magnitude or duration (for example, when entering water gets warmer in summer, one would expect lower power and shorter re-heats), but also the July, August, and September profiles are shifted several hours later than those from April and May, for instance.

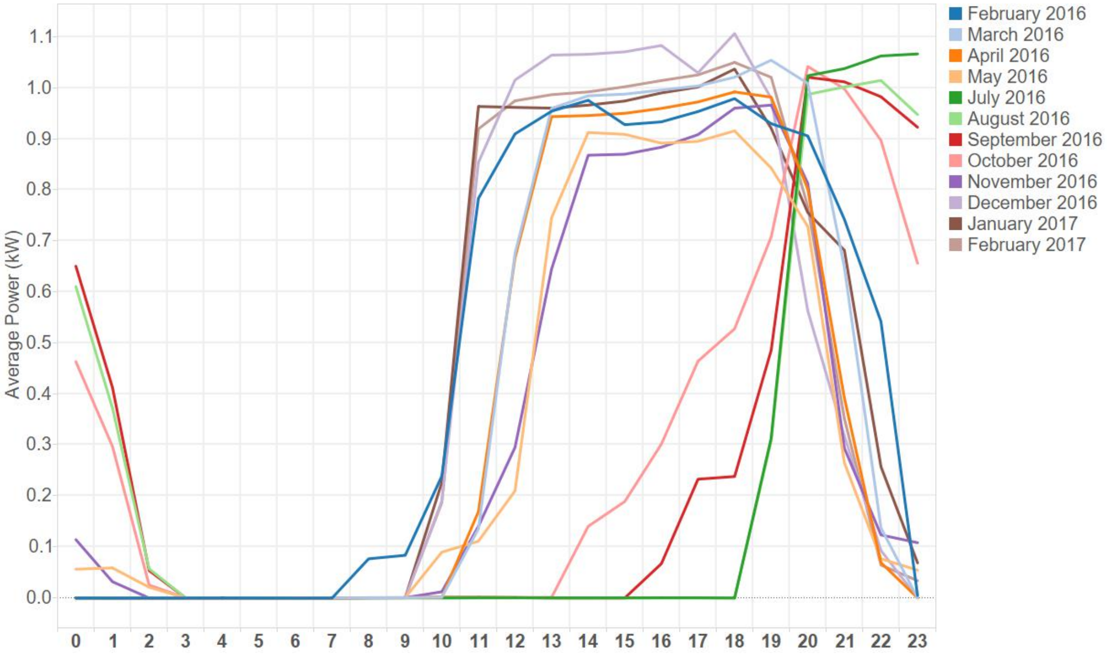

Figure 3-3
Hourly average power profile by month for the HPWH

The reason for this unexpected shift in power profile is clarified by examining daily profiles (shown in Figure 3-4) and considering the operating mode of the water heater. In the figure, five consecutive days in February, 2017, are shown, with the re-heat start time called out. For the first three days, the re-heat begins at exactly the same time. On the fourth day, the re-heat starts earlier; the re-heat on the fourth day is also visibly longer in duration. The fifth day, the re-heat begins at exactly the same time as the prior day.

The HPWH configuration consists of two stratified storage tanks, with hot water on top and cold water on the bottom, with a temperature-sensing probe located in the lower portion of one of the tanks. When the probe senses a set temperature, re-heat begins. However, if the probe does not sense the re-heat temperature, hot water is still available even if the tank is not fully charged. Based on discussions with the manufacturer, if there has not been a re-heat triggered in 24 hours, the system will initiate a re-heat. This shows why the system could have a regular, but shifting, re-heat schedule: On many days, 24 hours elapsed before the water draw triggered the temperature sensor to re-heat, and so the re-heat occurred at 24-hour intervals. On occasion, the water-draw triggered a re-heat, shifting the time of the 24-hour interval.

