Split HPWHs as an Efficient Solution for Multifamily Buildings with In-Unit Water Heaters

Preprint

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National Renewable Energy Laboratory

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Split HPWHs as an Efficient Solution for Multifamily Buildings with In-Unit Water Heaters

Bethany Sparn, Greg Shoukas, Erin Lewis, National Renewable Energy Laboratory

ABSTRACT

A quarter of all housing units in the United States are found in multifamily buildings, but few efficiency innovations have been made to improve electric water heating systems in this building type. Domestic hot water in multifamily buildings can either be provided by a large central water heater or smaller in-unit water heaters. Integrated heat pump water heaters that are installed in single-family homes are often a poor fit for individual multifamily units because the water heaters are often located in small internal closets. This confined space can limit the airflow to the heat pump, and the cold exhaust air can cause discomfort and reduced efficiency.

Split CO_2 HPWHs separate the tank from the heat pump, which allows for installation location flexibility. Further, CO_2 heat pumps can operate under colder ambient conditions, making them a better fit for multifamily units across a wide range of climate regions. As part of a larger project to characterize split HPWH performance, we evaluated the feasibility of installing an additional, parallel tank that could provide hot water to a second housing unit using a single CO_2 heat pump. This approach would reduce the first costs of these more expensive units. Based on the high draw volume that we imposed on both tanks, the same heat pump may be able to support more tanks, depending on hot water usage. This paper will describe the split CO_2 HPWH technology, how the two-tank system was controlled, and results from our laboratory evaluation.

Introduction

Advances in energy efficiency, both in terms of construction methods and efficient equipment, have led to dramatic improvements in the energy use in single-family residential buildings, but multifamily buildings have not received the same level of attention (Regional Energy Efficiency Organizations 2016). Some unique challenges in multifamily buildings include:

1. Limited policies and energy efficiency programs directly targeting the multifamily sector
2. Split incentives when the building owners pay for efficiency investments and the tenants pay utility bills. This is not always the case but is a common arrangement.
3. Inadequate data on energy use in multifamily buildings.

In the last decade, heat pump water heaters (HPWHs) have been developed further by several prominent water heater companies, and they provide an efficient alternative to standard electric water heaters. However, the products developed for single-family homes may not be a good fit for all types of multifamily units or buildings. Until now, HPWHs were mostly used as a replacement for electric resistance water heaters. However, in the interest to move toward full electrification, HPWHs offer an energy-efficient option for replacement of natural gas, propane or fuel oil water heaters as well. Several cities in California have banned natural gas appliances in new buildings and many other cities are considering similar bans (Ivanova 2019). Reducing natural gas consumption in buildings directly reduces carbon emissions, especially as more renewable generation sources are added to the grid. The transition to clean, efficient water heating is important in new construction as well as existing buildings.

As more electric water heaters are installed, the need and opportunity for this equipment to provide demand-side management services is expected to grow. This is still a nascent area of opportunity where more research and development are needed. Some residential HPWHs have adopted communication and control protocols that make it possible for the utility to initiate demand response. These water heaters are designed for use in single-family homes, and the implementation of demand response in multifamily dwellings may be executed differently.

Table 1. Number of housing units in millions for multifamily housing water heaters. Adapted from Table HC8.1 from the 2015 RECS Survey, EIA.

		Small Apartment Buildings (2-4 units)	**Large Apartment Buildings (5+ units)**	**Total Multifamily [a]**	**Total U.S.**
Number of housing units (million)		9.4	21.1	30.5	118.2
Fuel Type	Natural Gas	5.0	9.0	14.0	56.3
	Electric	3.9	11.2	15.1	54.6
	Fuel Oil or Other	0.5	0.7	1.2	7.3
Location	In-Unit	4.9	9.2	14.1	98.9
	Central[b]	4.4	11.8	16.2	16.3
Tank Size for In-Unit WHs	Small Tank (<30 gallons)	1.9	3.1	5.0	15.3
	Medium Tank (31-49 gallons)	2.0	4.9	6.9	51.8
	Large Tank (>50 gallons)	1.0	1.2	2.2	31.8

[a] Because of rounding, data may not sum to totals.

[b] RECS participants were asked if their water heater was in their apartment or somewhere else in the building, indicating that there may be more dedicated water heaters that were classified as “central” because they were installed in a hall closet or balcony shed or similar.

As of 2015, out of 118.2 million housing units in the United States, 30.5 million (or 25.8%) are apartments (U.S. EIA 2015). Large apartment buildings containing 5+ units account for a 21.1 million or 69% of all multifamily housing. Small apartment buildings (2-4 units) house 9.4 million units or 31% of multifamily dwellings. In-unit water heaters are slightly more likely in small apartment buildings (52%), while larger apartment buildings are more likely to have central DHW systems (56%). Across all apartment building sizes, smaller tank sizes (49 gallons and less) are more common (85%) than tanks 50 gallons or more when the water heater is installed in the unit.

It should be noted that the number of apartments with in-unit or dedicated water heaters may be higher than indicated by the RECS data because the question that participants were asked was about whether their water heater was in their apartment or somewhere else in the building. There are a number of common configurations in apartment buildings where the water heater is in a balcony shed or separate closet, so the water heater is not technically in the apartment but is also not served by a central water heater.

