Honda Smart Home US:
Multi-function heat pumps before they were cool.

James Haile, P.E., Frontier Energy Inc.

ABSTRACT

A common barrier to electrification retrofits is site electrical capacity, forcing homeowners to choose whether to electrify domestic hot water (DHW) or space conditioning loads, or embark on expensive breaker panel upgrades. Multi-function heat pumps are a potential solution to this problem. These systems serve indoor heating, indoor cooling, and domestic hot water (DHW) loads with a single compressor, taking up no more breaker space than a traditional air conditioner and furnace. Interest in these systems has been growing recently, but a trailblazer of the technology was the Honda Smart Home US (HSHus) in 2014.

The HSHus was an advanced 1,944 ft2 two-story home in Davis, CA built by American Honda Motor Company in collaboration with a robust team of experts. Construction was completed in early 2014 and occupied from October 2014 to September 2022. All house systems were monitored in detail and data was analyzed to assess their performance, making HSHus a "living laboratory" for the advanced systems it contained.

This included a multi-function water-to-water geothermal heat pump, which used mechanical valves to switch between serving DHW demand (served through an indirect tank) and indoor space conditioning (served through a radiant slab and ceiling) demands and incorporated waste heat recovery. A 2014 ACEEE Summer Study paper written by project team members described the concept, presented performance results from early three-function heat pump attempts, and provided an overview of how the design of the HSHus would build on the lessons learned. This paper provides an update, covering several years of performance data, challenges encountered, and optimizations attempted over eight years of continuous operation and monitoring.

Introduction

A common barrier to electrification retrofits is site electrical capacity, forcing homeowners to choose whether to electrify domestic hot water (DHW) or space conditioning loads, or embark on expensive breaker panel upgrades. (Pecan Street 2021) Multi-function, or "three-function," hydronic heat pumps are a potential solution to this problem. These systems serve the three major thermal loads of a dwelling with a single compressor: indoor heating, indoor cooling, and DHW production. Because the heat pump serves indoor heating load, it has a much higher capacity than most heat pump water heaters, eliminating backup heat for DHW. Backup heat is also eliminated for indoor heating, as the hydronic loop provides all the necessary thermal capacity and there is no need to draw heat for defrost directly from the house. This reduced equipment footprint enables electrification of these loads with no more breaker panel space than a traditional air conditioner and furnace. (Haile 2023)

In retrofits, this avoids the cost of electrical service and breaker panel upgrades, as well as the need for new electrical circuits (if the new equipment can use the existing equipment locations), saving homeowners from $2,000 to $30,000 on electrification. (Pena, et al. 2022) Because of this potential, interest in these systems has been growing, with evaluations completed and underway by Frontier Energy (Pallin and Haile 2022), the Minnesota Center for Energy Efficiency (MNCEE n.d.), and others, in both laboratory and field settings.

A trailblazer of this three-function heat pump concept was the Honda Smart Home US (HSHus). The HSHus, shown in Figure 1, was an advanced all-electric 1,944 ft^2 single family two-story home in the West Village Zero Net Energy (ZNE) development on campus at University of California, Davis (UC Davis). Design work began in 2012 and construction was completed by early 2014.

Figure 1. The Honda Smart Home US (circa 2014).

Designed and built by the American Honda Motor Co., Inc. (AHM) in collaboration with UC Davis, Frontier Energy, Inc. (then Davis Energy Group), and many other companies and consultants, the HSHus represented AHM's vision for sustainable zero-carbon living and personal mobility. Far from a "house of the future," the HSHus was a demonstration of what was achievable in the present day, showcasing a host of advanced and sustainable building techniques and optimally integrated residential systems.

This included a multi-function water-to-water geothermal heat pump, which used mechanical valves to switch between serving DHW demand (served through an indirect tank) and indoor space conditioning (served through a radiant slab and ceiling) demands and incorporated waste heat recovery. (Haile, Dakin and German 2023)

A 2014 ACEEE Summer Study paper written by project team members described the three-function heat pump concept and presented results from three other projects that attempted to incorporate the technology, each with varying degrees of success. That paper provided an overview of the HSHus three-function system and how it built on lessons learned from these previous attempts. (Modera, et al. 2014) This paper provides an update, with eight years of performance data, challenges encountered, and optimizations attempted over eight years of continuous operation and monitoring.

Three-Function Heat Pump System

Indoor heating and cooling, as well as DHW production, was provided by a 2-ton water-to-water ground-source heat pump (GSHP). Figure 2 below shows the layout of this hydronic system overlayed on a 3D model of the HSHus. This is less detailed than the overall system schematic in Figure 3 (for example, only four ground bores are shown), but is provided to help the reader visualize the system.

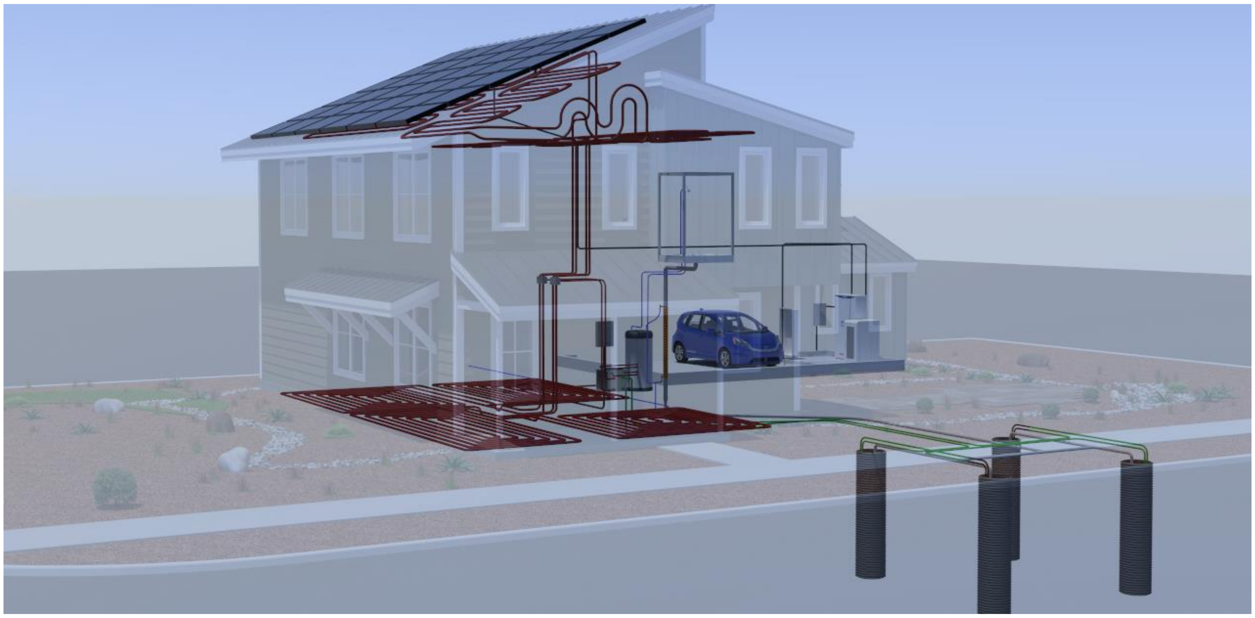

Figure 2. 3D layout of the mechanical systems in the house.