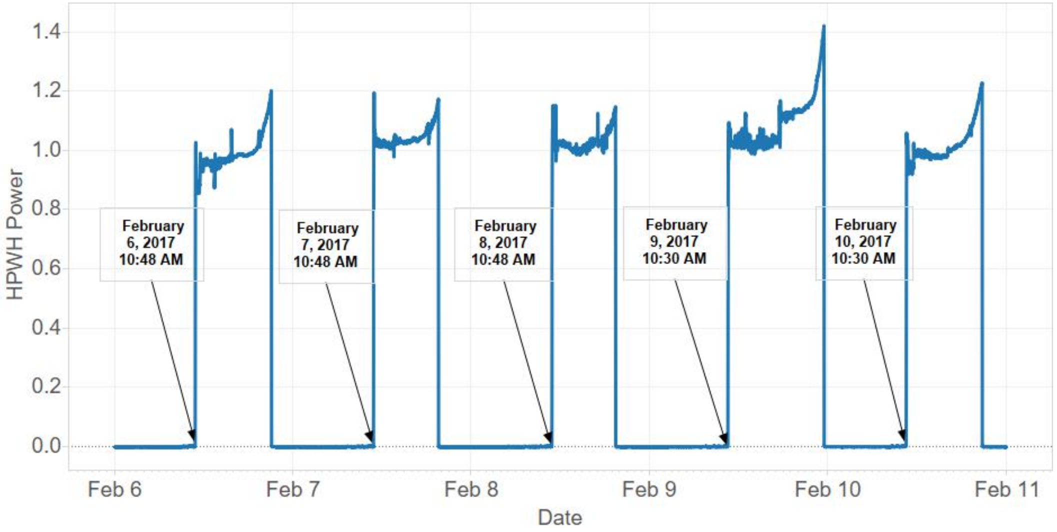

Figure 3-4
One-minute data showing HPWH power over several days in February, with a start time indicated for each re-heat

In some cases, the re-heat did not occur during water draws at all; for instance, for most of August and the first three weeks of September, the re-heat began at about 7:40 PM each day. Because the total daily usage of hot water was on the lower end of the range in those months (the entering mains water is warmer in summer, meaning less hot water is needed), the two tanks were often enough to ride through the day. One implication of this is that the storage on-site is sufficient to satisfy the loads and offer the potential for load shifting or scheduling. Because the daily draws do not necessarily exhaust the supply of hot water, the re-heat could be scheduled to start at any arbitrary hour. When usage is higher, a partial-re-heat could be performed on schedule or on an as-needed basis outside that time window. This is possible because of the large storage volume at this site, and because of the highly-stratified tank, which maintains high-temperature water at the top of the tank.

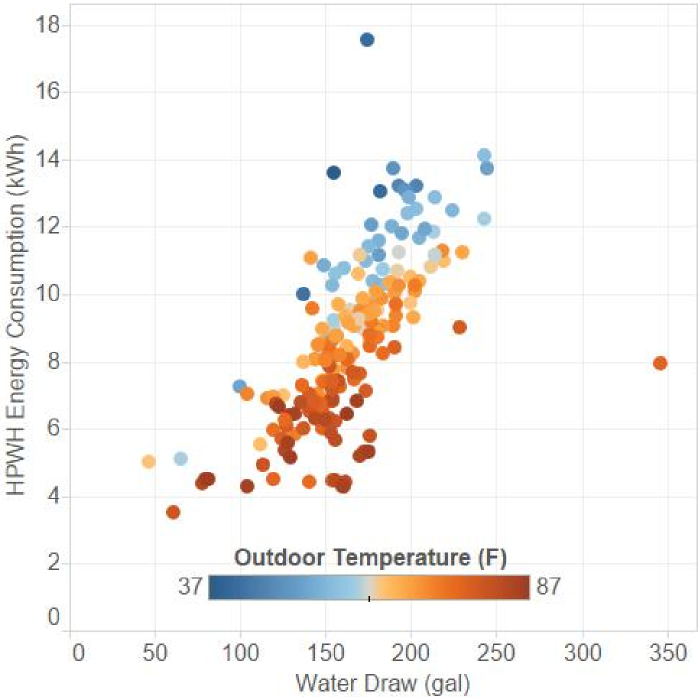

Figure 3-5
Daily energy consumption vs. water draw, with color indicating average outdoor temperature