Heat Pump Water Heaters as In-Unit Water Heaters

In some ways, a single water heater serving a single housing unit in a multifamily building looks identical to a water heater installed in a single-family home. Integrated HPWHs are a single piece of equipment with a heat pump sitting on top of a water tank (Hudon, et al. 2012). These HPWHs were designed to be a direct replacement for an electric water heater because they require the same electrical service, have identical plumbing connections, and have similar tank sizes to electric resistance water heaters. However, some of the differences between HPWHs and electric resistance water heaters may present more of a challenge when installed in a multifamily unit. The main issues are described in the following subsections.

Cold Air

A HPWH extracts heat from the air, which results in cold air being exhausted into the space around it. The cold outlet air can impact the space-conditioning temperatures and may impact the occupant's comfort, especially during winter months. Also, during the colder months this may increase energy use for space heating. When installed away from the living space, such as a basement, the impacts of that cold air are reduced. In a multifamily unit, water heaters are often installed in closets near the main living space (Chasar and Martin 2013) (Eversource & Steven Winters Associates 2018) (Steven Winter Associates 2019). Depending on the closet size, a louvered door or ducting may be needed (adding to installation costs) to ensure sufficient airflow to and from the HPWH. If the room does not have sufficient air volume and ducting or louvered doors are not added, cold exhaust air from the HPWH will cool the space around the water heater, which would then cause the system to operate at a reduced efficiency.

Noise

The heat pump on an integrated HPWH generates more noise than an electric resistance or natural gas water heater. For the same reason that the cold air is less of an issue in single-family homes, noise is also generally not an issue because the water heater is usually installed away from the main living spaces. This noise is more noticeable in multifamily units with the water heater installed in a centrally located closet. A multifamily deployment in Florida with over 1,000 HPWHs installed found that noise was the main complaint from residents (Chasar and Martin 2013). Newer HPWHs have improved the noise level but noise can still be a nuisance.

Space

Integrated HPWHs are taller than electric resistance water heaters because the heat pump is stacked on top of the tank. Opportunities to retrofit HPWHs in existing buildings can be limited by the space available and the height of the HPWH. Many multifamily units and apartments have small "lowboy" water heaters that are about 30 inches tall (Weber n.d.). HPWHs are typically 60 inches tall or more. Smaller tanks would help reduce the overall size of the integrated HPWHs, but most integrated HPWH products are sold with tanks greater than 50 gallons.

Split CO_2 HPWHs

Split HPWHs solve many of the issues associated with integrated HPWHs by locating the heat pump outside. The only split complete HPWH product that is commercially available in the United States is the SanCO_2, made by Eco_2 Systems, which uses CO_2 as the refrigerant. Water lines run between the indoor storage tank and the outdoor heat pump, as shown in Figure 1.

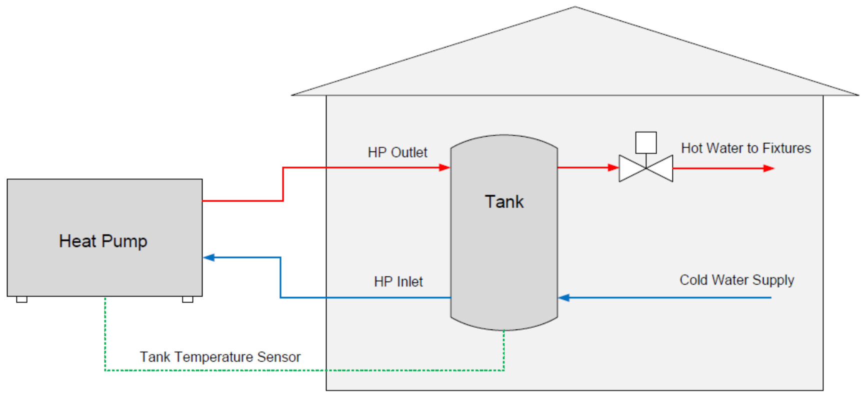

Figure 1. Basic components of split CO_2 HPWH, with the heat pump installed outside.

With a split system, the cold air and noise are moved outside where the heat pump is located while the hot water storage tank remains inside. Different tank options are available so that the storage tank can be sized to fit tight space constraints. Split heat pumps that use CO_2 as the refrigerant have the advantage of operating more efficiently at colder temperatures (-31.7°C/-25°F), which makes them an excellent option for outdoor installations in many regions of the country (Eco2 Systems n.d.). This system will heat the water in a single pass such that cold water from the tank enters the heat pump and is fully heated to the desired temperature as it exits. The outlet water temperature is hotter than most integrated HPWHs produce (60°-75°C/140°-165°F), so a mixing valve is needed to prevent scalding (Larson 2013). The mixing valve is typically set to supply water around 49°-52°C /120°-125°F. The flow rate of water between the tank and the heat pump is very low, which helps to preserves tank stratification. Cold water from the bottom of the tank is pumped through the heat pump and returns hot water to the top of the tank. There are no backup resistance heating elements in the tank. The data in Figure 2 shows how the internal water temperature increases from top to bottom when starting with a fully cold tank.