The heat pump heated or cooled the house through hot or chilled water circulated through tubing imbedded in the first-floor slab and through tubing imbedded in heat transfer plates installed above the drywall of the second-floor ceiling. This tubing heats or cools the floor and ceiling surfaces which in turn heat or cool the air and objects within the house, primarily through radiative heat transfer. (ASHRAE 2020) Radiative heat transfer is a direct method of heat transfer without moving air, which reduces the perception of drafts and indoor comfort cycling associated with conventional forced air systems. (D'Agnese 2023) There is no forced air movement, instead, heating and cooling is transferred through thermal radiation bolstered by natural convection.

Zone valves allowed thermal delivery to the first and second floors individually or simultaneously. The mass of the radiant floor served as a thermal buffer to prevent heat pump short-cycling, eliminating the need for buffer tanks. All heating and cooling functions were controlled by the home energy management controller. Relatively low water temperatures for heating and high temperatures for cooling were used to improve heat pump performance by reducing the thermal lift (and power) required.

The heat pump includes a desuperheater coil that reclaims waste heat during summer cooling operation for DHW. A desuperheater is typically installed immediately downstream of the compressor in the refrigeration circuit, providing the hottest refrigerant gas for increased water heating potential. This feature was included to both reduce the heat rejection load to the ground while providing “free” hot water during hot summer days.

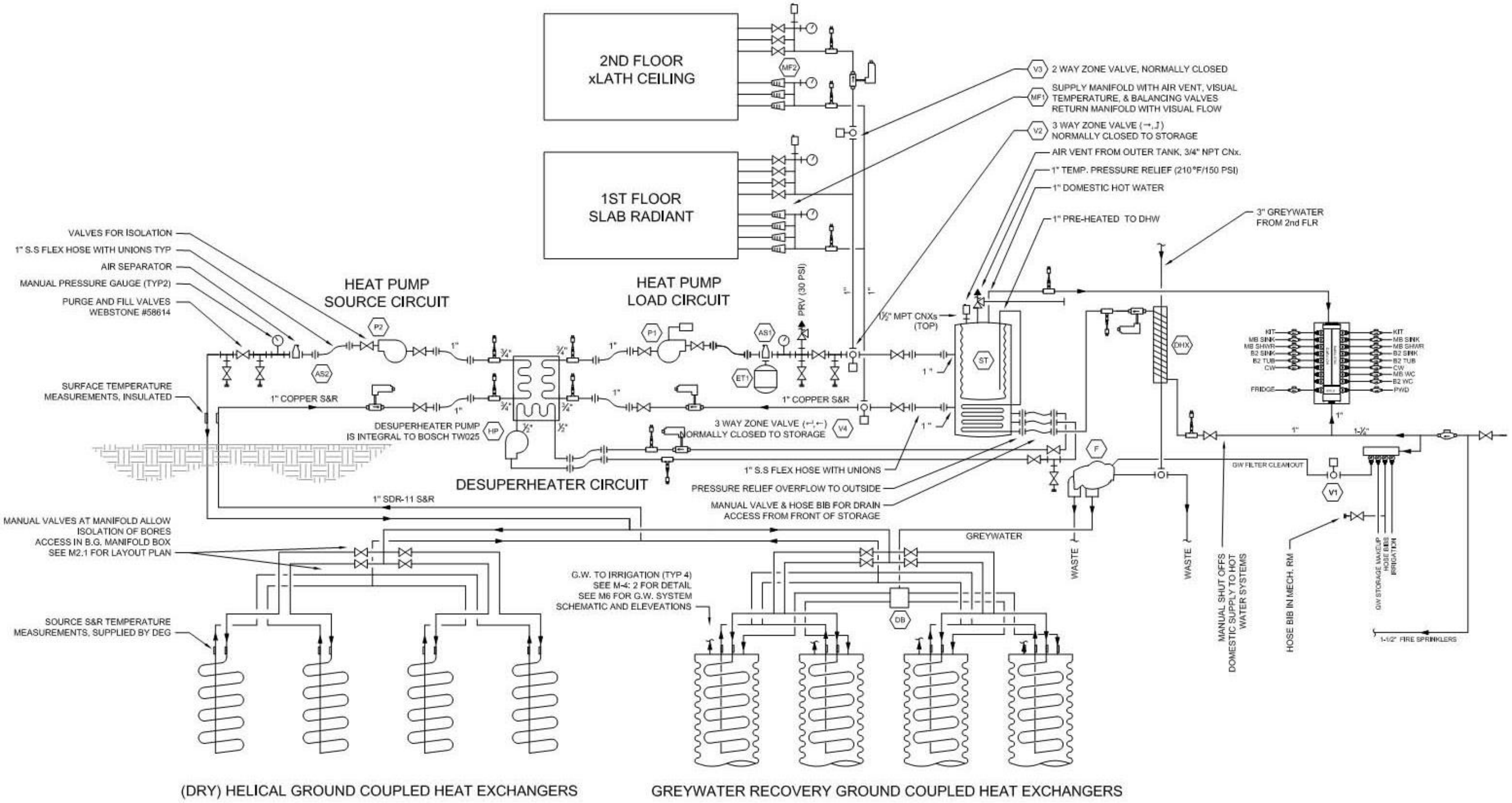

Figure 3. Schematic of as-built mechanical system configuration.

Ground Heat Exchangers

On the “source” side of the heat pump are eight vertical helical ground heat exchangers (GHEs), each consisting of 250 feet of tubing in a 24-inch diameter and 20 feet deep bore hole. One of the key experiments was the actual in-situ performance of the helical GHEs because of their potential cost savings relative to conventional vertical GHE designs.

Four of the GHEs were “dry,” meaning they were installed in native soil, and the other four loops were “wet,” meaning they were irrigated by house greywater to improve soil thermal conductivity and performance. Each wet bore was cased by a polyethylene corrugated pipe and backfilled with gravel. Pre-filtered household greywater was gravity fed to the wet boreholes to help moderate GHE temperatures. Overflow flowed by gravity to greywater storage for irrigation.

All eight bores plus two measurement bores were drilled using conventional auger-drilling equipment in less than one day. After drilling, the dry loops were set into place and then filled with spoil dirt screened for large rocks. The wet loops required more time to install due to the casings and irrigation system.