The daily energy consumption of the HPWH is plotted against the total daily water draw in Figure 3-5. The points are also color-coded by outdoor temperature. The graph shows that energy consumption generally increases with increasing hot water draw and increases with decreasing ambient air temperature, both of which are expected. The average energy consumption on these days was 8.6 kWh, and average water draw was 163.8 gallons. If all days are included, including those with little or no usage, the average water draw was 88.0 gallons per day, and the average energy consumption was 5.37 kWh. A frequency distribution of energy consumption for all days is shown in Figure 3-6. This graphs shows, similar to the water-usage graph in Figure 2-6, the many days of standby as well as a distribution on days where hot water is used. In this case, the energy consumption in typical standby days is mostly in the range of 1 to 3 kWh per day. There are a few days with zero or <1 kWh, which include maintenance days where the system was not on. On days where there is more substantial energy consumption, about 44% of the data falls between 4 and 11 kWh per day.

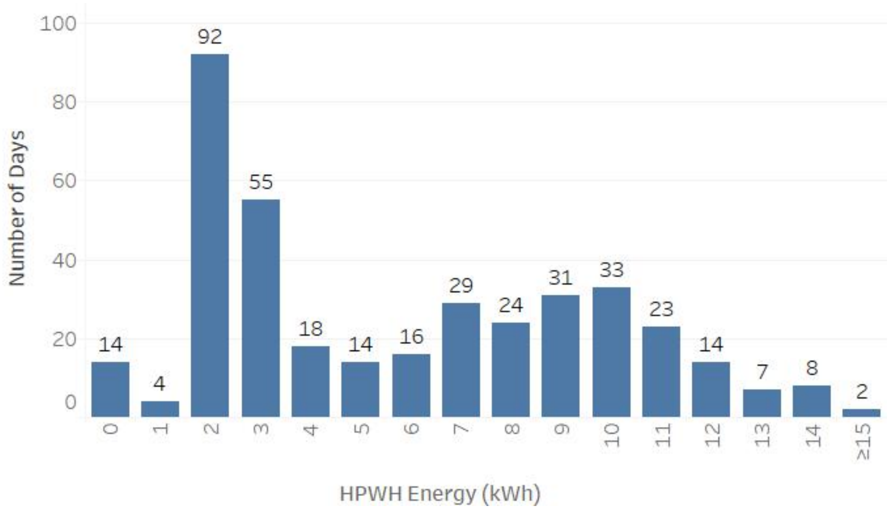

Figure 3-6
Frequency graph of daily energy consumption of the HPWH

The COP is shown in Figure 3-7, plotted against average outdoor temperature on the left graph and water draw on the right graph. In each case, the result is also color-scaled by water draw on the left and outdoor temperature on the right. The COP is generally higher with increasing water draw and with increasing outdoor temperature. The average COP was 2.9, and average outdoor temperature 68.9°F. If all days are included, the average COP was 2.1 and average outdoor temperature 70.9°F. The decrease of COP is not unexpected: on a day with zero flow, the COP is zero, even though the heat pump does provide heating because of standby losses. Similarly, on days with very low flow, standby losses are dominant, so COP is very low.