The installation process for a split CO_2 HPWH is more complex than a traditional integrated HPWH, because water lines need to be run outside. When installed in cold climates, these water lines need to be well-insulated, and heat trace may be added for additional freeze protection (Steven Winter Associates 2019). Additionally, electrical service (240V, 15A) is needed outside for the heat pump. The tank can be located anywhere inside as it does not require power, airflow, or a condensate drain, all of which are needed for integrated HPWHs. In addition to the increased complexity and costs during installation, CO_2 split HPWHs are about twice the cost of integrated HPWHs, which are already more expensive than traditional gas and electric water heaters (Weber n.d.).

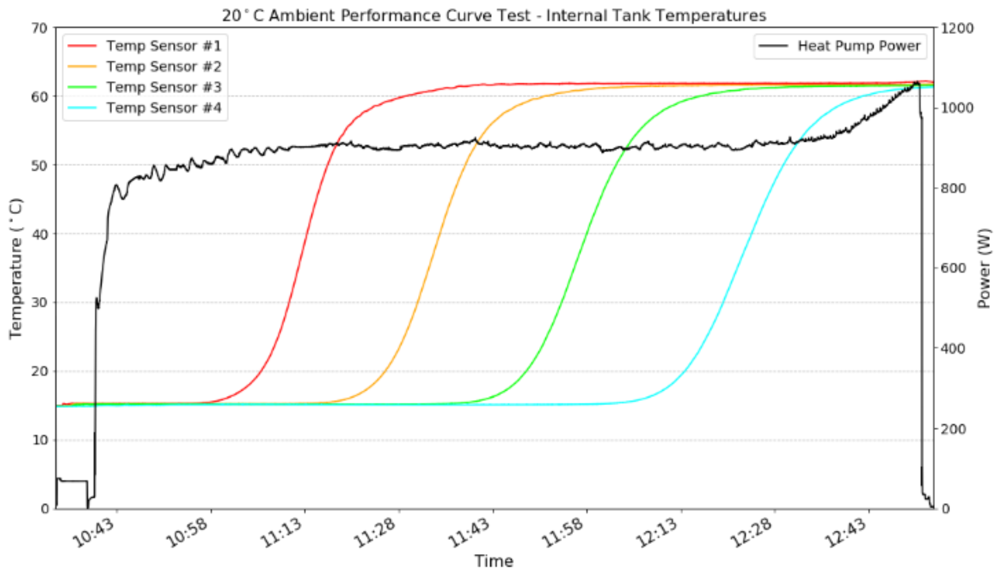

Figure 2. Internal tank temperatures and power during heating cycle of the SanCO_2 HPWH. Temp Sensor #1 is toward the top of the tank and Temp Sensor #4 is at the bottom of the tank.

One way to reduce the cost of split CO_2 HPWHs in multifamily buildings is to use a single heat pump connected to tanks in multiple units. The co-location of dwellings in a single building provides the opportunity to split the expense of the more costly HPWH when shared by neighbors. According to (Weber n.d.), the heating capacity of a single SanCO_2 heat pump may be sufficient for up to four tanks.

After completing a series of laboratory tests looking at the performance of the SanCO_2 heat pump in a standard, single tank configuration, the experimental setup was modified to connect the heat pump to a second tank. The following sections describe the laboratory setup, the controls implemented, the results from the two-tank experiment, and proposed next steps.

Experimental Design

Two 43-gallon tanks were connected in parallel to a single SanCO_2 fourth-generation heat pump. This tank arrangement replicates the scenario of a split HPWH servicing two separate multifamily units. The 43-gallon tank size was chosen because nearly 85% of multifamily units with in-unit water heaters have tanks smaller than 50 gallons (U.S. EIA 2015). Figure 3 shows the laboratory setup with a single heat pump and two tanks. There are two different systems that need to be switched between the two tanks: the water circuit between the tank and the heat pump, and the tank temperature sensors. This ensures both water tanks can be heated by a single heat pump.

Two three-way, diverting valves were installed on the water loop between the heat pump and tanks. By turning the diverting valve, the cold water to the HPWH and hot water return could be switched between Tank 1 or Tank 2. The valves are controlled by a common control signal so that the valves are switched together. The manufacturer's tank-mounted thermistor, when connected to the heat pump control board, is used to trigger heating if the water temperature falls below the setpoint. The SanCO_2 control board could be modified in the future to allow multiple tank thermistors to be connected to a single HPWH, but for this experiment, an external controller was built to switch between tank thermistors. During the experiment, one tank thermistor was connected to the heat pump control board while the other was monitored by the external controller. In other words, if the heat pump was reading the tank temperature for Tank 1, the external controller was measuring the tank temperature from Tank 2, and vice versa. Additionally, the controller was used to send signals to both three-way diverting valves and to measure the power consumption of the heat pump. Figure 4 shows a simplified schematic diagram of the external controller and piping.

