Residential Heat Pump with 3-Pipe Heat Recovery for DHW and Space Conditioning - Energy and Performance Results and Findings

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ABSTRACT

Heat pumps are extremely energy efficient when both high performance hardware and software are well-tuned for an application. Some heat pump manufacturers have brought 3-pipe heat recovery to 3-5-ton sized single phase equipment intended for small light commercial applications. These sizes could make them also suitable for residential applications. This paper summarizes results and findings from tests on one such heat pump system conducted at PNNL's Lab Homes located in Richland, WA, a pair of identical 1,500 square-foot homes built in 2011 that are highly instrumented and used for testing new building technologies. The heat pump system tested was setup to perform space conditioning and domestic hot water (DHW) using one outdoor unit (combi heat pump) along with simultaneous heating and cooling capability. The baseline comparison home has a single stage heat pump from 2011 for space conditioning and a unitary heat pump water heater located in conditioned space for DHW. This system can do heat pump water heating without producing cold air or generating any compressor or fan noises indoors when heating water – therefore expanding the number of homes that can use a heat pump for DHW. The results found this system to have negative savings compared to the baseline home's equipment when using the out-of-the-box firmware. The research found ways in which the equipment's hardware and control logic was not optimized for the application of serving space conditioning and DHW together in one system. Some firmware changes have resulted in significantly reduced negative energy savings and showing some positive, 15%, energy savings on some days based on data spanning February 16 to May 15, 2024.

Introduction

Modern unitary heat pump water heaters (HPWHs) have an UEF of 2.8 or greater making them much more efficient compared to electric resistance (ER) water heaters (DOE, 2024). However, they generate cold air when operating, produce some noise from the compressor and fan, as well as generate condensate, by products that can be undesirable or unacceptable in some installation locations. The heat pump operation is limited to when the ambient air temperature is above freezing, the exact heat pump cut-off temperature varies by make and model but ranges typically from 37 °F to 45 °F, below this temperature the HPWH will only use the electric resistance elements for water heating. They also require 120v or 240v circuits to be available near the water heater tank location, thus the upgrade path from a naturally drafted gas water heater to a HPWH can be challenging. Lastly, unitary HPWHs are limited to fitting the compressor and evaporator in the area available on top of a water heater tank. This limits most HPWHs to using a small compressor and evaporator with capacities typically under 5000 BTUH, resulting in slow recovery rates in heat pump only mode. These are challenges to unitary HPWHs that limits suitability to only certain installation locations. What if there was a heat pump water heater that operated by using the heat produced by the heat pump used for space conditioning? Such a HPWH wouldn't generate cold air or produce noise around the area of the tank, and it wouldn't produce condensate. Many modern cold climate heat pumps can produce 100% or near 100% of the rated heating capacity down to temperatures as low as 5 F, if a HPWH used heat produced from such a heat pump, it could provide HPWH down to much lower temperatures than current unitary HPWHs. Homes with an air conditioner or heat pump already have electrical service to power the outdoor unit (ODU). Thus, such a HPWH would not need a dedicated circuit to the water tank area. Lastly, if a HPWH had access to the large compressor and outdoor heat exchanger of the space conditioning heat pump, it could heat water a lot faster than the small heat pumps found in unitary HPWHs. A heat pump system that serves both domestic hot water heating and space conditioning is called a combination heat pump (combi heat pump) or an integrated heat pump. This paper will use the term combi heat pump.

The industry has a few different types/style of combi heat pumps as detailed in Table 1 below.