Figure 4. (Left) Drilling rig boring holes for GHEs. (Right) Lowering helix coil for dry bore in ground.

Radiant Slab and Ceiling

The heat pump design at the HSHus fell outside the skill sets of traditional trades and required significant coordination with the design team and consultants. An HVAC contractor installed air-side components such as the ventilation cooling fan and exhaust ventilation ductwork, but they were not responsible for the installation of the hydronic system. A plumber installed all pipes and valves, including the heat pump and GHE system, but their lack of familiarity with HVAC systems and controls meant that they could not commission the system. Installation of the radiant ceiling panels (Figure 5) and radiant tubing in the slab (Figure 6) required close coordination with multiple subs. The plumber was not comfortable with installation of the radiant ceiling panels, so the panel manufacturer was brought in to install the panels and tubing, which also required close coordination with the sheetrock subcontractor.

Figure 5. Installed radiant ceiling panels pre-drywall.

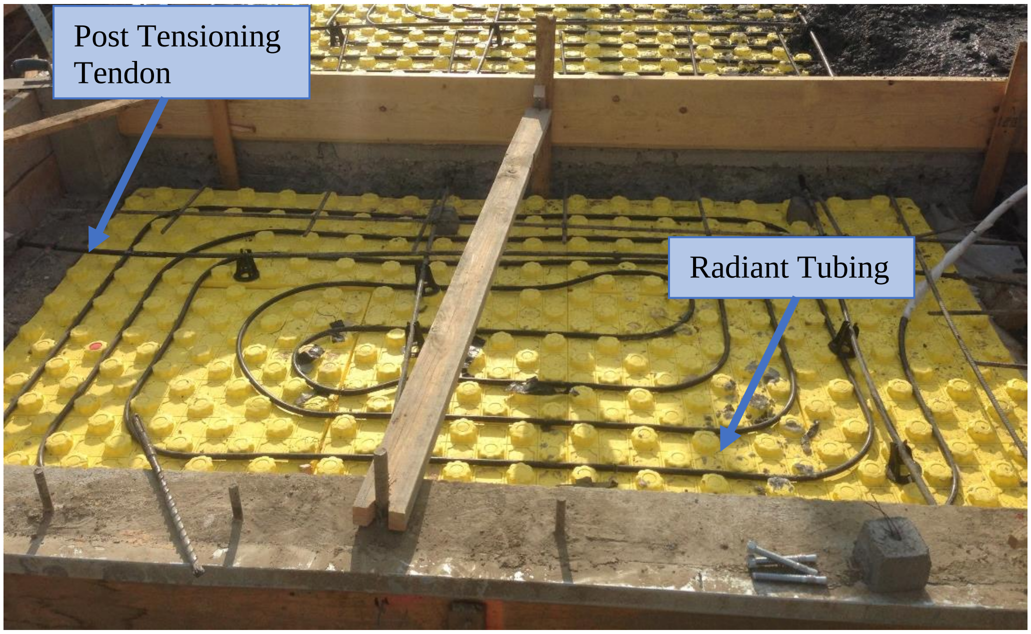

Figure 6. Concrete being poured over radiant tubing to create the radiant slab.

Domestic Water Heating

Figure 7 shows a simplified schematic of the DHW system at the HSHus, as originally built in 2014. The heat pump control logic prioritizes DHW over heating and cooling functions. In DHW mode, the heat pump delivered heated water to the primary heat exchanger in the indirect tank. The heat pump includes a desuperheater coil that reclaims waste heat during summer cooling operation to heat water in the indirect tank. This feature reduces the heat load on the ground loop while providing “free” hot water during cooling operation. Additionally, a drain water heat recovery (DWHR) heat exchanger extracts heat from all second-floor hot water fixture drains (this includes the sinks and showers of 2 bathrooms and a clothes washer) to preheat the cold-water make-up entering the storage tank, further reducing the hot water load.

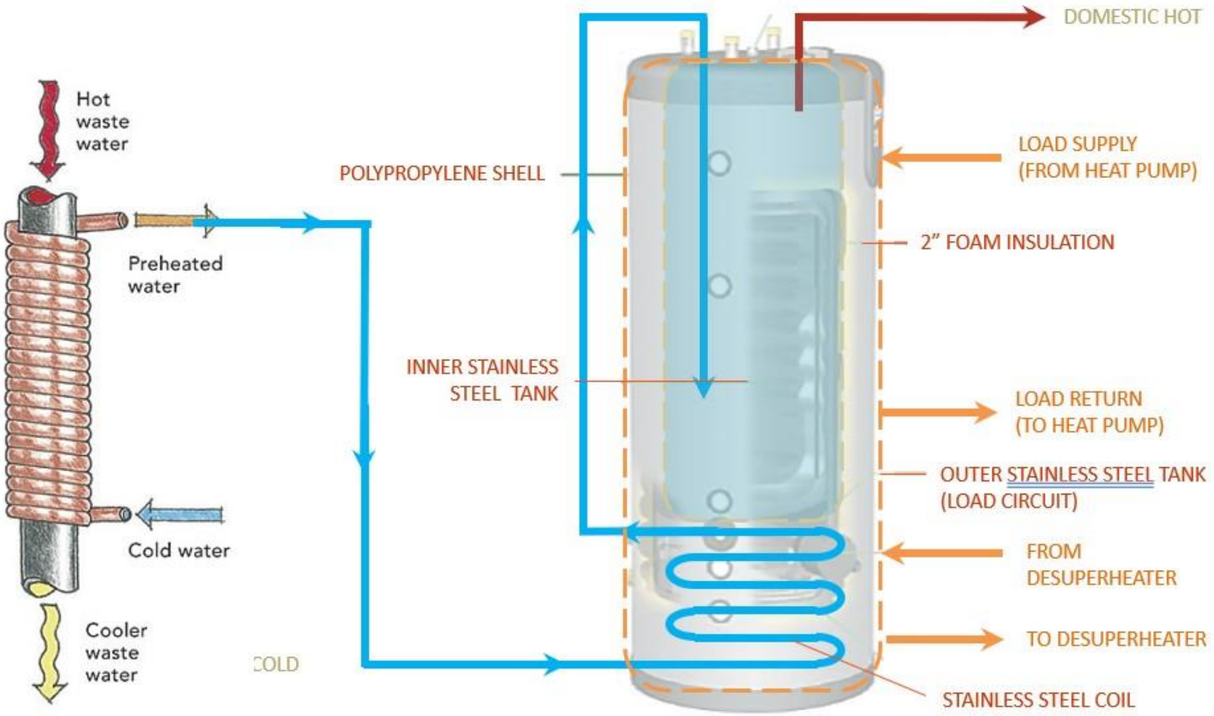

Figure 7. DHW, DWHR & Desuperheater Schematic

While the heating and cooling components of the system changed little over the eight years of operation, the arrangement and composition of several DHW components underwent several iterations after the original indirect tank failed in 2019.