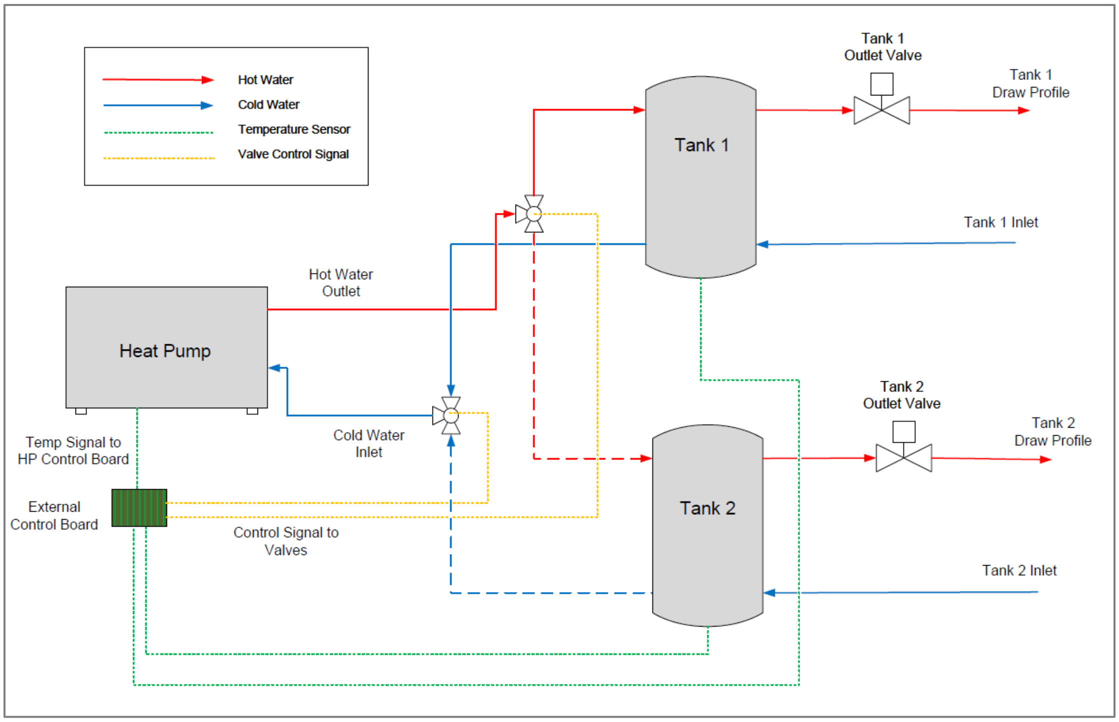

Figure 3. Laboratory setup for the two-tank experiment with the SanCO_2 heat pump.

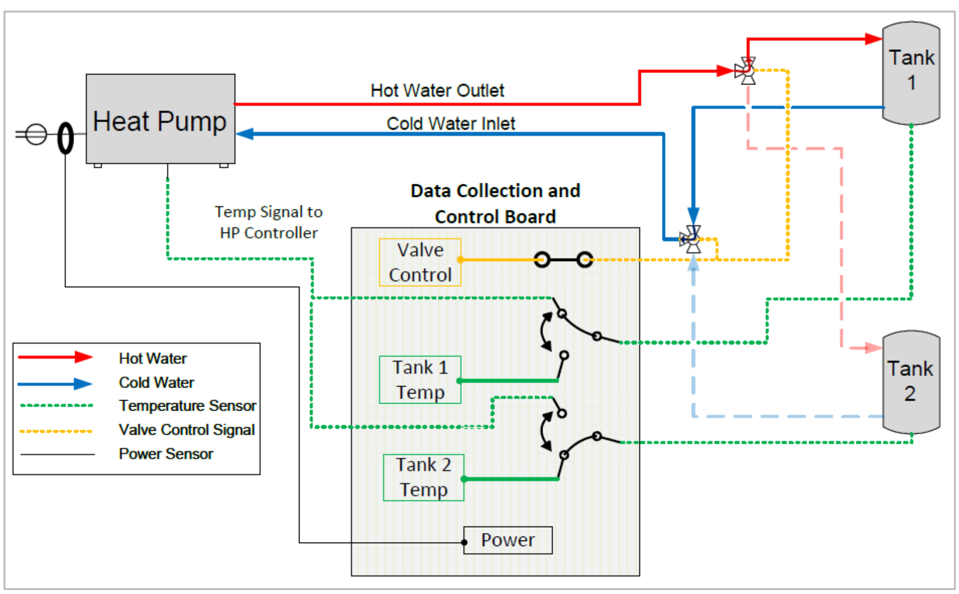

Figure 4. Sensor and control diagram for the external control board.

During periods when heating was not needed by either tank, the controller relays switched between the two thermistors every minute to monitor the water temperatures in both tanks. If heat was required in either of the tanks as sensed by the HPWH control board, the heat pump would turn on. At this point, the external controller sensed the power draw from the system and the diverting water valve positions were changed to ensure the appropriate tank requiring heat was connected to the HPWH. While the water was heated, the controller paused switching between thermistors readings. For example, if the Tank 1 thermistor was connected to the heat pump control board and the heat pump turned on, the external controller would set the inlet and outlet valves to connect the heat pump water circuit to Tank 1. While Tank 1 was heating, the Tank 2 temperature was monitored by the external controller. If the temperature of Tank 2 dropped below a threshold prior to Tank 1 completing its heating cycle, the external controller would switch the valves between the two tanks every 10 minutes. This provided heat to both tanks, one at a time. When either of the tanks reached its setpoint, the external controller would switch the valves to the other tank. The HPWH would operate and shutdown after the second tank reached its setpoint.