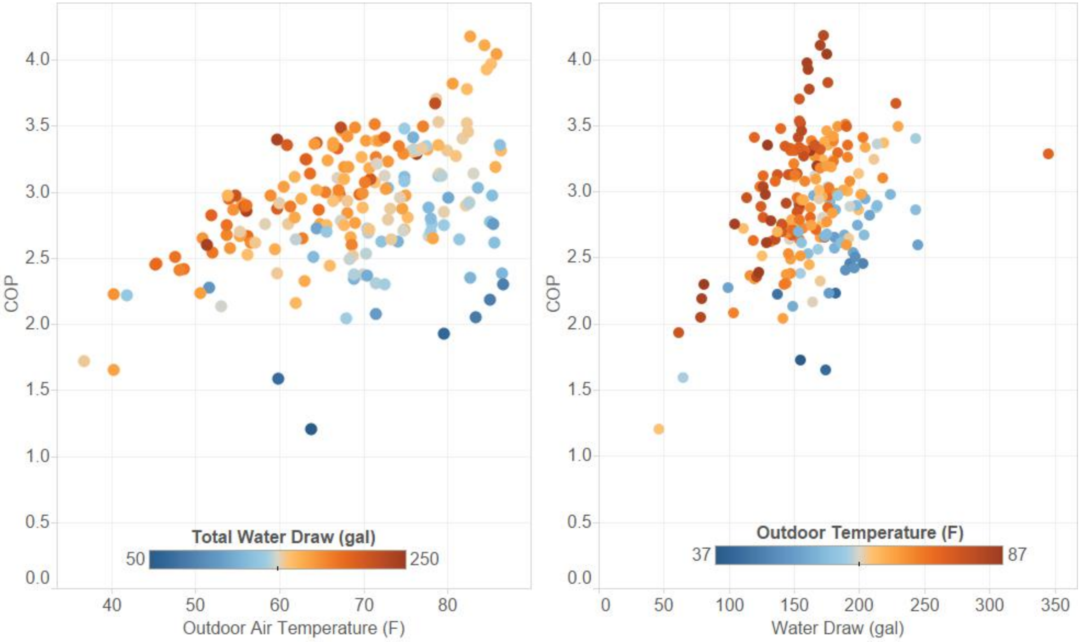

Figure 3-7
Average daily COP vs outdoor air temperature (left) and water draw volume (right)

Also of interest, the daily average temperature of the supply water is shown for a period of interest in Figure 3-8. The data again shows only days where there was significant water usage, so the clusters are typically of five (weekdays), and the first day of usage in each set generally has lower temperature of the supply water. This may be explained by considering that after several days of no usage, the tank will only have been re-heated for short periods to make up standby losses. Because the tank is stratified and heated top-down, the lower portion of the tank may be hot but not quite at the set-point, while only the top of the tank has been recently heated by the heat pump. Because the heat pump turns off based on hot water returning to the heat pump from the tanks, it may stop while a significant portion of the tank is close to, but below, the set-point.

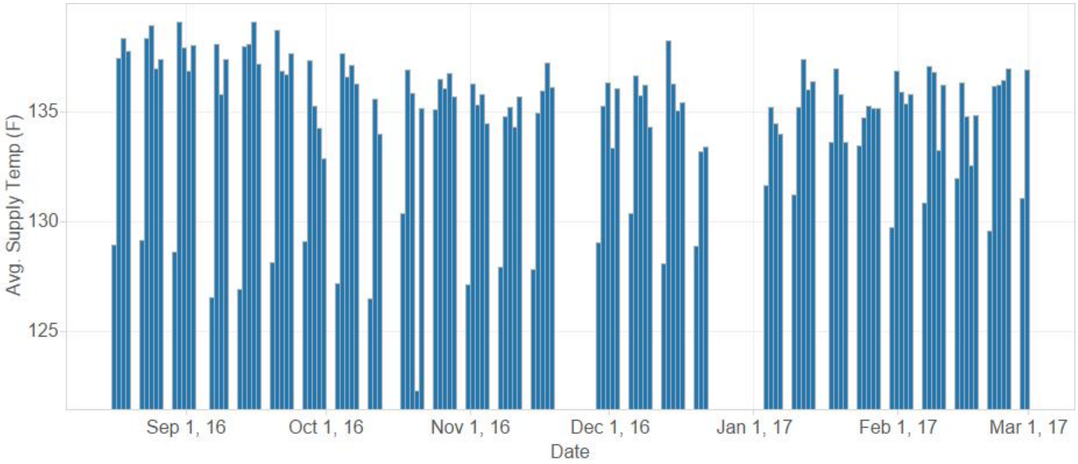

Figure 3-8
Daily average supply water temperature for days with at least 50 gallons of draw for a range of dates

A topic of particular interest for CO_2 HPWHs is performance in cold ambient conditions. Manufacturers claim that systems can provide adequate heating in very low ambient temperatures and without electric-resistance re-heat. The system tested here has a variable-speed compressor. There was only limited operation of the system during cold weather (due to both the climate and the once-per-day operation of the HPWH, which tended to be in late morning or afternoon). However, the results can provide some insight into the operation of the system.

Because the re-heat only happens for a period of several hours, the COP is also plotted against the average temperature during the re-heat period only, in Figure 3-9. Comparing the results with laboratory testing can support the findings here, although the field-measured COP includes standby losses, which means that one should expect significantly lower COPs than the laboratory results, which include only the draw and re-heat.