Table 1. Different Type/Style of Combi Heat Pumps

Type	Example Brands	Pros	Cons
Air-to-Water Monobloc (CO_2 Ref)	• SANCO2	• Low GWP refrigerant • Good COPs • Higher DHW temps possible	• Space heating only • Potable water runs to the outdoors, risk of freeze damage from power outage occurring in freezing weather, freeze protection valves can mitigate
Air-to-Water Monobloc (Non-CO_2 Ref)	• SpacePak • Arctic Heat Pumps • Chiltrix • Taco System M • Daikin Altherma M • Mitsubishi Ecodan Monobloc • THERMA V Monobloc	• Heat and cooling.	• Heat **or** cooling but not simultaneous • Simultaneous heating and cooling require buffer tanks since heat pump can only be in one mode at a time • System COP could be low due to intermediary heat transfer fluid (glycol mix) • Water-to-air coils are typically physically larger for the same capacity than refrigerant coils • Modest DHW temps
Air-to-Water Monobloc Heat Recovery (Non-CO_2 Ref)	• Multiaqua	• Simultaneous heating and cooling	• Working ambient temp only to 0 F • Modest DHW temps

Air-to-Water Split (Non-CO_2 Ref)	• Daikin Altherma R • Mitsubishi Ecodan Split • LG THERMA V Split	• No risk of freeze damage • Most use air-to-air for space conditioning	• Heat **or** cooling but not simultaneous • DHW heating means no space cooling during that time • Modest DHW temps
Split with Heat Recovery (Non-CO_2 Ref)	• LG Muti V S Heat Recovery • SAMSUNG DVM S Eco Heat Recovery	• Simultaneous heating and cooling • Heat recovery • No freeze damage risk • Air-to-air for space conditioning	• Typically, higher first cost and more complexity to install • Modest DHW temps

The increase in climate change fueled extreme weather events means even geographic locations that once didn't need air conditioning would benefit from having the option of space cooling. The first category of combi heat pumps is challenged by prolonged power outages that can occur during below freezing weather, which could occur more frequently now due to climate change (Lindsey 2021). Due to the intermediary working fluid, the second and third category of combi heat pumps are not as efficient in cooling versus systems that can utilize an air-to-air setup. This project selected a heat pump from the fifth category due to the research questions around possible efficiency benefits due to simultaneous heating and cooling via heat recovery.

Methods

The methods section begins by providing an overview of the equipment in the combi heat pump system as well as the baseline home, followed by an overview of the PNNL Lab Homes, and followed by an overview of the testing conditions.

Combi Heat Pump System and the Baseline Home Equipment

The heat pump system tested consists of a 4-ton outdoor unit connected to a 3-branch heat recovery unit. The first branch is connected to a 2.5-ton multi-position air handler unit. The second branch is connected to a 2-ton, Hydro Kit, a device that contains a refrigerant to water brazed plate heat exchanger, circulation pump, expansion tank, temperature sensors, control board, and user interface. The device is currently not sold in the U.S. market but is available in some markets and is advertised to serve DHW, hydronic fan coil units, and radiant floor applications. In the test setup it is used for DHW only by connecting it to an 80-gallon indirectly fired water heater tank that has an internal single-wall heat exchanger located in the lower half of the tank. The system setup is shown in Figure 1 below.

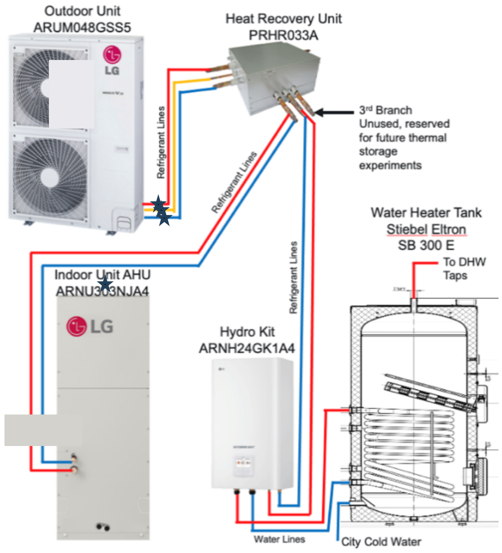

Figure 1. System diagram for the test combi heat pump system. ★ Denotes location of liquid line, low pressure vapor, high pressure vapor temperature, and supply air temperature sensor. The Baseline home's liquid and vapor line temperatures are measured at an equivalent location.

The manufacturer's performance specifications for the combi heat pump are shown in Table 2 below along with the specifications of baseline home's equipment. The baseline home has a single stage heat pump from 2011 for space conditioning and a unitary heat pump water heater located in conditioned space for DHW.