The original DHW storage tank at the HSHus was a 70-gallon stainless steel tank that had a “tank-in-tank” design. This provided a large heat exchange surface area between the closed heat pump hydronic loop (outer tank) and the open loop containing DHW (inner tank). This design also allowed heat to continue to be exchanged after heat pump flow had stopped.

Additionally, the bottom of the outer tank contained a secondary coiled heat exchanger. As originally built in 2014, the cold-water make-up entering the storage tank from the DWHR first flowed through this lower secondary coil, further preheating the make-up water before entering the inner DHW storage tank and cooling the bottom of the outer tank heat exchanger which improved stratification and allowed greater desuperheater heat extraction.

Unfortunately, this lower secondary coiled heat exchanger was constructed of carbon steel and not intended for potable water. After 5 years of operation, the coil corroded and failed, necessitating the replacement of the indirect tank. The leaking coil was discovered by December 2018 and bypassed until April 2019. The model of the original tank was no longer available, requiring a redesign of the DHW system around a new indirect tank.

The new indirect tank included two cylindrical heat exchangers inside the storage tank instead of the “tank-in-tank” design of the original indirect tank. A comparison of the two tanks is shown in Table 1.

Table 1. Comparison of original and replacement indirect tanks.

	Original Tank	**Replacement Tank**
Domestic Storage Capacity (gallons)	70	64
Primary Exchanger Capacity (gallons)	33	1
Secondary Exchanger Capacity (gallons)	3	1
Primary Exchanger Surface Area (ft2)	29	12.5
Secondary Exchanger Surface Area (ft2)	20	12.5
Height	77	72
Diameter	32	22
Tank Exterior Surface Area (ft2)	152.2	90.2

Though the total heat exchanger surface area of the replacement tank is smaller, the ratio of domestic capacity to heat exchanger surface area is greater. A plumbing diagram of the redesigned system is shown in Figure 9. Changes included:

- Make-up cold water from the DWHR exchanger was plumbed directly to the cold-water inlet of the indirect tank.
- During a DHW call, water is pumped through the load side of the GSHP and both tank heat exchangers in series.
- During a cooling call, water is pumped between the desuperheater coil to the lower heat exchanger only. In this configuration, the desuperheater still benefits from stratification, but also has the potential to be more effective, exchanging heat with the DHW tank instead of with water in an outer tank that surrounds the DHW tank.
- In addition to the changes shown, the redesign included new fill and purge valves for the source and load side loops of the GSHP, an air separator on the source side loop, and an air separator and expansion tank on the desuperheater loop.

All installation and commissioning activity for the new tank and configuration was completed in May 2019 and performance was evaluated in 2020. That evaluation found that the redesign and new tank significantly reduced system losses, but also reduced thermal energy contribution from the desuperheater. Although the 2019 redesign system performed better than the previous system, its performance could still be further improved. Recommendations were made, and improvements were completed by March 2021. These included:

- **Desuperheater plumbed directly to the bottom of the storage tank.**
  Turned out that the desuperheater coil was double-walled and rated for use with potable water the entire time. Removing a layer of heat exchanges would improve desuperheater effectiveness and eliminate switching valve operation, simplifying controls.
- **Thermostatic mixing valve on the DHW supply.**
  All prior configurations had controls to limit the storage tank temperature to 130F. A mixing valve eliminates the need for such limits, allowing for the maximum possible contribution from the desuperheater.
- **Indirect tank heat exchangers in parallel instead of in series.**
  A parallel configuration of the heat exchangers provides greater capacity than a series configuration, which was used previously to accommodate using the lower heat exchanger with the desuperheater.

Figure 10 shows a plumbing diagram of the designed system. However, due to miscommunication with the plumber, the desuperheater was plumbed to draw from the bottom of the tank and return to the top of the tank, instead of both supply and return at the bottom of the tank. This resulted in destratification of the tank whenever the desuperheater was activated, which resulted in unnecessary DHW calls.

In early May 2022, the plumber returned to the house to correct the mistake from 2021 and arranged the system as depicted in Figure 10. Despite the project coming to a close, and primary analysis only covering data through the end of 2021, some data from summer 2022 is presented to show the change in performance of the desuperheater.

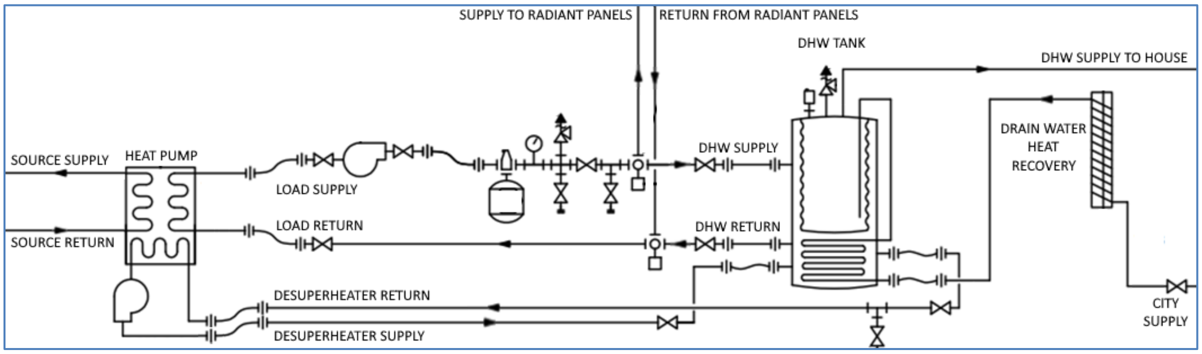

Figure 8. Plumbing diagram of pre-2019 hydronic system.

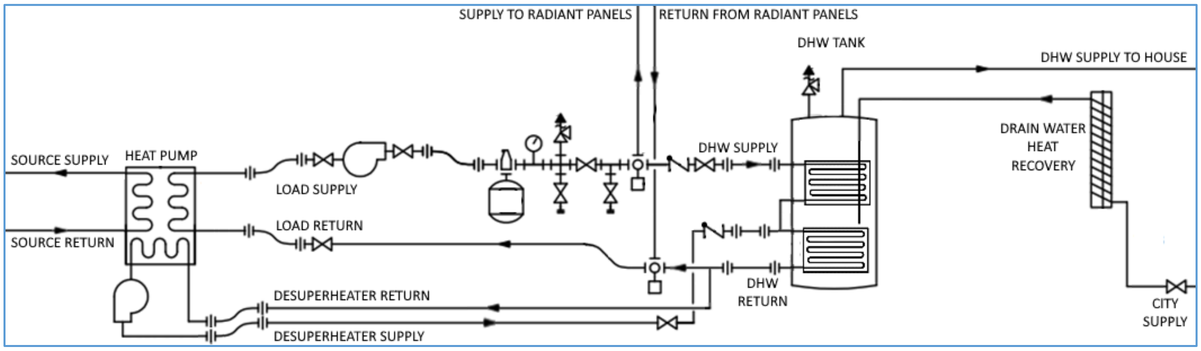

Figure 9. Plumbing diagram of 2019 redesigned hydronic system.