The COP was measured for tests with 45˚F air, with 50˚F entering water or 65˚F entering water. The results were 3.35 and 3.06, respectively. At an outdoor temperature of 75˚F, with 64˚F entering water and 81˚F entering water, COPs of 4.01 and 3.97 were recorded. In both cases, the laboratory COPs are considerably higher, although the range of field-measured COPs at an outdoor temperature of 75˚F approached this laboratory-measured range when there was a large volume of water draw for the day. The most likely contributor to the differences is standby losses, which would be expected to increase with lower outdoor temperature and have a larger impact on COP with a smaller volume of water draw.

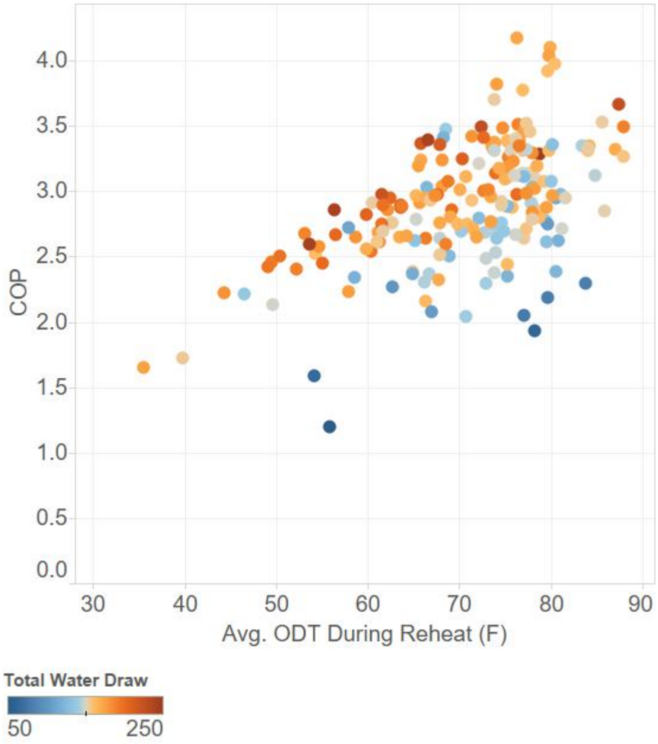

Figure 3-9
Average COP vs. average outdoor temperature during re-heat period only

Figure 3-10 shows the outdoor temperature, HPWH power, cumulative water draw, and supply water temperature for December 9, 2016. The temperature reached as high as 50°F and as low as 35°F during the period in which the heat pump was running. The heat pump power increased in a step change from 1.2 kW to 1.4 kW, at the time when the outdoor temperature crossed approximately 42°F.

