Heat Pump Showdown - A Direct Comparison of Multi-Function and Single Function Heat Pumps

James Linwood Haile, P.E., Frontier Energy Inc.
Ryan Fidler, Frontier Energy Inc.
Antonea Frasier, Frontier Energy Inc.

ABSTRACT

Multi-function heat pumps (MFHPs) serve more than one type of load using a single compressor. The most common example of a multi-function heat pump serves both indoor space conditioning load and domestic hot water production. This is also called a "three-function heat pump" for obvious reasons. The most common of these use air-to-water heat pumps (AWHPs), which heat and cool a water loop. That process water is then used for space conditioning and domestic water heating. A simple switching valve diverts water flow between the AWHP and the two loads. The primary benefit of MFHPs is reduced needed utility service and breaker space for an all-electric installation.

An experiment at one of the Central Valley Research Homes (CVRH), four unoccupied laboratory houses in Stockton, CA, was conducted to evaluate the performance of a three-function AWHP system relative to separate heat pumps (an air-to-air ducted heat pump and an integrated HPWH). Both systems were installed in the same house and operation was alternated between the two. Occupancy was simulated using interior sensible and latent gains to match California code compliance energy modelling assumptions. The experiment found that though the AWHP could match the ducted heat pump in space conditioning energy use, the three-function mode used over 6 kWh/day more than the traditional separate systems in heating (for a winter day with 50F average outdoor air temperature) and 10 kWh/day more in cooling heating (for a summer day with 90F average outdoor air temperature). Potential causes of this large difference are discussed.

Introduction

Heat pump space conditioning and water heating can greatly reduce the carbon footprint of residential buildings relative to both electric resistance and natural gas combustion equipment. In California new construction environments, many new developments are not providing natural gas connections making all-electric solutions necessary. (CPUC, 2022) Electrification retrofits of existing homes are also increasing due to the lowering cost of equipment and residential solar, rising cost of natural gas, incentive programs, and a general cultural trend toward climate action.

While electrification of new construction is straightforward from an installation and home infrastructure perspective, electrification retrofits have significant barriers. Chiefly, electrical utility service connections and breaker panels were sized for the loads of the home at the time of construction, which in most cases did not include heat pumps or associated resistance heat backups. Most Californians are finding that they need prohibitively expensive electrical upgrades to pursue heat pump retrofits and incentives. (EFCA, 2022)

Electrification in both new construction and retrofits encounter the issue of resistance heat. Resistance heat is required when a heat pump cannot provide sufficient heat due to low outdoor temperatures. It also improves comfort during defrost cycles and recovery from setback.

But these resistance heat systems require additional electrical infrastructure capacity, both at the dwelling unit and on the grid. As more heat pump systems are installed, more resistance heat is installed, threatening grid stability at a time when it is already strained due to the rapid deployment of intermittent renewable resources.

Three-function heat pumps (TFHPs) offer a potential solution to these issues. A TFHP is a single-compressor heat pump system that can serve the three primary thermal loads of a building: indoor cooling, indoor heating, and domestic hot water (DHW) production. There are two primary types of TFHPs: hydronic systems and multi-split systems. This paper deals with monobloc air-to-water heat pump (AWHP) based hydronic TFHPs, as they are more easily retrofittable and utilize less refrigerant, and refers to these systems as "three-function air-to-water heat pumps" or TF-AWHPs.

AWHPs are air source heat pumps with refrigerant to water heat exchangers that chill and heat water. In residential HVAC applications, this conditioned water is pumped to an indoor space conditioning delivery system. (Caleffi, 2020) Unlike conventional direct expansion (DX) systems, AWHP-based hydronic systems can be more easily integrated with waste heat recovery devices, desuperheaters, and solar thermal systems, and more easily serve multiple loads by using a three-way switching valve to divert water flow between different heat exchangers.

In retrofits, TF-AWHPs can be installed on the existing air conditioner breakers while replacing the gas furnace and water heater, avoiding costly electrical upgrades. Resistance heat for water heating is avoided because TF-AWHPs have five to twelve times the capacity of a typical heat pump water heater (HPWH) when providing DHW, even at low ambient temperatures below which a HPWH would switch to resistance heat. Resistance heat in space heating is avoided through right sizing and because heat is not drawn from the indoor space during defrost. Instead, heat for defrost is drawn from a thermal store built into the system: the hydronic circuit or the buffer tank.

Additionally, because water is plumbed into the house instead of refrigerant and monobloc AWHPs ship from the factory as pre-charged package units, the refrigerant-containing components are never even touched by the installer. Even pre-charged air-to-air split systems often need refrigerant charge adjustment after installation, and installation of split system linesets is challenging and fraught with issues, especially debris and leaks. Monobloc AWHPs reduce installation complexity and provide better refrigerant leak mitigation for the entire lifetime of the system. This also enables safer use of low-GWP refrigerants because all refrigerant-containing components are located outside the building.

More major manufacturers have begun providing AWHP and hydronic solutions over the last few years, including monobloc AWHPs with both space conditioning and DHW capabilities.

However, this does beg the question: How well does a single heat pump serving multiple functions perform relative to using separate heat pumps for each of those same functions? This study focused on comparing the performance of a TF-AWHP, coupled to a ducted hydronic fan coil for space conditioning and an indirect tank for DHW production, to two separate heat pumps, one an air-to-air ducted heat pump for space conditioning and the other an integrated HPWH for DHW production. The goal was to determine the benefits associated with each to help designers and installers make a decision on what is best for their single family application.

Project Overview

This project was conducted during the winter heating season of 2023-2024 and summer cooling season of 2024. The project was funded by Pacific Gas and Electric's (PG&E's) Code

Readiness program, with oversight by Thomas Mertens of PG&E, as well as Edie Taylor and Decker Ringo of West Monroe Partners.