Table 2. Manufacturer's performance specifications for the combi heat pump and the baseline home's equipment.

Specification	Combi Heat Pump	Baseline Home
ODU modulation range	12-165 Hz in 1 Hz increments	Single speed
ODU heating capacity BTUH at 47 F	54,000	30,000
ODU cooling capacity BTUH at 95 F	48,000	29,400
HSPF	11.5	8
EER (95 F)	12.25	12
SEER	20.4	13
IDU heating capacity BTUH at 47 F[1]	34,000	30,000
IDU cooling capacity BTUH at 95 F[2]	30,000	29,400
AHU Aux Heat (kW)	None	5 kW stage 1 + 10 kW stage 2
Hydro Kit heating capacity BTUH	24,200	-
Hydro Kit cooling capacity BTUH	24,200	-
HPWH UEF	-	3.45
Water heater capacity Gal	80	50
Water Heater Tank Electric Element (kW)	3.0	4.5

1. Heating performance is based on inlet/outlet temp 86 °F/ 95 °F and outdoor air temp 47 °FDB/43 °FWB
2. Cooling performance is based on inlet/outlet temp 23 °C/18 °C, and outdoor air temp 35 °CDB/24 °CWB

The size of the outdoor unit relative to the indoor equipment for the combi heat pump system was selected based on the manufacturer's standard combination ratio rules of 50-130% where the combination ratio is calculated by dividing the sum of the nominal cooling capacity of indoor units by the nominal cooling capacity of outdoor unit. As a result with the 4-ton ODU selected, the combination ratio is 113% which is within the 50-130% range. The different water heater storage capacities between the combi system versus baseline home are due to two factors, (1) the height limit inside the Lab Home's water heater closet prevents an 80-gallon unitary HPWH from being installed and (2) an 80 gallon indirectly fired water heater tank was the size available in September 2022 when all the equipment purchasing occurred. In addition to these two factors, another important factor is that an 80-gallon regular water tank is the same height as a 50-gallon unitary HPWH. Thus, if one has the height to fit a 50-gallon unitary HPWH, an 80-gallon tank connected to the combi heat pump system would fit as well.

PNNL Lab Homes

The PNNL Lab Homes are in Richland, WA, they are a pair of identical 1,500 square-foot homes built in 2011 that are highly instrumented for temperature and energy use. Figure 2 shows a picture of the Lab Homes and Figure 3 shows the floor plan. The utility room houses the air handler unit, and in the home with the combi heat pump system, it also houses the Hydro Kit and the heat recovery unit. In both homes the water heater tank is located in the water heater closet as shown in Figure 3, the door to the closet is an exterior door with weatherstripping, the closet is in conditioned space, it has high and low louver grilles to connect its air volume to that of the master bedroom closet, and the wall between the master bedroom closet and the hallway also has high and low louver grills. This setup is the best that can be done for a unitary HPWH given the Lab Home's layout and it simulates the less than perfect air volume HPWHs are commonly installed into in a typical residential home. Each home is equipped with two Campbell Scientific CR1000 or CR1000X dataloggers, the first one records the energy data from Magnelab SCT-0750 current transducers on each circuit, the second one records indoor and outdoor ambient temperature and relative humidity data from Omega type T thermocouples and Campbell Scientific HC2S3 temperature and relative humidity probes. Additional temperature sensors for measuring refrigerant pipe temperature and hot water tank outlet pipe temperatures, Hydro Kit inlet and outlet, return air temperature, and supply air temperatures are monitored via Onset HOBO MX2303 and MX2302 sensors connected to an Onset MX Gateway in each home. Blower door and duct leakage tests were performed to ensure that the two home's envelope and duct leakage rates are similar, and that the leakage isn't significant. Both homes have enveloped leakage at around 4 ACH50 and 50 to 75 CFM of duct leakage to the outside at 25 Pa which is low for a 1,500 ft^2 home. While the Lab Homes has the capability of adding internal thermal loads from human occupancy, e.g. a human body at rest produces about 100 W of heat at rest, such loads were not added to this experiment.