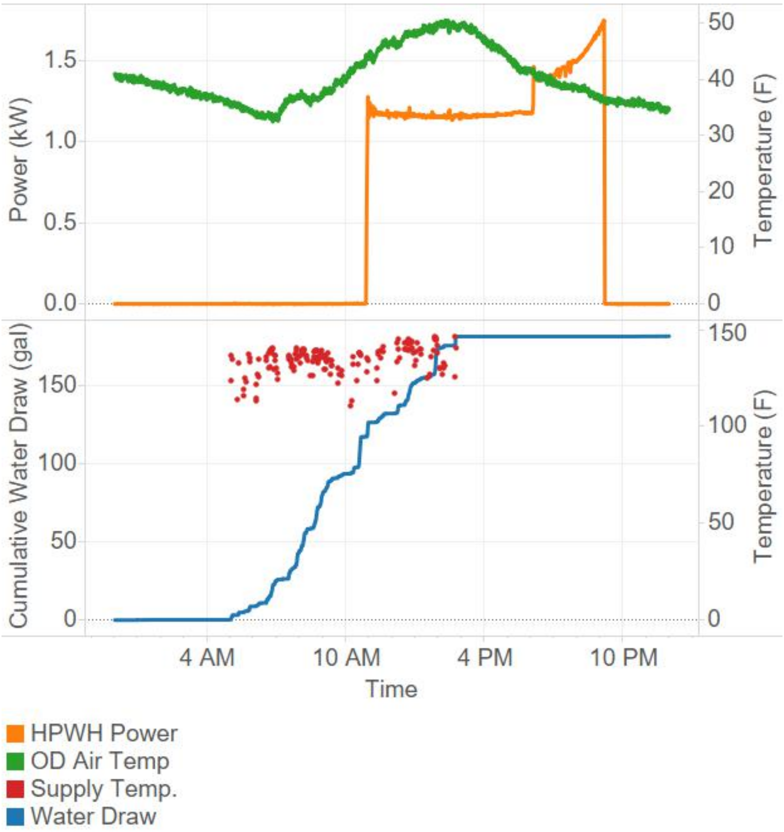

Figure 3-10
One-minute data from December 9, 2016, showing HPWH power, outdoor temperature, supply water temperature (during water draws), and cumulative water draw total

A similar observation can be made from the power profile on December 19, shown in Figure 3-11. In this case, when the HPWH started running, the temperature was 37°F. The temperature increased in the later part of the day, and when the temperature crossed approximately 42°F, the power decreased (appearing to possibly switch between two levels briefly), remaining low until the temperature again decreased.

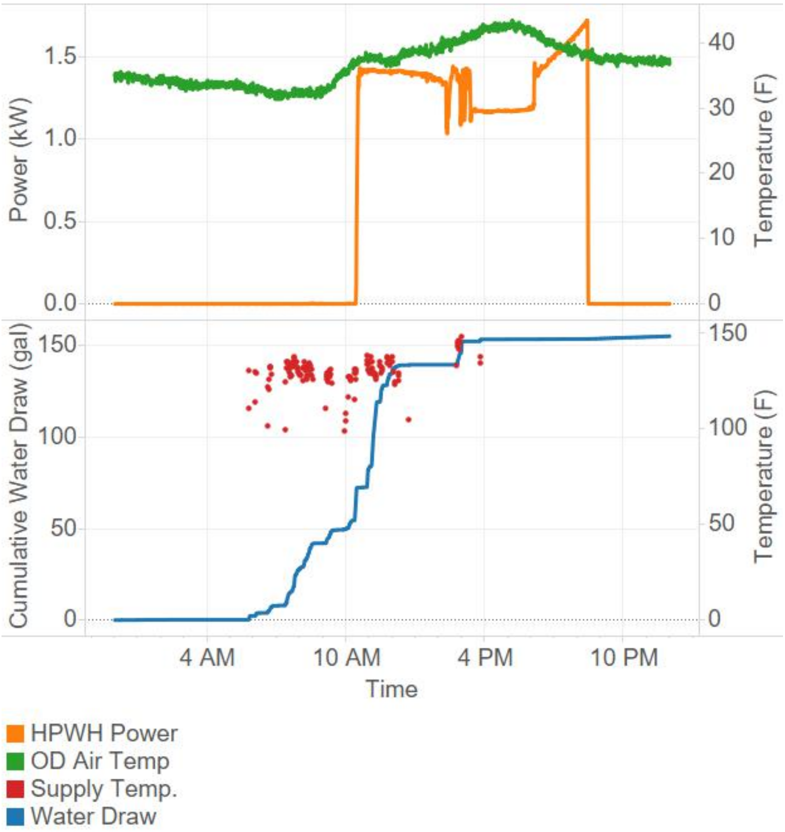

Figure 3-11
One-minute data from December 19, 2016, showing HPWH power, outdoor temperature, supply water temperature (during water draws), and cumulative water draw total

These two days of observations show that the HPWH, while on an inverter-driven compressor, appears to operate between discrete steps based on temperature. This is also supported by Figure 3-12, which is a scatter plot of power versus outdoor temperature in one-minute intervals for November and December of 2016. This graph shows power increasing with outdoor temperature, with the most dense population of points (meaning the most run-time) following a line that appears to have at least two discrete steps, the first around 55°F and the second around 42°F. In addition, the power increases toward the end of each re-heat as temperature of water entering the heat pump starts to increase. Within the heat pump, to provide the same supply temperature means increasing the rate of the pumped water flow; as shown in the accompanying laboratory test report, the rate of water flow could be expected to increase significantly, doubling or more, as the refrigerant temperatures entering and leaving the gas cooler also slightly increase during this period near the end of each re-heat.