Test Location

These evaluations were performed in one of the four unoccupied laboratory houses in the Central Valley Research Homes (CVRH) project. Located in Stockton, CA, the Fedelia house has been used to evaluate hydronic systems using AWHPs since 2015. Prior CVRH evaluations have included comfort performance, energy use, condensation risk, methods of dehumidification, and the effects of ceiling fans on panel cooling performance. (Haile & Springer, 2018) (Haile & Chally, 2022) (Chally & Haile, 2022) Hydronic work at CVRH since 2019 has focused on using hydronic fan coils as the indoor comfort delivery method, due to the reduced market barriers and wider applicability, while still retaining all the benefits of the AWHP technology.

The Fidelia house pictured in Figure 1, is an 1,894 ft2, two story home with slab on grade construction and mid-story entry built in 1996. Table 1 summarizes key characteristics of the house prior to testing. While this study focuses on a single home and climate (CA Climate Zone 12, DOE 3B), the Fedelia site was intentionally selected as a representative vintage slab-on-grade residence with severe attic thermal exposure, providing a stress test for distribution system performance under hot-dry conditions.

Figure 1. Front of the Fedelia house.

Table 1. Fidelia house characteristics

Blower Door Air Leakage Rate	1,168 CFM50 (5.2 ACH50)
Attic Insulation	R-49 (846 ft2 ceiling area)
Attic Ventilation Area	10.5 ft2 (1 ft2 vent/ 85 ft2 ceiling area)
Wall Insulation	R-13
IAQ Ventilation Rate	ASHRAE 62.2-2010 compliant bath exhaust fan, 57 CFM

Three-Function Air-to-Water Heat Pump

The installed TF-AWHP is a variable capacity monobloc AWHP with a nominal cooling capacity of 2.5 tons (95°F ambient and 54°F leaving water temperature) and 33.8 kBtu in heating (43°F ambient and 95°F leaving water temperature). Nominal efficiencies are 12.7 Energy Efficiency Ratio (EER) and 3.9 Coefficient of Performance (COP). The AWHP has an internal pump which circulates water between the AWHP's refrigerant to water heat exchanger and *either* a 40-gallon buffer tank for space conditioning *or* a heat exchanger in a 40-gallon indirect tank for DHW production. DHW calls are given priority over space conditioning calls. There is no backup resistance heat for the buffer tank or DHW tank.

Figure 2 shows a diagram of the whole hydronic system. Figure 3 shows pictures of the installed AWHP, ducted hydronic fan coil, and indirect DHW tank.

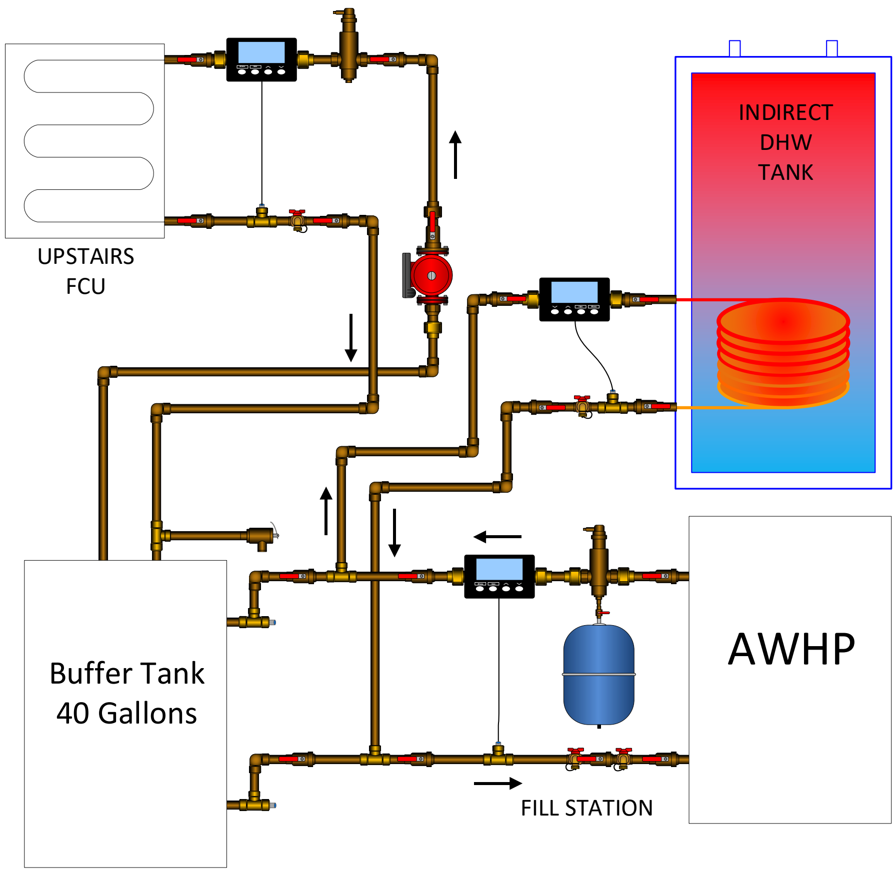

Figure 2. Diagram of hydronic system.

For space conditioning operation, the AWHP is controlled by an aquastat on the buffer tank which signals the AWHP to operate. The AWHP maintains the buffer tank at 105°F in heating and 50°F in cooling. Leaving water temperature targets are 105°F in heating and 45°F in cooling. To avoid unnecessary cycles on low load days, the signal from the aquastat is interrupted outside cooling or heating calls from one of the zone thermostats. The hydronic fan coil duct system is located entirely within the conditioned space and zoned upstairs and downstairs. Thermostat setpoints were fixed at 76°F in cooling and 68°F in heating. During an active call, a secondary pump would flow water between the buffer tank and the fan coil.