Figure 2. Picture of the PNNL Lab Homes

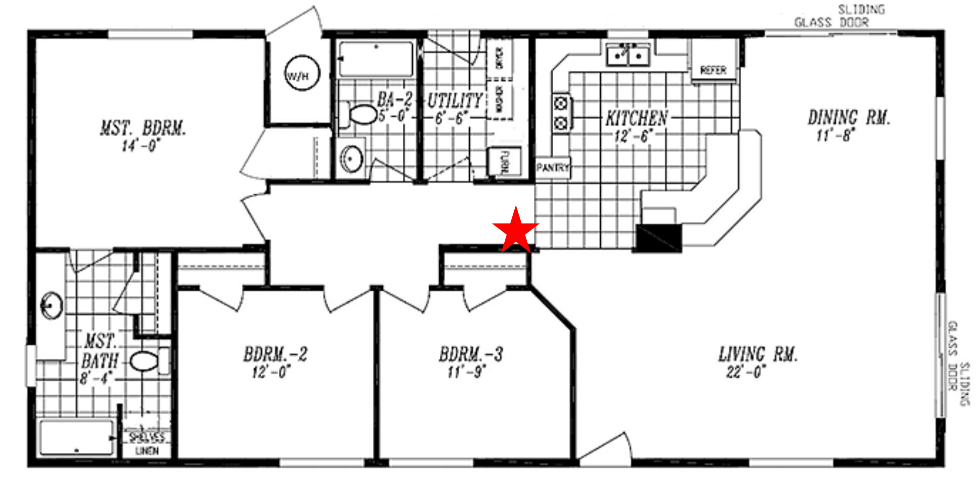

Figure 3. PNNL Lab Home floor plan. The red star denotes the locations of the thermostat.

The Lab Homes also have an automated hot water draw system for scheduling automated water draws. The start time, duration, and flow rate can be entered into the scheduler. The water draw system was custom made by PNNL staff and runs on VOLTTRON and Raspberry Pi. The system modulates the water flow rate using a Belimo PIQCV Series valve which combines a differential pressure regulator with a 2-way characterized control valve, it monitors and tracks the gallons of hot water flowed using an Omega FPR301 impeller flow meter.

Test Conditions

During the winter heating season period and the summer cooling season period the Lab Home thermostats were set to 72 F. The baseline home's single stage heat pump was controlled using an Ecobee thermostat, the combi heat pump required the use of an LG thermostat. Since each brand of thermostat reads slightly differently, during the testing period, the thermostat setpoint temperature was adjusted based on the calibrated Omega type T thermocouple near the home's thermostat so that both home's interior air temperature near the thermostat area is as close each other as possible.

The DOE ASHRAE Standard 118.2-2022 (U.S. DOE 2023) high usage draw pattern was used to simulate occupancy hot water usage. This draw profile draws 84 gallons of water each day according to the schedule shown in Table 3. The draw profile was selected because it is a moderately demanding on the water heating equipment.

Table 3. DOE ASHRAE Standard 118.2-2022 High Usage Draw Pattern 84-Gal/Day

Draw Number	Time Duration Test, hh:mm	Volume, gal (L)	Flow Rate, GPM (L/min)
1	00:00	27.0 (102)	3.0 (11.4)
2	00:30	2.0 (7.6)	1.0 (3.8)
3	00:40	1.0 (3.8)	1.0 (3.8)
4	01:40	9.0 (34.1)	1.7 (6.4)
5	10:30	15.0 (56.8)	3.0 (11.4)
6	11:30	5.0 (18.9)	1.7 (6.4)
7	12:00	1.0 (3.8)	1.0 (3.8)
8	12:45	1.0 (3.8)	1.0 (3.8)
9	12:50	1.0 (3.8)	1.0 (3.8)
10	16:00	2.0 (7.6)	1.0 (3.8)
11	16:15	2.0 (7.6)	1.0 (3.8)
12	16:30	2.0 (7.6)	1.7 (6.4)
13	16:45	2.0 (7.6)	1.7 (6.4)
14	17:00	14.0 (53.0)	3.0 (11.4)

On some days, the experimented deviated from this draw schedule and instead used a schedule that draws 3 GPM over 30 minutes for a total of 90 gallons starting at 5 or 6am and another one starting 5 or 6am.