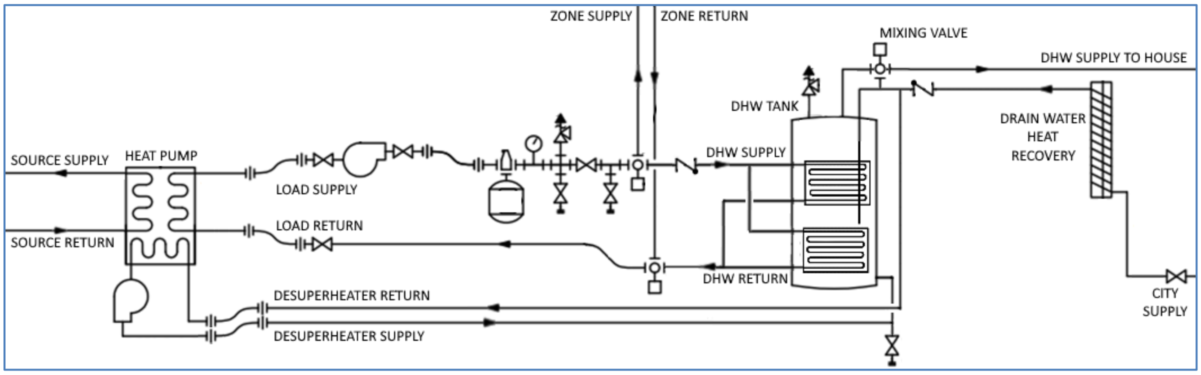

Figure 10. Plumbing diagram of 2021 redesigned hydronic system, as-designed (and final 2022 as-built).

Occupants

A summary of the occupancy schedule is shown in Table 2.

Table 2. HSHus Occupancy Summary

Occupancy Period		Description
October 2014	July 2017	Family of four: two adults and two children.
July 2017	August 2017	Vacant (tours and maintenance only)
August 2017	December 2017	Three graduate students.
December 2017	June 2018	Three graduate students and one infant.
June 2018	August 2019	Two graduate students.
September 2019	April 2020	Family of three: two adults and one child.
April 2020	August 2020	Vacant (COVID pandemic)
September 2020	December 2021	Two adults.
December 2021	August 2022	One adult.
August 2022	Present	Vacant (tours and maintenance only)

Performance

Annual heat pump operating coefficients of performance (COPs) for 2015 through 2021 were calculated, both considering only the energy use of the compressor during a cycle (Table 3) and for the entire system including circulation pumps and standby energy (

Table 4). System COPs are typically 22% to 30% lower than heat pump COPs due to circulation pump energy use.

Table 3. Comparison of average COP by mode, based on only cycle compressor energy use.

Mode	2015	2016	2017	2018	2019	2020	2021
DHW	2.56	2.86	2.94	2.79	3.09	2.82	2.64
Heating	4.85	4.83	4.73	4.30	4.43	4.49	4.33
Cooling	3.52	4.10	4.61	4.82	4.64	4.43	4.46

Table 4. Comparison of average COP by mode, based on whole system energy use (incl. pumps).

Mode	2015	2016	2017	2018	2019	2020	2021
DHW	2.21	2.50	2.55	2.42	2.64	2.43	2.30
Heating	4.15	4.15	4.09	3.72	3.83	3.84	3.74
Cooling	3.01	3.53	3.90	4.06	3.87	3.69	3.74

Cooling COP improved in 2017 and 2018; by 13% relative to 2016 and by 32% relative to 2015. This is likely a result of shorter heat pump runtimes and fewer operating hours during the summer. This reduced ground temperatures, improving heat rejection to the ground. The reverse was seen in 2019 with new occupants using setpoints that were very low for a radiant system. In 2019, the average cooling setpoint was 70°F, with half of August at 67°F. This resulted in more cooling operating hours and higher average ground loop return temperatures, as well as more frequent triggering of the radiant system's dewpoint limit control, resulting in short cycling throughout the summer.

Although lower cooling setpoints contribute to higher cooling energy consumption and reduced efficiencies for all cooling systems, the design strategy at HSHus lead to outsized increases when setpoints were decreased. On an ideal cooling day, the nighttime ventilation pre-cooling would cool the thermal mass of the house overnight using fan power only and the house would be able to "coast" for the rest of the day as the indoor air temperature slowly increased towards setpoint, then cool again overnight with little or no mechanical cooling. The radiant slab complements this strategy because of the large thermal mass of the slab, providing mechanical cooling by the same heat transfer phenomena as the pre-cooled thermal mass of the house. The ventilation pre-cooling system also assists the radiant system by acting as a dedicated outdoor air system to control humidity. However, lower setpoints require earlier and more frequent mechanical cooling, colder slab temperatures, lower dewpoints, requiring disproportionately higher energy than might have been expected in other systems.

Heating COP when down in 2018 and stayed below 4.0 for the rest of the project. Heating setpoints are higher in 2018 through 2021 than in 2015 through 2017, and there is an associated reduction in average ground temperatures and subsequent reduction in heat extraction from the ground. Heating setpoints were also adjusted by occupants more frequently in the 2018 through 2021 period (up and down), and heating setpoints were adjusted more frequently than cooling setpoints in general. Additionally, in the fall of 2017, the heating control was changed to allow running the low-mass ceiling panels without the slab with the heat pump in first stage only. This may have also contributed to lower heating COPs.

Table 5 compares the annual energy use (kWh) by heat pump mode. Trends in annual energy use support the discussion above regarding changes in COP over the years. For example, cooling energy use goes down each year until 2019 when very low cooling setpoints were used.

Table 5. Comparison of annual energy use (kWh) by mode, including compressor and pumps.

Mode	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
DHW	544	704	798	1082	718	545	462
Heating	544	471	357	590	744	707	967
Cooling	3238	1886	1114	689	1296	1267	1038

Table 6 presents the annual energy use for DHW, normalized by gallons of hot water use.

Table 6. Comparison of degree day and hot water demand normalized energy use by mode.

	Mode	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Wh/Gallon Hot Water	**DHW**	44.3	50.2	52.6	51.0	45.2	54.8	47.3

Any discussion of DHW mode COP (Table 3 and

Table 4) and energy use (Table 5 and Table 6) needs to be in the context of the desuperheater and the tank replacement that occurred in 2019. Figure 11 shows monthly total thermal input to the DHW tank from all sources (heat pump, desuperheater, and drainwater heat recovery) divided by monthly DHW consumption in terms of heat for 2016 through 2019 (the year the tank was replaced).