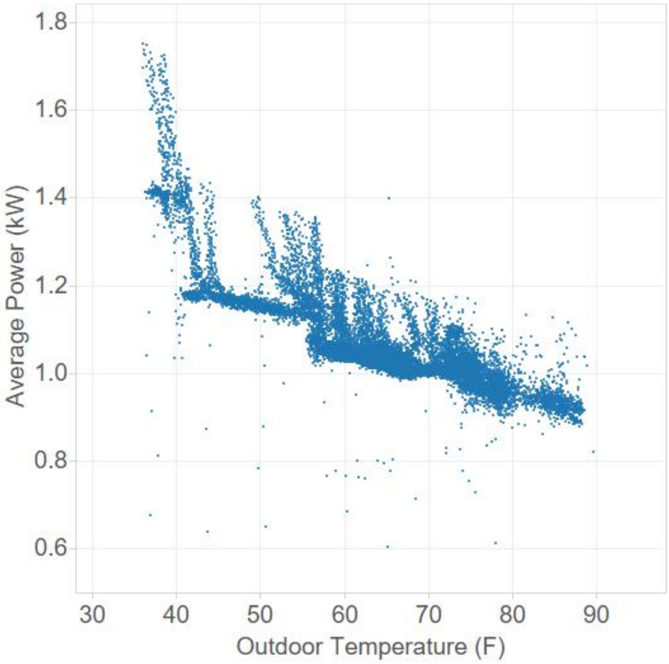

Figure 3-12
One-minute data showing average HPWH power vs. outdoor temperature

Section 4: Summary

This report summarizes a field demonstration of a CO_2 heat pump water heater in a small commercial application. A single HPWH with a nominal heating capacity of 4.5 kW was installed with two 83-gallon storage tanks outdoors adjacent to the cafeteria of Faith Academy, a private school in Mobile, Alabama. The HPWH and tanks were installed on a concrete slab outside the cafeteria. The system was installed to replace two existing electric-resistance water heaters and was instrumented to capture data on delivered hot water, energy consumption, and ambient conditions.

The HPWH was installed over the winter break of 2015-2016. Data-collection equipment was installed in February, and the first full day of data collection was February 12, 2016. One of the electric-resistance water heater was discarded. Because the HPWH provided full water heating for the cafeteria the remaining electric-resistance water heater was turned off and bypassed in piping, although it was left in place as an emergency backup.

Because of the school's schedule, the water draw was nearly zero for almost half of the days examined; weekend days had mostly near-zero water draw, as did various school holidays and vacations. On days where there was usage, the usage was typically in the range of 120 to 210 gallons per day. The HPWH energy consumption was typically in the range of about 4 to 11 kWh per day, and on average 5.4 kWh per day on days with usage. On days where there was little or no water draw, the standby re-heating energy was typically about 1 to 3 kWh per day.

The COP of the system on days with water usage was on average 2.9. The range of COP was typically between 2.0 and 4.0, with the higher COP calculations correlating with higher outdoor temperature and with higher usage of hot water (which is expected, as standby loss becomes a smaller proportion of the re-heat). Because there is no backup electric-resistance element in the tested HPWH, there was no discontinuity in efficiency like is sometimes seen with other HPWHs below a certain temperature or above a certain volume in draw of hot water.

The storage of hot water in the installed system was also more than enough for the site, and no instances of running out of hot water were observed. An unexpected observation at the site was that the system was often observed to begin running at the exact same time of day for several consecutive days or weeks. It was found that, especially in summer when the draw of hot water is lower, the tanks had enough storage capacity that the re-heat would not be triggered by the draws. In that case, the system under test was programmed to attempt to trigger re-heat every 24 hours. This observation shows a benefit of the stratified tank approach: Because the tank does not mix during normal use, the supply temperature only slowly decreases due to standby losses, but hot water is generally available throughout the usage period. This shows the potential for these systems for future demand-response or load-shifting applications, where re-heat could be scheduled to mostly occur during specified hours, with partial-re-heats as needed.

Section 5: References

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