Two uses cases were tested using this configuration—a high-volume use case with 93 gallons of mixed water drawn and a medium-volume use case with 43 gallons of mixed water drawn from each tank. These volumes were selected to represent an average hot water usage in a home and a much larger usage volume to push the system. Each tank had a dedicated mixing valve set to 51.7°C (125°F), as the heat pump produced hot water around 63°C (145.4°F). The draw profile was developed over an 8-hour period for the high-use profile and 5-hour period for the medium-use case. The profiles were identical for the two tanks but staggered slightly so that draws did not overlap between the tanks. The tanks were not conditioned to be fully heated at the start of the draw profile—rather, they were left on from the previous day of testing and the test began with the tanks in their current state.

Each tank had four internal thermocouple measurements that were spread 7 inches apart along the height of the tank. The average tank temperature was calculated by evenly weighting the four internal thermocouples. Due to the unique geometry of the tank, the top thermocouple is not at the very top of the tank and so the average tank temperature calculation may not represent the true average tank temperature, but is still a good proxy for tank conditions.

Results

The results from the two draw profiles are presented in the following graphs, starting with the medium-volume use case. Figures 5-7 show results from the medium-volume use case. Figures 8-10 show results from the high-volume use case.

Figure 5 shows average tank temperature for both tanks, along with power and the flow rate from the draw profiles. We started these tests without preconditioning the tanks, and Tank 1 started off nearly 10°C colder than Tank 2. Even at the start of the test, this cooler tank temperature was not sufficiently low to trigger heating from the heat pump. The heat pump turned on at the end of the first draw and continued through the duration of the draw profile period. By the end of the experiment, both tanks were fully heated.

Data from the same medium-volume draw profile are shown in Figure 6, with delivered water temperature shown, measured just downstream of the mixing valve. The target delivered temperature (51.7°C/125°F) is shown by the brown dotted horizontal line, while the minimum acceptable delivered temperature (43.3°C/110°F) is represented by the orange dotted horizontal line. This minimum temperature is based on comfort metrics and is used in National Renewable

Energy Laboratory simulations and laboratory evaluations as the minimum acceptable hot water temperature (Wilson, et al. 2014).

At the start of each draw, it took about 10 seconds for the hot water to reach the thermocouple inserted in the piping, which is why each draw started with colder temperature readings. The delivered temperature readings, after the cold slug of water cleared, show that most draws delivered water at or above the desired temperature of 51.7°C/125°F. The first two draws from Tank 1 did not reach the 51.7°C target temperature though, due to the colder tank temperature at the start of the experiment. For those draws, the lowest delivered temperature was 46.6°C/116°F, which is still above the 43.3°C threshold needed to maintain hot water comfort. For this reason, we considered this experiment successful, as there were no draws where the delivered water temperature dropped below 43.3°C.

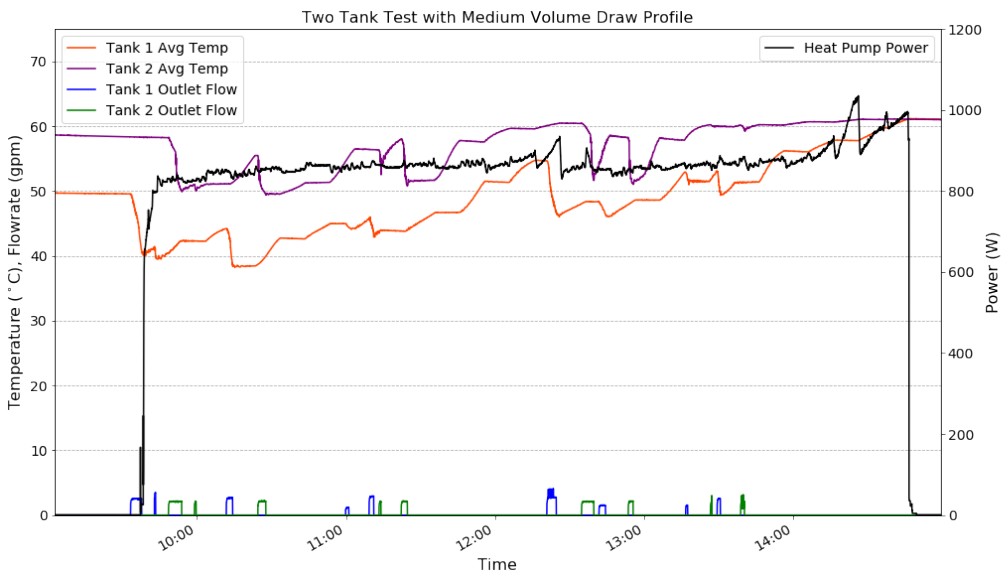

Figure 5. Medium-draw profile (43 gallons per tank) with power, average tank temperatures and draws shown.