For DHW operation, a thermistor in the storage tank thermowell (connected directly to a built-in control on the AWHP) automatically switches away from space conditioning when DHW heating is needed. The DHW storage temperature setpoint is 120°F with a 4°F deadband (meaning the AWHP operates for DHW when the tank is below 116°F) and a daily 24-hour water draw schedule totaling 55 gallons is used. It is not necessary to program a secondary leaving water temperature for DHW. The AWHP simply operates at maximum capacity, delivering the highest water temperature possible to quickly satisfy DHW demand and quickly return to space conditioning operation. Though the storage temperature was set to 120°F, because water temperatures in the top of storage tanks tend to be higher than the control sensor measurement point approximately ¾ the height of the tank) a mixing valve was also installed (set to 120°F) to ensure that draw temperatures were 120°F.

Figure 3. Three of four primary components of the Three-Function AWHP system are pictured including a ducted fan coil unit (top photo) outdoor AWHP (bottom left), and a DHW tank (silver water tank in the bottom right).

Separate Heat Pumps

An air-to-air ducted heat pump and a HPWH were used as the reference for comparison to the TF-AWHP.

1. Amana air-to-air heat pump central HVAC unit, or the “Chitwood Special.”
2. Rheem heat pump water heater (HPWH).

This combination heat pumps is referred to as the “Separate HPs” system in this paper.

The Amana air-to-air heat pump system is a two-stage 2-ton heat pump selected and installed by legendary (now retired) home performance contractor Rick Chitwood. Rick independently selected non-AHRI-rated pairing for outdoor unit and indoor coil that he knew would achieve better performance for the specific house and climate than any of the manufacturer rated pairings. Rick then modified the heat pump’s defrost, crankcase, and staging controls to minimize defrost and crankcase heater operation and lockout second stage heating. Rick also designed the duct system, installed within conditioned space, such that nearly equal airflows of approximately 450 cfm/ton are achieved regardless of zonal configuration.

As such, this heat pump does not represent a typical reference case, but is the reference case that was available in the house at the time of the project. This should be kept in mind while judging the outcomes of the evaluation.

The HPWH is a Rheem 40-gallon unit purchased from Home Depot in 2023 and used the same storage temperature setpoint (120°F) and the daily 24-hour hot water draw profile as the TF-AWHP. The Amana used the same thermostat setpoints as the TF-AWHP. Figure 35 shows a picture of the installed Separate Heat Pumps. The HPWH used the default “hybrid” mode.

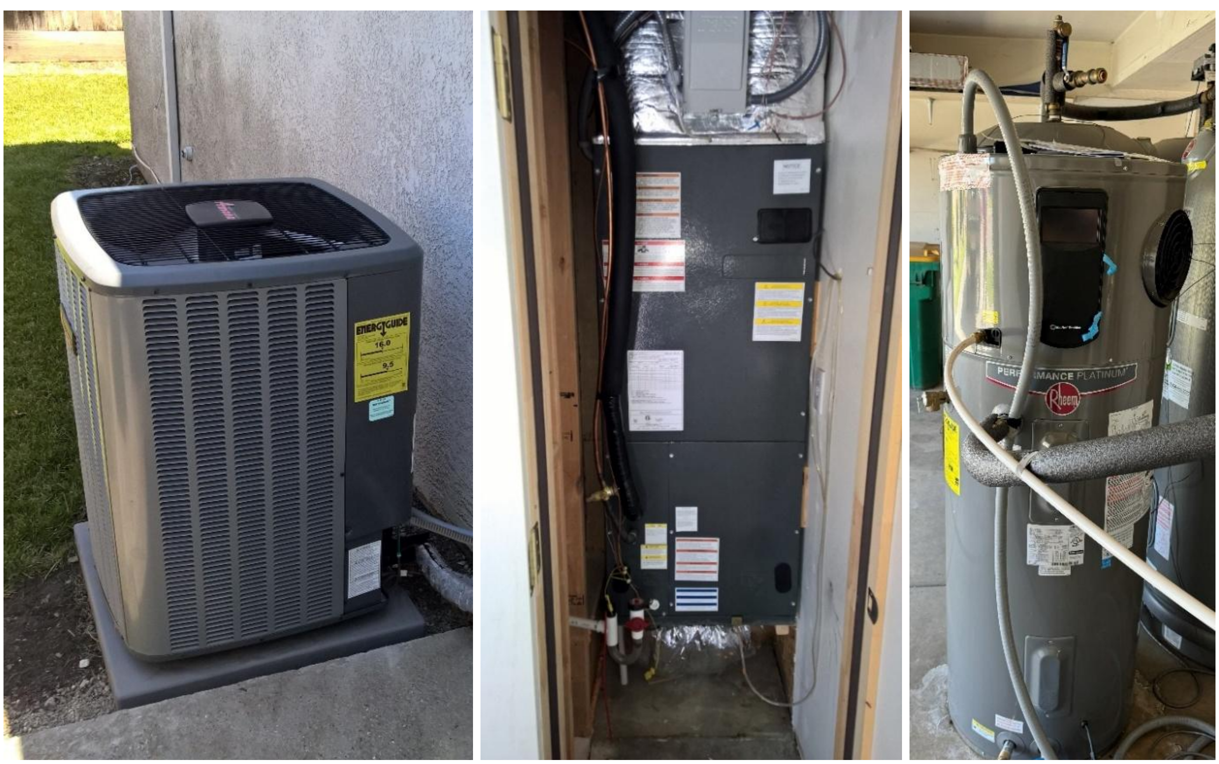

Figure 4. Separate Heat Pumps system components left to right: outdoor unit, indoor unit, and HPWH.

Test and Evaluation Methods

Daily total system energy use of the Three-Function AWHP and Separate Heat Pumps were compared during high outdoor temperature (peak cooling), low outdoor temperature (peak heating) days and in aggregate for entire seasons.

Comfort performance was compared during peak days and in aggregate for entire seasons using the criteria provided in ACCA Manual RS for air temperature distribution and deviation from setpoint (ACCA, 1997). The bounds for these metrics are specified in Table 2 and referred to in this report as the “comfort criteria.”

Table 2. ACCA criteria for multi-zone systems.