Results

The equipment was installed in early January 2023. System calibration took much of January 2023. Thus, the winter heating season results are from the end of January 2023 to end of April 2023 and from the end of October 2023 to early February 2024. The summer cooling season results are from early May 2023 to the middle of October 2023.

First Winter Heating Season Results

The daily HVAC + DHW energy use by the combi system consist of summing the energy use by the ODU, heat recovery unit (HRU), Hydro Kit, air handing unit (AHU), and DHW tank electric element. The daily HVAC + DHW energy use by the baseline home's system consist of summing the energy use by the ODU, AHU, stage 1 auxiliary heat, stage 2 auxiliary heat, and the unitary HPWH. Despite the better equipment specifications, SEER, HSPF, and EER, operating the combi system using the out-of-the-box control logic through the first winter heating season found negative energy savings compared to the baseline home's system as shown in Figure 4. In fact, on average, the system used 34 percent more energy than the baseline home.

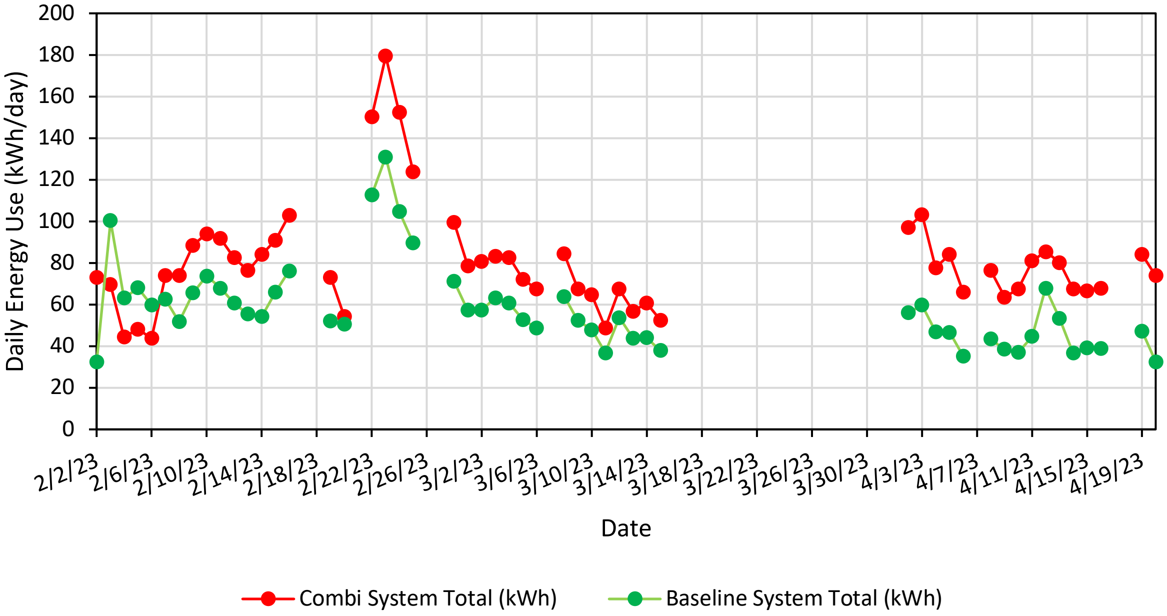

Figure 4. First winter, daily energy (kWh) usage, combi system versus baseline home's system. The daily total is the sum of all the HVAC + DHW equipment energy usage.