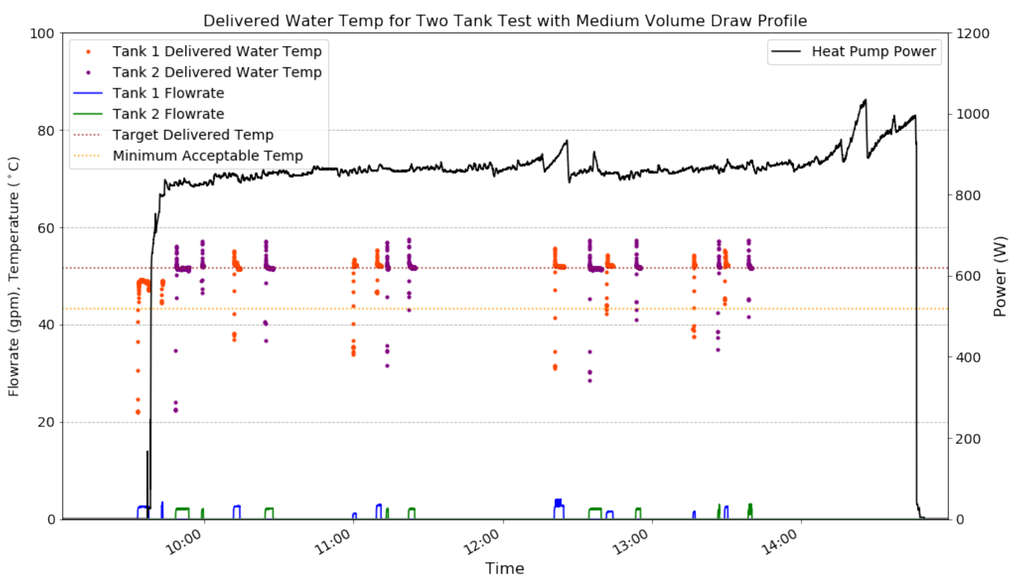

Figure 6. Medium-draw profile with power, delivered water temperatures, and draws shown. The horizontal dotted lines represent the mixing valve setpoint (51.7°C) and the minimum acceptable temperature for comfort (43.3°C).

Tank thermistor measurements from the external controller are shown below in Figure 7. The temperature readings from the tank thermistors are similar to the average tank thermocouple temperature shown in Figure 5, but the average tank temperature came from four separate internal measurements, while the tank thermistor is a single reading from the outside of the tank. At the beginning of the test, the external controller switched between the tank thermistors every minute. Once Tank 1 began heating, the external controller continuously measured the thermistor of Tank 2. When Tank 2 required heating, the external controller began switching back and forth between the tank thermistors and three-way diverting valves every 10 minutes.

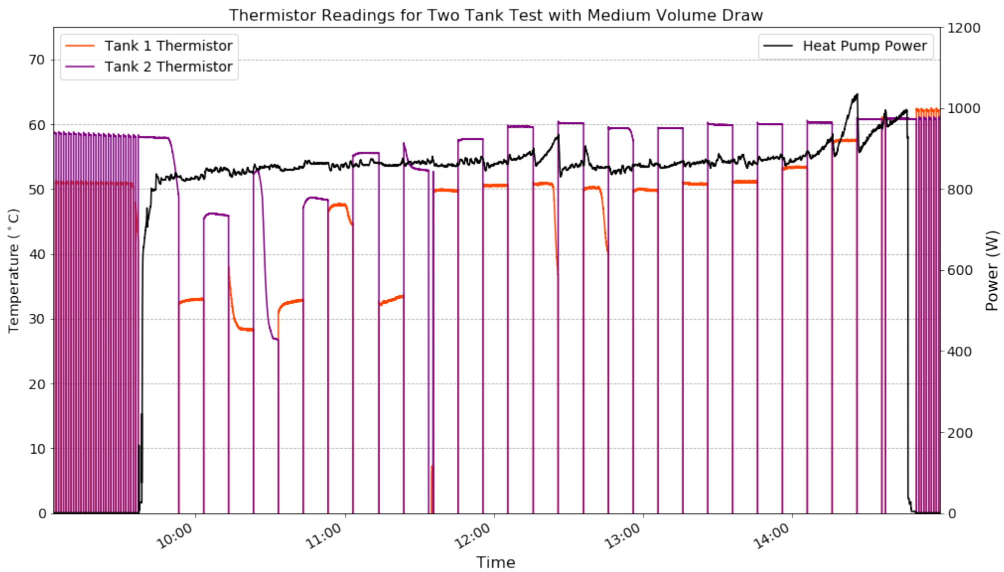

Figure 7. Thermistor readings and power during the medium-volume test.

Three similar plots are shown below for the high-volume draw profile test. Average tank temperature is shown in Figure 8. In this case, the two tanks started out at nearly the same average temperature. The first draw initiated heating for Tank 1 and the HPWH continued running through the entire test. There are periods of time where the average Tank 2 temperature was below 20°C/68°F, as shown in Figure 9; however, this did not result in cold water being delivered because the hot water is delivered to the very top of the tank where it is drawn. The average temperature for Tank 1 also dropped to about 25°C/77°F but again, the delivered water temperature was not affected.