	Room-to-Room		Floor-to-Floor		Room-to-Setpoint
Zone Type	Average	Maximum	Average	Maximum	Maximum
Multi-Zone	2	4	2	4	2
Single Zone	3	6	3	6	3

These comfort criteria are based on temperature differences between each room and setpoint, each room and each other room, and floor-to-floor. Indoor temperatures in real houses may or may not meet these criteria, but they are a useful tool for evaluating comfort and serve as an indicator of how effectively a system maintains and distributes comfort throughout a space.

For example, significant noncompliance with the floor-to-floor criteria implies a zoning controls issue. Significant noncompliance with room-to-room criteria indicates poor distribution. Significant noncompliance with the room-to-setpoint test implies a sizing issue. Low noncompliance with distribution criteria, but high noncompliance with room-to-setpoint criteria, implies that distribution is effective, but the system is not appropriately sized.

A modified version of ASHRAE Standard 55 was also used to evaluate relative comfort, using measured air temperatures in each room and mean radiant temperatures in two rooms (Living and Master Bedroom).

Comfort Performance Results

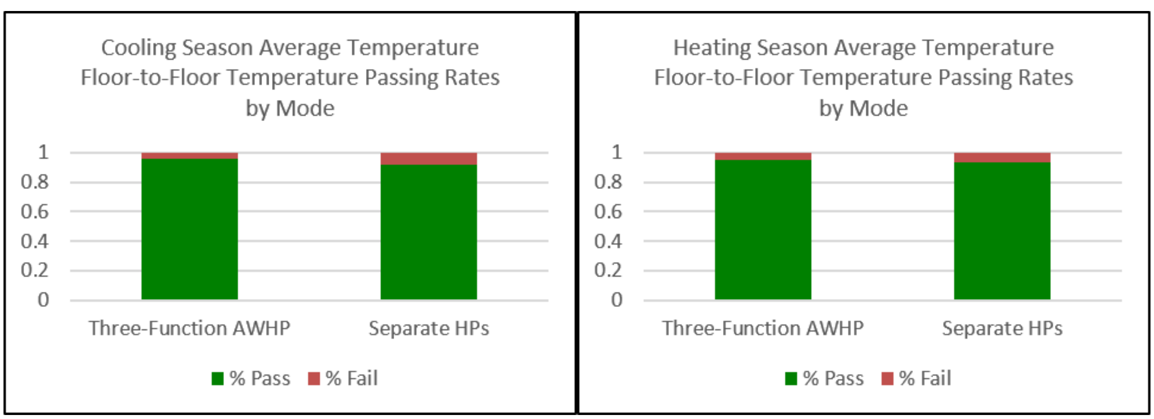

Figure 5 details the cooling and heating season floor to floor temperature differences.

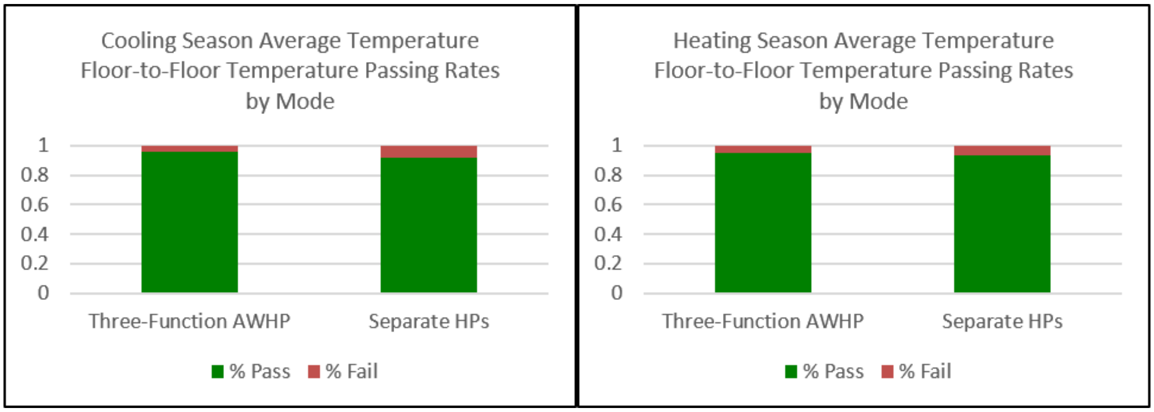

Figure 5. Cooling season (left) and heating season (right) compliance rates for floor-to-floor temperature difference comfort criteria by mode.

Cooling season floor-to-floor and floor-to-setpoint temperature differences stayed within the ACCA comfort criteria 92% of the time or more for both systems. The Three-Function AWHP system stayed with the ACCA floor to floor temperature difference tolerance 3% more often than the Separate HPs. Similar to the cooling season results, the Three-Function AWHP system stayed within the ACCA acceptable range more often than the Separate HPs. In heating season, the Separate HPs system stayed within the ACCA floor to floor temperature difference tolerance 93 percent of the time while the Three-Function AWHP stayed within the ACCA floor to floor temperature difference tolerance 95 percent of the time.

Error! Reference source not found. show the percentage operation time that room and floor conditions were above, within and below ACCA floor to setpoint comfort levels, for each system configuration in cooling season.