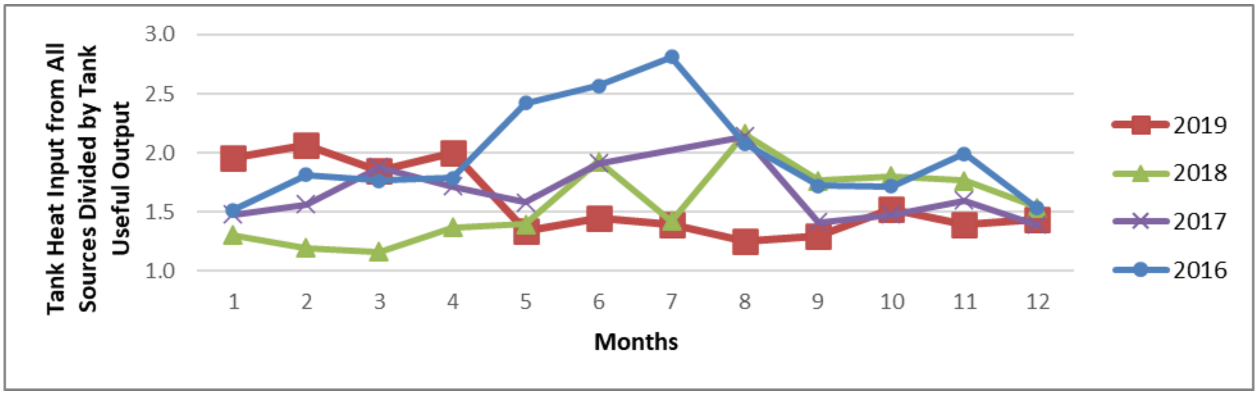

Figure 11. Monthly DHW tank heat input from all sources divided by heat output.

In all months for all years, heat input to the tank is greater than the total heat drawn from the tank. This is expected due to thermal losses. However, prior to the redesign (May 2019), total heat input to the tank was often double the actual load or more, implying substantial system losses in the original design.

Table 7 shows the calculated standby losses of the original tank to the standby losses of the replacement tank. This analysis requires back-to-back heat pump cycles for DHW with no other cycles, hot water draws, or contributions from other heat sources between them. When the only heat pump operation is to recover from tank losses, the heat input to the tank by the heat pump is equal to the tank losses. Dividing this loss by the time elapsed between those cycles and normalizing by the exterior surface area of the tank, yields the standby loss of the two tanks.

Table 7. Standby losses of the tank configurations for 2016 and 2019.

	Original Tank	**Replacement Tank**
Standby Losses (Btu/hr/ft^2)	9.72	3.71

Clearly the standby losses with the new tank are considerably lower than the standby losses with the previous tank. The original indirect tank had fifteen ports and one thermowell, while the new indirect tank has only seven ports and one thermowell. Fewer ports mean fewer thermal shorts through the indirect tank insulation and reduced standby losses. Additionally, check valves were installed between the three-way valves on the load side and the heat exchanger of the DHW tank, as well as on the desuperheater loop. These acted as heat traps, reducing any losses associated with convection in the water lines. (Wilson 2009)

The annual energy use for DHW normalized by hot water consumed shown in Table 6 reinforces this observed trend. With the new configuration, despite reduced contributions from the desuperheater, less electrical energy was used per unit of hot water delivered in 2019. In the previous configuration, any benefit provided by the desuperheater was likely overshadowed by the system losses. Electrical energy per gallon hot water rose again in 2020, but this was due to low occupancy during the COVID pandemic (lots of tank temperature maintenance cycles, but no hot water use). Electrical energy per gallon hot water was back down again in 2021.

Yet, DHW performance was not as good as it should have been in 2021. This is because in March 2021, changes were implemented to further improve desuperheater performance (see system description in previous sections). However, these changes were implemented incorrectly. Instead of both the desuperheater supply and return terminating in the bottom of the tank, the desuperheater supply terminated in the bottom of the tank while the return terminated at the top of the tank. This resulted in destratification of the domestic storage volume every time desuperheater flow was initiated. This effect can be seen in Figure 12, which shows how destratification results in increased heat pump operation for DHW.

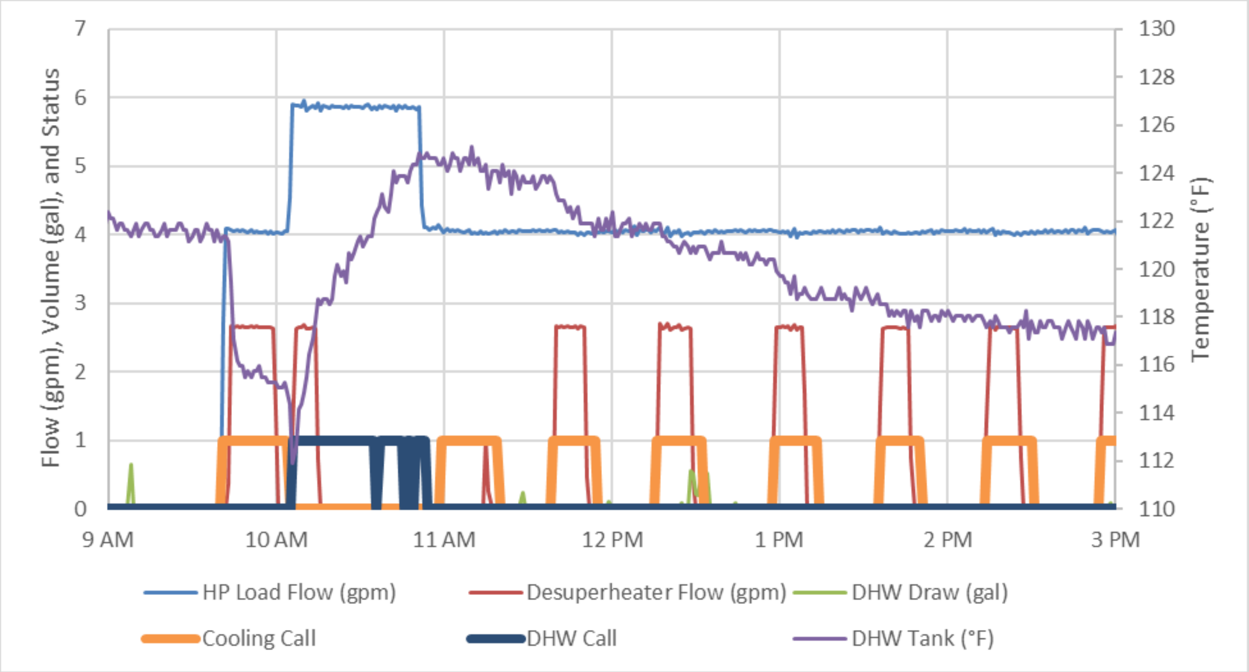

Figure 12. Time series plot of 6/26/2021 showing desuperheater flow destratifying the tank.