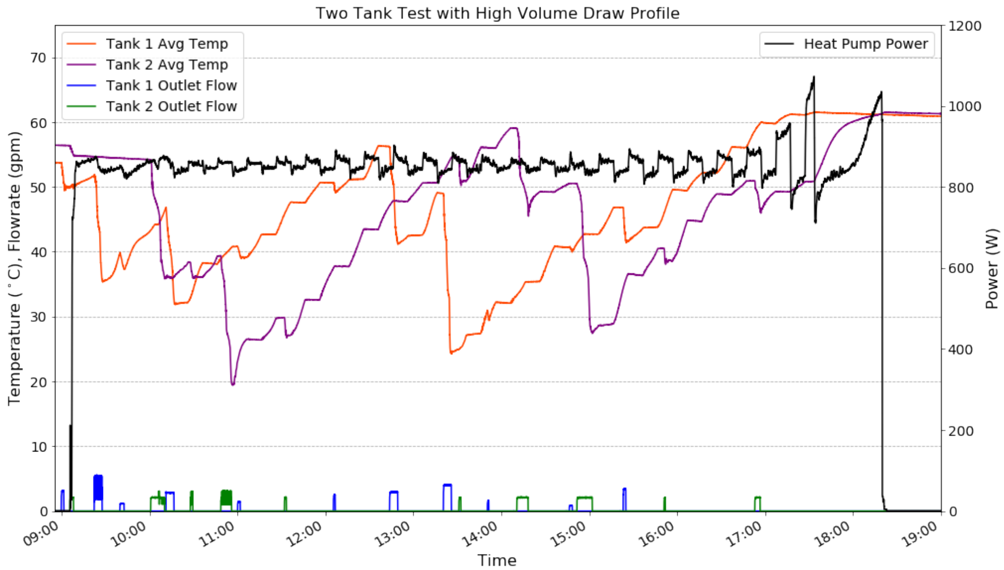

Figure 8. Two-tank test with the high-volume (93 gallons) draw profile.

Delivered water temperature for the high-volume test is shown in Figure 9. As discussed before, the first few seconds of each draw are below the desired temperature, but they quickly warm up as the cold slug of water passes through the piping. All the draws delivered water at the desired temperature of 51.7°C/125°F, despite the high total volume drawn over the day. Even during periods of time when the average tank temperatures in Figure 8 suggest that the tank was full of cold water, the delivered water never dropped below 51.7°C/125°F.

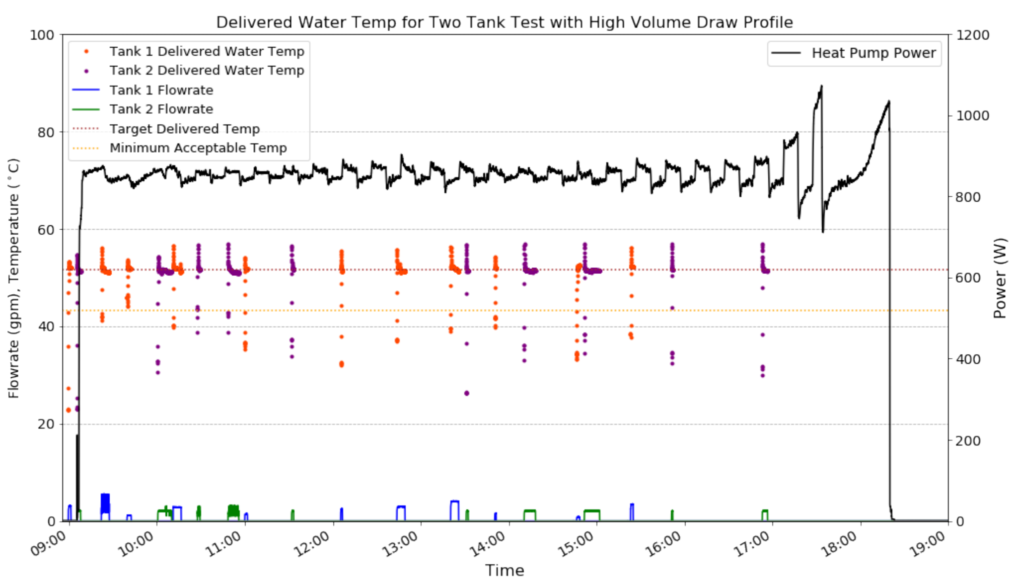

Figure 9. High volume draw profile delivered water temperature, with all draws delivered at 125°F.

The tank-mounted thermistor readings from the high-volume test are shown in Figure 10. This test was longer than the medium-volume test, so it is harder to see the values during the idle period when the external controller switched between the two sensors every minute. Heating was initiated by Tank 1, and it took some time before Tank 2 required heating. This can be seen in

Figure 10 where the thermistor on Tank 2 was measured by our external controller for nearly an hour before the valves were used to switch between the tanks. Once Tank 2 required heating, the controller switched between the two tanks for the remaining duration of the draw period. Tank 1 reached its heating setpoint first, and Tank 2 needed another hour of heating before the heat pump turned off.