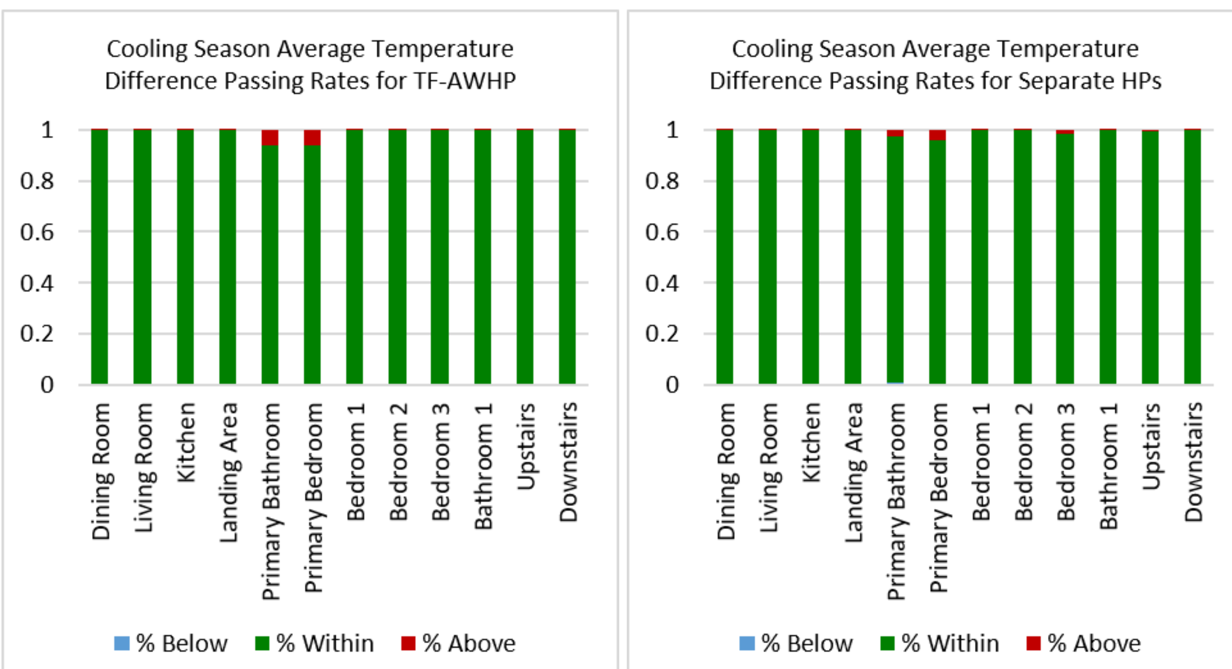

Figure 6. Summer compliance rate for room-to-setpoint temperature difference comfort criteria.

The average of all cooling season days floor to setpoint temperatures indicate that the Separate HPs system minimizes overall comfort concerns. Both systems results in some under cooling in the primary bedroom based on the ACCA single-zone requirements. The Separate HPs system undercooled the upstairs bedroom about 4 percent of the time. During cooling season the Three-Function AWHP undercooled the primary bedroom 6 percent of the time.

Figure shows comfort plotted on a psychrometric chart similar to ASHRAE 55 guidelines for cooling and heating.

Overall, both the Three-Function AWHP and the Separate HPs provided similar comfort based on daily average zonal temperature and humidity in heating season and cooling season. Heating season results indicate that on average both systems lead to indoor comfort levels outside of the 1.0 clo comfort bounds for ASHRAE 55, but this is because of the winter setpoint of 68°F which is below the approximately 69°F edge of the comfort region at 40 percent relative humidity. As expected the upstairs zone is closer to the comfort zone because heat rises to the second floor of the home. The average temperature of upstairs and downstairs zones for the Three-Function AWHP are closer together than the Separate HPs system due to less temperature difference between the two floors during heating season. Cooling season results indicate that average indoor comfort levels are within the 0.5 clo comfort bounds for ASHRAE 55. The Three-Function AWHP has slightly warmer indoor temperatures during the summer which causes the perceived comfort to be further into the 0.5 clo comfort zone than the Separate HPs.

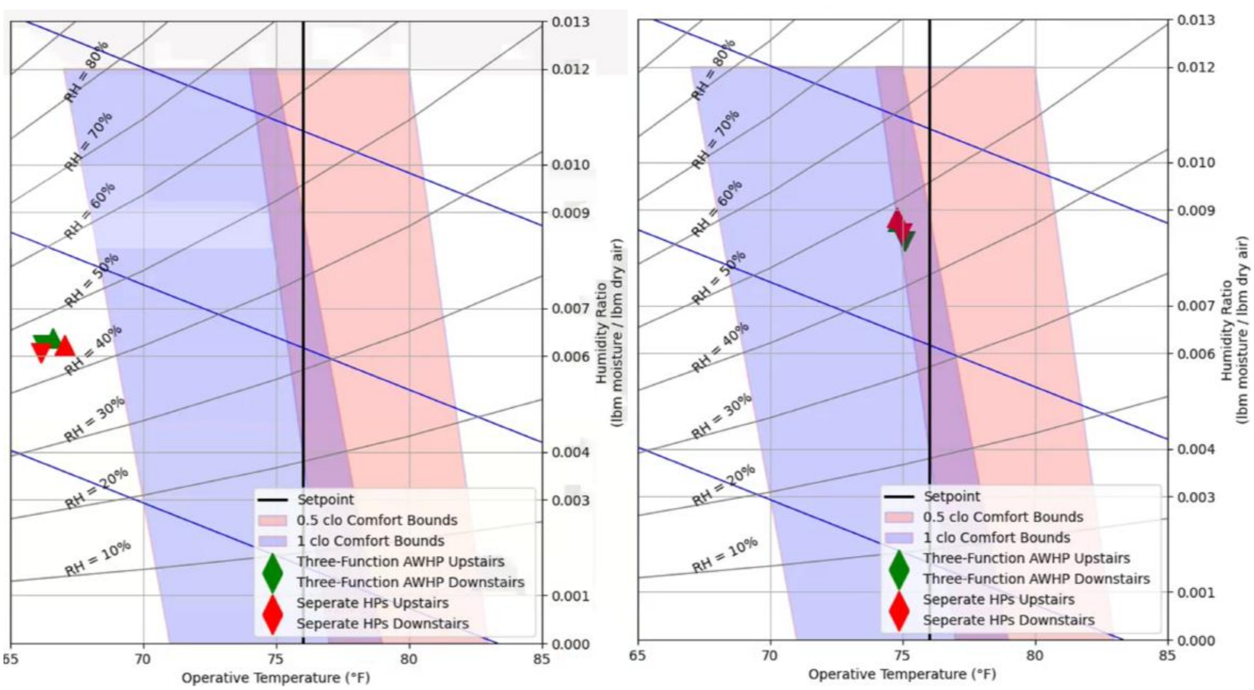

Figure 8. Average of all heating season days (Left) and cooling season (Right) based on average indoor temperature and humidity in upstairs and downstairs zones on the ASHRAE 55 Guideline Plot with 0.5 clo and 1 clo temperature comfort zones.