When the desuperheater comes on at 9:40 AM, it circulates cold water from the bottom of the tank to the top, causing the water at the tank sensor to immediately drop 6 degrees. This interrupted cooling operation with a DHW cycle just after 10 AM. Once the DHW cycle is done, cooling operation resumes, but with the desuperheater pump keeping the tank destratified. Though the desuperheater is still contributing heat to the tank, by eliminating stratification it is causing more heat pump cycles for DHW instead of fewer.

As previously mentioned, in 2022, despite the end of the project being nigh, the plumber was called out to correct the mistake. Though too late to allow for an annual analysis, the project team felt duty bound to give the desuperheater a fair chance of demonstrating its worth.

Additionally, control of the desuperheater was transferred from the integrated house controls to the heat pump's built-in control, which included in refrigerant and desuperheater return water temperature sensors. This built-in control likely would have done a better job of controlling the desuperheater pump for overall system efficiency. Using the built-in heat pump desuperheater controls, the desuperheater also operated during both heating and cooling modes. In cooling, this is advantageous as it reduces the heat needed to be absorbed by the ground loop while also serving two loads simultaneously. In heating, simultaneous operation advantage is preserved and efficiency impact is minimized by the built-in control.

An example of cooling operation is shown in Figure 13, a time series plot of data from 6/26/2021, and an example of heating operation with the desuperheater is shown in Figure 14, a time series plot of data from 12 PM on 5/9/2022 through 12 PM on 5/10/2022, the last two days of heating operation.

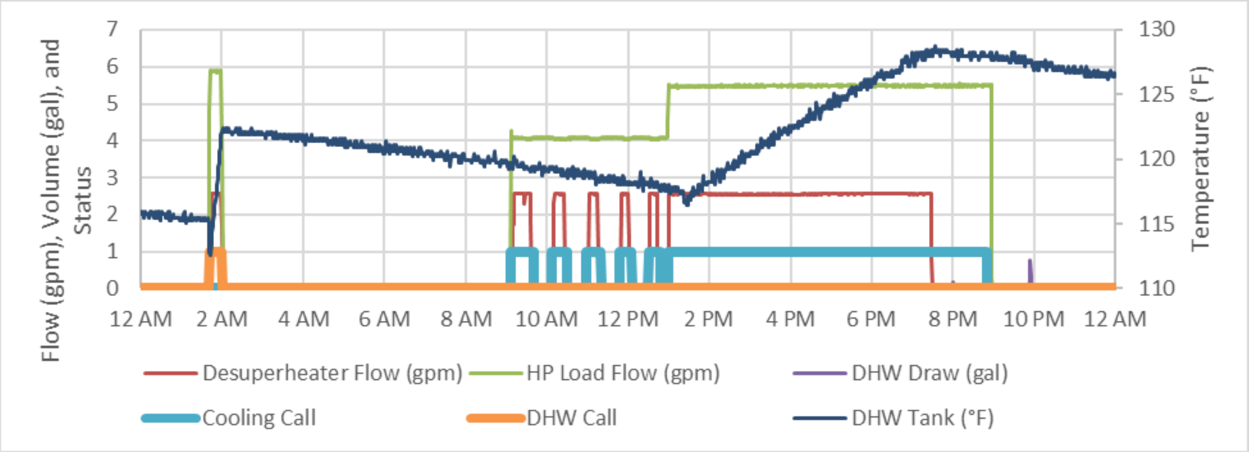

Figure 13. Timeseries plot of 6/26/2022 showing desuperheater increasing DHW tank temperature during cooling.

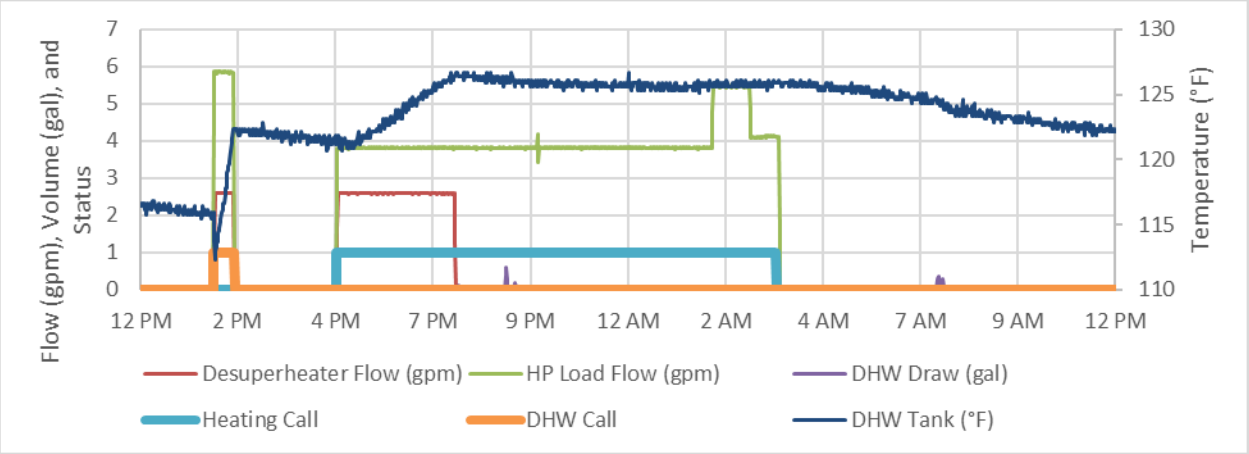

Figure 14. Timeseries plot of 12 PM on 5/9/2022 through 12 PM on 5/10/2022 showing desuperheater operation during space heating.

In the cooling example, significant cooling load enabled the desuperheater to maintain and increase the tank temperature. In this configuration, the desuperheater was able to contribute heat to the tank without destratifying it, avoiding DHW heat pump cycles instead of adding more DHW heat pump cycles. In the heating example, desuperheater operation raised the DHW tank temperature almost 6 degrees without interrupting space heating. Meanwhile, the built-in control limited the operation of the desuperheater to the first few hours of the heating cycle (compare to desuperheater operating during cooling cycles), to minimize the impacts of an oversized condenser on heating efficiency.

Comfort

Table 8 shows the percentage of time each year that the DHW tank temperature was below 105 and 112 (excluding periods the systems was down for maintenance or experiments) for 2015 through 2019. These two temperatures were chosen as representative of “unacceptable” DHW supply temperatures. There are no standards for temperature maintenance with heat pump water heaters or acceptable amounts of “unmet load”, but these are provided that the reader may judge for themselves.