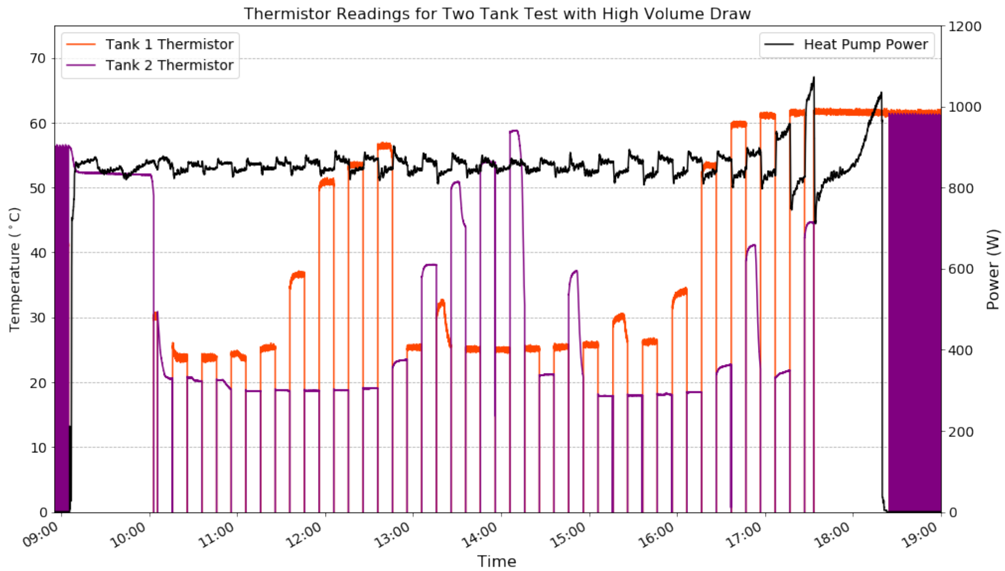

Figure 10. Thermistor readings and power for the high-volume profile.

Conclusions and Next Steps

These experiments were designed to investigate the feasibility of using more than one tank with a SanCO_2 heat pump, and the results are very encouraging. The high-volume draw profile used over 90 gallons during an 8-hour period. This is much higher than most homes typically use and therefore it seems feasible that this heat pump could support more than two tanks. This system takes full advantage of tank stratification by returning hot water to the very top of the tank and drawing the coldest water from the bottom. This allows the system to maintain comfort for the user, even with a heat pump that has a slower heat recovery time compared to an electric element.

The experimental configuration used an external controller to switch between tanks, but this could be simplified if the manufacturer provided such control capability as part of the heat pump. This would require multiple tank thermistor connections on the heat pump control board and the ability to switch between multiple water circuits. The heat pump control board would also need some embedded controls allowing the manufacturer's systems to switch water heating between multiple tanks. There is likely a more optimized control strategy than was used in this experiment, but this simplistic approach demonstrated a first proof of concept.

This strategy is intended to share the more expensive costs of split CO_2 HPWHs to provide a more economic and energy-efficient solution for water heating in multifamily buildings. While these results are promising, it is worth mentioning that the stainless-steel tanks, which should have a longer service life, are fairly expensive. A shared heat pump with two tanks does not cut the per unit equipment costs in half; rather, it reduces the cost per unit by about 1/3.

To make the shared economics more favorable, the heat pump could be connected to a conventional insulated glass-lined steel water tank.

As with any shared equipment, there are challenges associated with utility billing if two or more units are using a single heat pump. Depending on how the electric utilities are metered among housing units, this scenario could pose challenges.

Despite the potential challenges associated with updating the heat pump control board and billing, this solution shows promise for application in multifamily buildings with in-unit or dedicated water heaters.

References

Chasar, D., and E. Martin. 2013. *Efficient Multifamily Homes in a Hot-Humid Climate by Atlantic Housing Partners.* Golden, CO: U.S. Department of Energy's Building America Program.

Eco2 Systems. n.d. *SanCO2 Product Information.* Accessed March 16, 2022. https://www.eco2waterheater.com/product-info.

Eversource & Steven Winters Associates. 2018. *Guidelines for Integrated Heat Pump Water Heaters in Multifamily Buildings.* Boston, MA: Eversource Energy.

Hudon, K., B, Sparn, D. Christensen, and J. Maguire. 2012. "Heat Pump Water Heater Technology Assessment Based on Laboratory Research and Energy Simulation Models." *ASHRAE Winter Conference.* Chicago, IL: ASHRAE.

Ivanova, Irina. 2019. December 6. https://www.cbsnews.com/news/cities-are-banning-natural-gas-in-new-homes-because-of-climate-change/.

Larson, Ben. 2013. *Laboratory Assessment of Sanden GAU Heat Pump Water Heater.* Seattle, WA: Bonneville Power Administration.

Regional Energy Efficiency Organizations. 2016. "Multifamily Energy Efficiency Retrofits: Barriers and Opportunities for Deep Energy Savings."

Steven Winter Associates. 2019. *Heat Pump Retrofit Strategies for Multifamily Buildings.* New York, NY: Natural Resources Defense Council .

Sullivan, G.P, and J.P. Petersen. 2015. *Demand-Response Performance of Sanden Unitary/Split-System Heat Pump Water Heaters.* Richland, WA: Pacific Northwest National Laboratory, PNNL-24224.

U.S. EIA. 2015. *Residential Energy Consumption Survey.* Washington D.C: U.S. Energy Information Administration.

Weber, Robert. n.d. *Energy-Efficient Replacement of Electric Resistance Water Heaters in Low-Rise Multifamily Buildings.* Seattle, WA: Bonneville Power Administration.

Wilson, E., C. Engebrecht Metzger, S. Horowitz, and R. Hendron. 2014. *2014 Building America House Simulation Protocols.* NREL/TP-5500-60988, Golden, CO: National Renewable Energy Laboratory.