Overall System Performance Results

Overall system performance is provided as an average daily performance relative to the outdoor air temperature and average for heating and cooling season days. Average heating and cooling season performance was analyzed in three ways, a single peak day performance for each configuration where the outdoor ambient conditions were similar, aggregated for all heating and cooling days and a similar heating, and similar days to evaluate the effective performance loss associated with DHW.

The average daily energy use of each system configuration was plotted vs. average outdoor air temperature. Figure 10 compares the daily average total system energy associated with the combine HVAC and water heating systems during the cooling season, while Figure 11 shows the heating season.

There is a strong linear relationship between the average outdoor temperature and the total system energy used by both the Three-Function AWHP and the Separate HPs to cool the home and supply hot water. The Three-Function AWHP has a steeper slope fit line compared to the Separate HPs data set. This means that as the days get hotter, the Three-Function AWHP system uses more energy than the Separate HPs per degree of outdoor air temperature. The Three-Function AWHP uses about 10 kWh more energy than the Separate HPs on days with average outdoor air temperatures above 90°F.

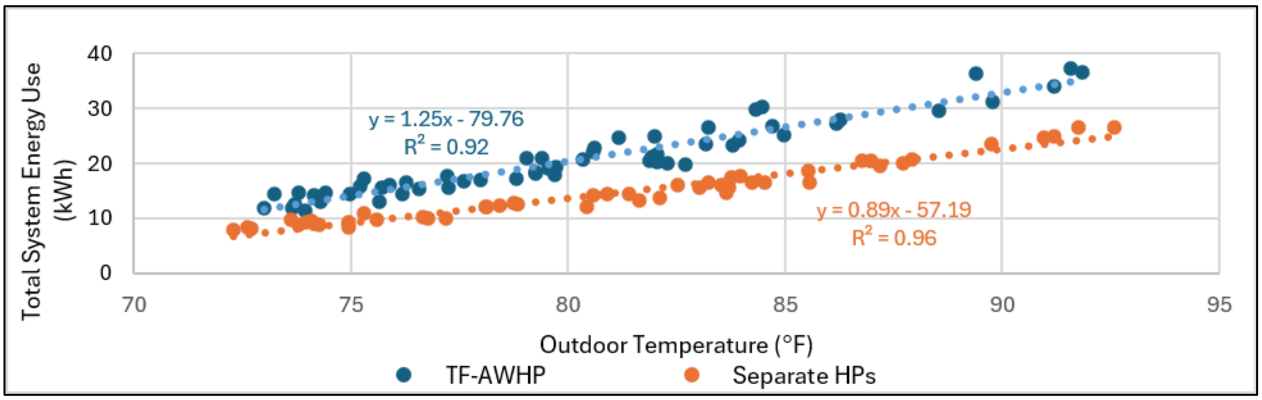

Figure 7. Cooling Season Daily Energy Use vs. Average Daily Outdoor Air Temperature.

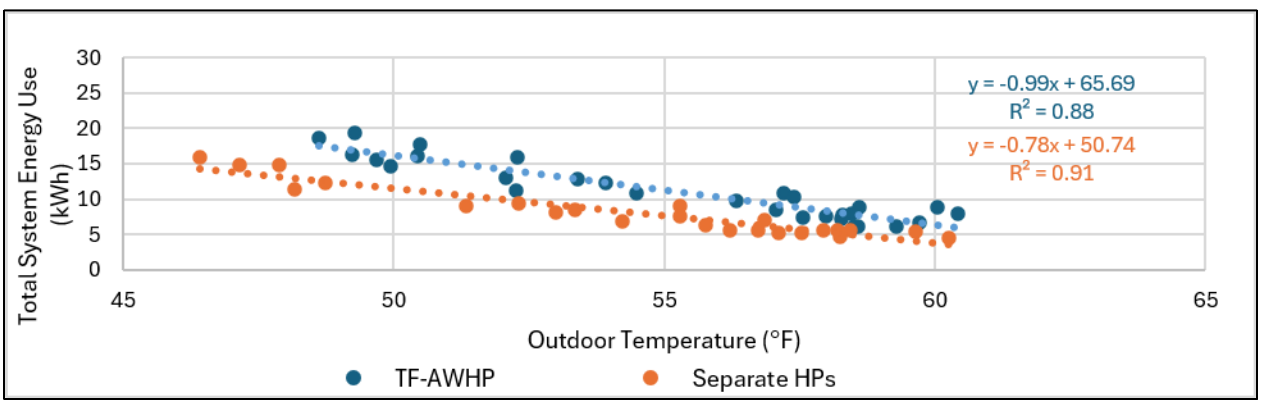

Figure 8. Heating Season Daily Energy Use vs. Average Daily Outdoor Air Temperature.

Similar to the cooling season results, there is a strong linear relationship between the average outdoor temperature and the total system energy to heat the home. Again, the Three-

Function AWHP has a steeper slope fit line compared to the Separate HPs data set. Different from cooling though, this means that as the days get hotter, the Three-Function AWHP system uses closer to the amount of energy as the Separate HPs per degree of outdoor air temperature. The Three-Function AWHP also uses about 6 kWh more energy than the Separate HPs on days with average outdoor air temperatures below 50°F.

Table 3 lists average performance of similar high average outdoor temperature cooling days and low outdoor temperature heating days for each system configuration including temperatures and total daily energy use including standby.