Figure 15 shows the daily minimum, mean, and maximum indoor temperatures and the average of the 1st and 2nd floor setpoints. The pink and blue bands show the bounds for temperature deviation from setpoint for zoned systems in ACCA Manual RS for heating and cooling, respectively. (ACCA 1997)

Table 8. Percentage of time DHW tank temperature was below 105°F and 112°F.

DHW Tank Temp.	2015	2016	2017	2018	2019
% Time < 105°F	0.95%	1.70%	4.03%	2.21%	3.17%
% Time < 112°F	0.77%	1.03%	2.63%	1.69%	2.59%
Avg. GPD	30	38	42	58	43

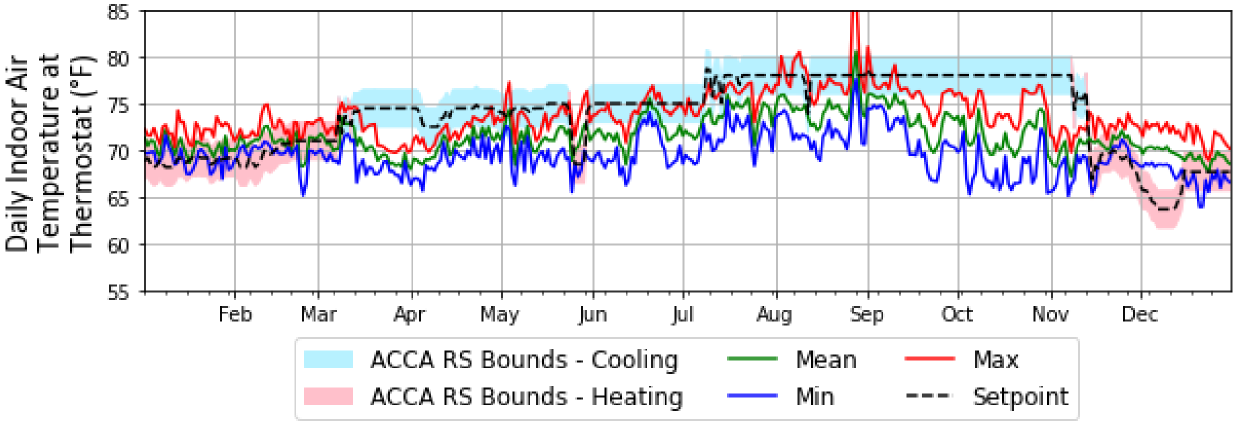

Figure 15. Daily minimum, mean, and maximum indoor temperatures and setpoints for 2017.

Conclusions

As discussed in the introduction, multi-function heat pump systems have the potential to ease electrification and provide the same benefit of discrete systems with reduced equipment footprint and therefore reduced equipment costs and maintenance. Hydronic heat pump systems offer the simplest and most advantageous path for creating a multi-function heat pump system. These systems allow for using a single packaged heat pump, hermetically-sealed and factory charged. The installer does not interact with the refrigerant, eliminating all the typical issues around heat pump installation and refrigerant circuits, as well as enabling the safe use of near-zero natural GWP refrigerants, which are often either flammable (R-290) or toxic (R-717).

Additionally, as demonstrated at the HSHus, besides the basics of a single compressor system switching between space heating, space cooling, and DHW production, hydronic systems can be integrated with a host of other features, including waste heat recovery devices and multiple indoor comfort delivery methods (in the case of HSHus, both high and low mass radiant surfaces). All of this can be done while achieving good comfort and efficiency.

In the years since the HSHus was designed and built, multi-function heat pumps have become something that you don’t need an army of consultants and engineers to design and maintain. Most air-to-water heat pump manufacturers provide three-function controls out of the box, and they and their distributors stand ready to assist with product selection and system design. Since these systems are pre-charged, they have become popular with the “do it yourself” crowd, as you don’t need an EPA certification to install them. Many easy to install delivery options exist, including both ducted and ductless fan coils.

Even the HSHus itself is benefiting from the advances in hydronic systems controls and best practices that have been developed since 2014. Ownership of the HSHus has been transferred to UC Davis and is undergoing a transformation into the EEI Smarthome. Frontier Energy is in the midst of updating the hydronic system to conform to current best practices and installing an “off the shelf” controller that doesn’t require a seven-foot-tall server rack.

References

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

ASHRAE. 2020. *ASHRAE Handbook HVAC Systems and Equipment.* Atlanta: ASHRAE.

D'Agnese, Joseph. 2023. *Radiant Floor Heating: Why It’s Worth It.* https://www.thisoldhouse.com/heating-cooling/21015149/radiant-floor-heating.

Haile, James. 2023. "Doing More With Less: Multi-Function Heat Pumps and Electrification." *Association of Energy Services Professionals 2023 Annual Conference.* New Orleans. https://www.researchgate.net/publication/373683268_Doing_More_With_Less_Multi-Function_Heat_Pumps_and_Electrification.

Haile, James, Bill Dakin, and Alea German. 2023. "Consolidated Learnings from the Mechanical Systems at Honda Smart Home US." https://www.researchgate.net/publication/373683334_Consolidated_Learnings_from_the_Mechanical_Systems_at_Honda_Smart_Home_US.

MNCEE. n.d. "Discovering Air-to-Water Heat Pumps." *MNCEE website.* https://www.mncee.org/discovering-air-water-heat-pumps.

Modera, Mark, Jonathan Woolley, Bill Dakin, David Grupp, and Michael Koenig. 2014. "One Machine for Heating, Cooling, and Domestic Hot Water: Multi-Function Heat Pumps to Enable Zero Net Energy Homes." https://www.aceee.org/files/proceedings/2014/data/papers/1-483.pdf.

Pallin, Simon, and James Haile. 2022. "Residential Hydronic Heating and Cooling Applications by Air-to-Water Heat Pump Systems." https://sonomacleanpower.org/uploads/documents/Task-4.2-Lead-Locally-EPC-2017-041_-Hydronic-Heating-and-Cooling-by-Air-to-Water-Heat-Pump.pdf.

Pecan Street. 2021. "Addressing an Electrification Roadblock: Residential Electric Panel Capacity." https://www.pecanstreet.org/2021/08/panel-size/.

Pena, Shoshana, Collin Smith, Greg Butsko, Rick Gardner, Sean Armstrong, Emily Higbee, Dylan Anderson, and Rebecca Hueckel. 2022. "Service Upgrades for Electrification Retrofits Study Final Report." https://www.redwoodenergy.net/research/service-upgrades-for-electrification-retrofits-study-final-report-2.

Wilson, Alex. 2009. *Improving Water Heater Efficiency.* October 21. https://www.greenbuildingadvisor.com/article/improving-water-heater-efficiency.