Table 3. Peak day cooling and heating system performance

System	TF-AWHP	Separate HPs	TF-AWHP	Separate HPs
Mode	Cool	Cool	Heat	Heat
Outdoor Temp. (°F)	91.2	91.8	49.2	48.2
Indoor Temp. (°F)	76.4	76.3	67.8	68.0
Daily Energy Use, Including Standby (kWh)	34.1	26.6	16.3	11.3

A comparison of similar high average outdoor temperature cooling days and low temperature heating days indicate that the Separate Heat Pumps provided higher system performance than the Three-Function AWHP. Separate Heat Pumps were 7.5 kWh or 22 percent lower during comparable peak cooling days and 5.0 kWh or 31 percent lower on comparable peak heating days.

Table 4 lists average performance of all valid cooling days and heating days for each system configuration.

Table 4. Average of cooling and heating system performance for all valid days.

System	TF-AWHP	Separate HPs	TF-AWHP	Separate HPs
Mode	Cool	Cool	Heat	Heat
Outdoor Temp. (°F)	80.3	81.8	55.0	54.8
Indoor Temp. (°F)	76.1	76.0	68.5	68.2
Daily Energy Use, Including Standby (kWh)	20.8	15.1	11.1	8.2

A comparison of all valid spring/summer cooling days provides similar results to the peak day analysis, but less of a difference between the two systems. Separate Heat Pumps provided higher system performance than the Three-Function AWHP. Separate Heat Pumps were 5.7 kWh or 27 percent lower for the average of all cooling days and 2.9 kWh or 26 percent lower for the average of all heating days.

Further analysis shows the performance of the decoupled systems (HVAC separate from water heating). The Three-Function AWHP had nearly identical energy usage as the Separate HPs during heating season. This is much different than the combined energy for space conditions and DHW. It is clear that the AWHP uses significantly more energy for DHW than the Rheem HPWH. During cooling season, the Separate HPs used significantly less energy than the Three-Function AWHP for space conditioning only. Figure 12 compares the daily average conditioning system energy associated with the Three-Function AWHP and the Separate HPs during the cooling season, while Figure 13 shows the heating season.

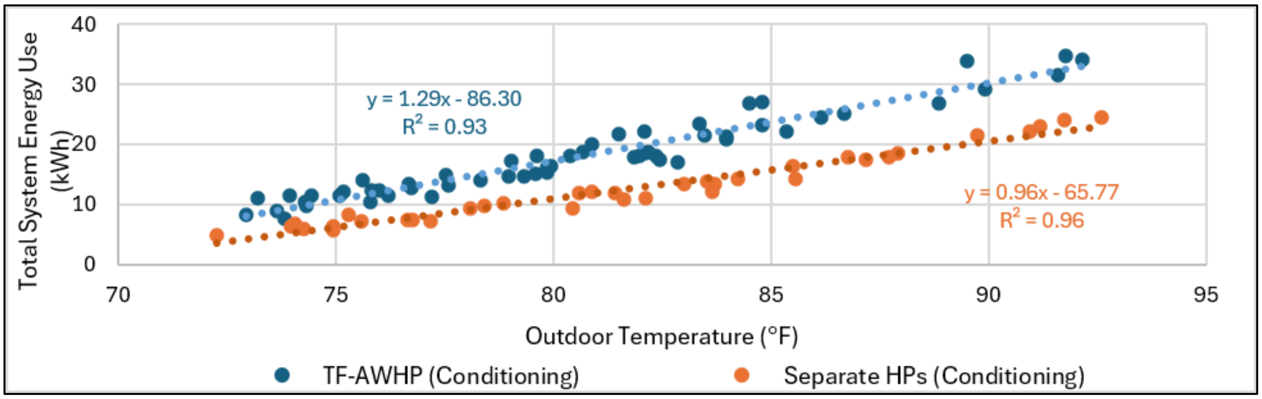

Figure 9. Cooling Season Daily Energy Use for Space Conditioning Only vs. Avg. Daily Outdoor Air Temperature.

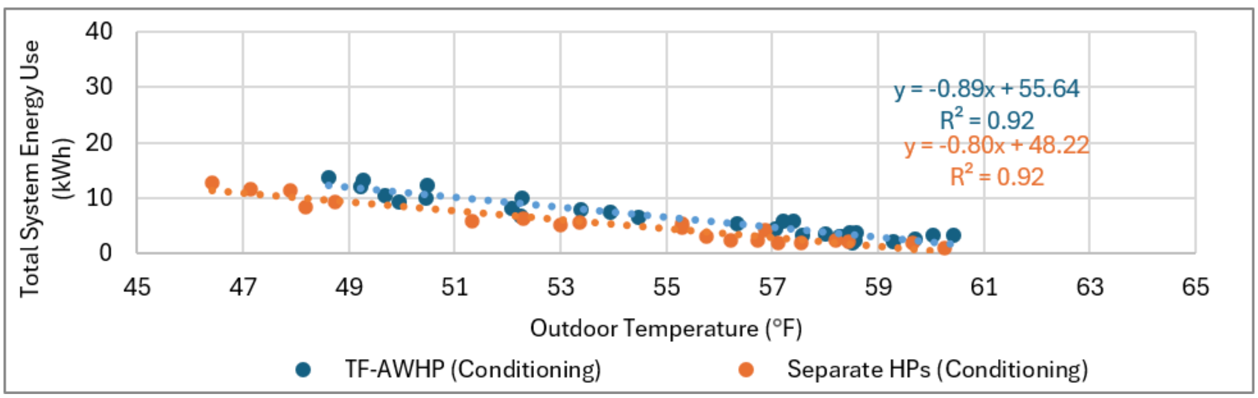

Figure 10. Heating Season Daily Energy Use for Space Conditioning Only vs. Avg. Daily Outdoor Air Temperature.

An analysis of peak days compares similar 90°F outdoor air temperature days for each system and similar 50°F outdoor air temperature heating days for each system to quantify the impact of DHW for each system. The Separate Heat Pumps use 7.5 kWh, or 28%, less conditioning energy during comparable peak cooling days and 5.0 kWh, or 44%, less conditioning energy during comparable heating days. The interesting data here is that the energy used for HVAC was much higher (7.5 kWh higher) for the Three-Function AWHP than the Separate HPs, but DHW energy use was only higher by 0.3 kWh. During comparable 50°F heating days the energy use was only slightly higher (3.7 kWh higher) for the Three-Function AWHP than the Separate HPs, but DHW energy use for the Three-Function AWHP was higher by 1.9 kWh. The larger difference in conditioning energy use between the TF-AWHP and the Separate Heat Pumps in cooling implies that there is a significant efficiency penalty incurred by switching from space conditioning to DHW modes during cooling season, possibly 2.8 kWh to

3.8 kWh. The energy penalty occurs when the Three-Function AWHP outdoor unit has to cool down the remaining hot water in the system to reach the target cooling water temperature.

During the heating day the DHW energy use was 25% for the total energy used by the Three-Function AWHP, but only 19% for the Separate HPs system. Because the energy for space conditioning was much smaller during heating days than during cooling days, the relative portion of total energy used by the Three-Function AWHP for DHW was much higher during the heating day than the cooling day.

Table 5 lists average performance of similar cooling days and heating days for each system configuration separated into HVAC and DHW usage.

Table 5. Average of similar cooling day and similar heating day system performance separated by HVAC and DHW operations for both the Three-Function AWHP and Separate HP systems.

System	TF-AWHP	Separate HPs	TF-AWHP	Separate HPs
Mode	Cool	Cool	Heat	Heat
Outdoor Temp. (°F)	91.2	91.8	49.2	48.2
Daily HVAC Energy Use Excluding Standby (kWh)	31.6	24.1	11.9	8.2
Daily DHW Energy Use Excluding Standby (kWh)	2.2	1.8	4.0	2.1
Daily HVAC and DHW Standby (kWh)	0.3	0.6	0.3	0.9
Total System (HVAC & DHW) Daily Energy Use, Including Standby (kWh)	34.1	26.6	16.3	11.3
Increase to Include DHW (%)	6.5%	6.9%	24.8%	18.8%

Conclusions

This project was focused on assessing the energy and comfort performance associated with a Three-Function AWHP compared to a baseline of a high-quality installation, though non-variable speed, air-to-air heat pump combined with an off-the-shelf HPWH in a two-story single family home during heating and cooling season. These two configurations indicate the range in performance for different temperature days and the energy benefit of using Separate HPs instead of a Three-Function AWHP.

Both the Three-Function AWHP and Separate HPs provided a high likelihood of comfort satisfaction during the cooling season based on the ACCA guideline for multizone HVAC.

System efficiency results indicate that the Separate HPs configuration used at least 10 kWh less per day during high load cooling days and 6 kWh less during moderate load heating days. Energy use of these two systems diverged more significantly during cooling season, but with energy use for DHW by the TF-AWHP higher in cooling season than in heating season. Furthermore, the TF-AWHP provided space heating performance nearly identical to the reference heat pump when DHW energy was not included. Though the DHW-only mode of the unit used in this project was not evaluated, when tested in rating labs as HPWHs, AWHPs from the same manufacturer perform incredibly well, with some models achieving UEFs of 4.95. (Chiltrix Inc., 2026)

All of this implies that there is a significant penalty to mode switching between space conditioning and DHW that bares further study. What controls or configuration modifications can mitigate this impact? How can this impact be accurately modeled to ensure compliance with energy codes? The potential benefits of the technology are well worth the effort to find answers to these questions.

References

ACCA. (1997). *ACCA Manual RS: Comfort, Air Quality, and Efficiency by Design.* Washington, D.C.: ACCA.

ASHRAE. (1985). *ASHRAE Handbook: Fundamentals.* Atlanta: ASHRAE.

Caleffi. (2020, July). Design details for air-to-water heat pumps. *idronics*, 58-72. Retrieved from https://www.caleffi.com/sites/default/files/media/external-file/Idronics_27_NA_Air-to-water%20heat%20pump%20systems.pdf

Chally, S., & Haile, J. (2022). Evaluation of Condensation Risk Mitigation Methods for Residential Radiant Ceiling Cooling Systems. *ACEEE Summer Study.* Asilomar. Retrieved from https://www.researchgate.net/publication/373682874

Chiltrix Inc. (2026, June). *DHW Efficiency & Official EnergyGuide Labels*. Retrieved from Chiltrix website: https://www.chiltrix.com/energyguide-labels/

CPUC. (2022, September 15). *CPUC Decision Makes California First State in Country to Eliminate Natural Gas Subsidies to Accelerate Building Decarbonization.* Retrieved from CPUC Website: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M496/K979/496979465.PDF

EFCA. (2022, June 30). *Are we overlooking the first step towards electrification?* Retrieved from Efficiency First California: https://efficiencyfirstca.org/blog/are-we-overlooking-the-first-step-towards-electrification/

Haile, J., & Chally, S. (2022). Sol et Aquilo, Round 2: Hydronic vs. Hydronic, Comparing Performance of Air-to-Water Heat Pumps Coupled with Radiant Ceilings and Fan Coils. *ACEEE Summer Study.* Asilomar. Retrieved from https://www.researchgate.net/publication/373683298

Haile, J., & Springer, D. (2018). Sol et Aquilo: Improving Sensible Comfort and Energy Efficiency with Hydronic Radiant Ceiling Panels. *ACEEE Summer Study.* Asilomar. Retrieved from https://www.researchgate.net/publication/373682921

Pallin, S., & Haile, J. (2022). *Residential Hydronic Heating and Cooling Applications by Air-to-Water Heat Pump Systems.* Retrieved from https://www.researchgate.net/publication/378710604_Residential_Hydronic_Heating_and_Cooling_Applications_by_Air-to-_Water_Heat_Pump_Systems