Detailed data from February 24, 2023, is shown below because it was one of the colder winter's days during the test period to see the capabilities of the heat pumps. The daily high, low, and average temperature for February 24 was 33, 10, and 20.4 °F respectively. The baseline home's heat pump is equipped with 5 kW of stage 1 auxiliary heat and 10 kW of stage 2 auxiliary heat. During defrost both stage 1 and stage 2 auxiliary heat is turned on for approximately 4 minutes as indicated by the green peaks in Figure 5. While the peaks in Figure 5 make it look like the heat pump in the baseline home uses more energy, the actual daily sum shows the combi system to use more energy, 152 kWh versus 105 kWh.

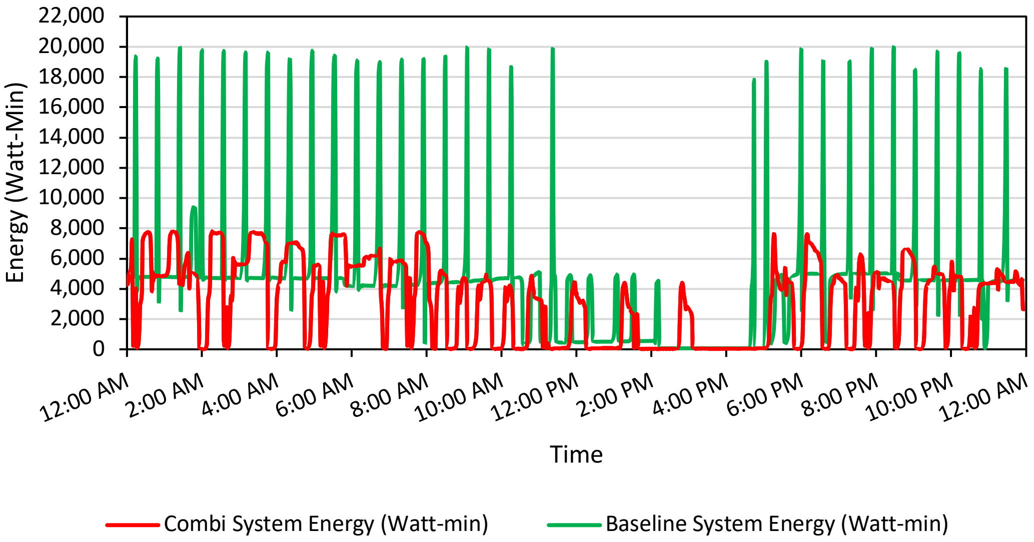

Figure 5. HVAC + DHW equipment total energy usage on February 24, 2023.

The reasons for the high energy usage by the combi heat pump system can be seen by looking at the refrigerant temperatures as shown in Figure 6. The temperature of the hot gas produced by the combi system can be as much as 80 °F hotter than the baseline home's heat pump. The default control logic produces high refrigerant temperatures to ensure quick DHW heating, and satisfactory DHW temperatures. High refrigerant temperatures are also important for applications that have ductless indoor units, these indoor units tend to blow air on people thus higher discharge air temperatures are needed to ensure occupants feel warm air.

High liquid line temperatures are also observed which is an indicator of an inefficient heat exchanger. The reason is because the heat exchangers from the Hydro Kit to the DHW tank aren't efficient for heat pump water heating. The system setup comprises of a refrigerant to water heat exchanger in the Hydro Kit, an intermediary closed loop of water to transfer the heat from the Hydro Kit to the DHW tank, and a water-to-water single-wall spiral heat exchanger inside the tank. The Hydro Kit's default logic for temperature hysteresis and controlling the water circulation pump adds to the inefficiency by starting a DHW heating cycle before the lower tank temperature has cooled enough and circulating water too quickly and thus not giving enough time for the heat exchanger to transfer the heat to the DHW tank. The high return water temperature results in high refrigerant liquid line temperatures.

The DHW side triggers the ODU to generate high temperature hot gas which is unnecessarily high for an AHU, the result is higher than needed supply air temperatures that are approximately 25 °F hotter than the baseline home's heat pump. It takes more compressor energy to produce higher pressure refrigerant to get the higher temperatures, thus an efficient system should produce the minimum pressure refrigerant needed for the application.

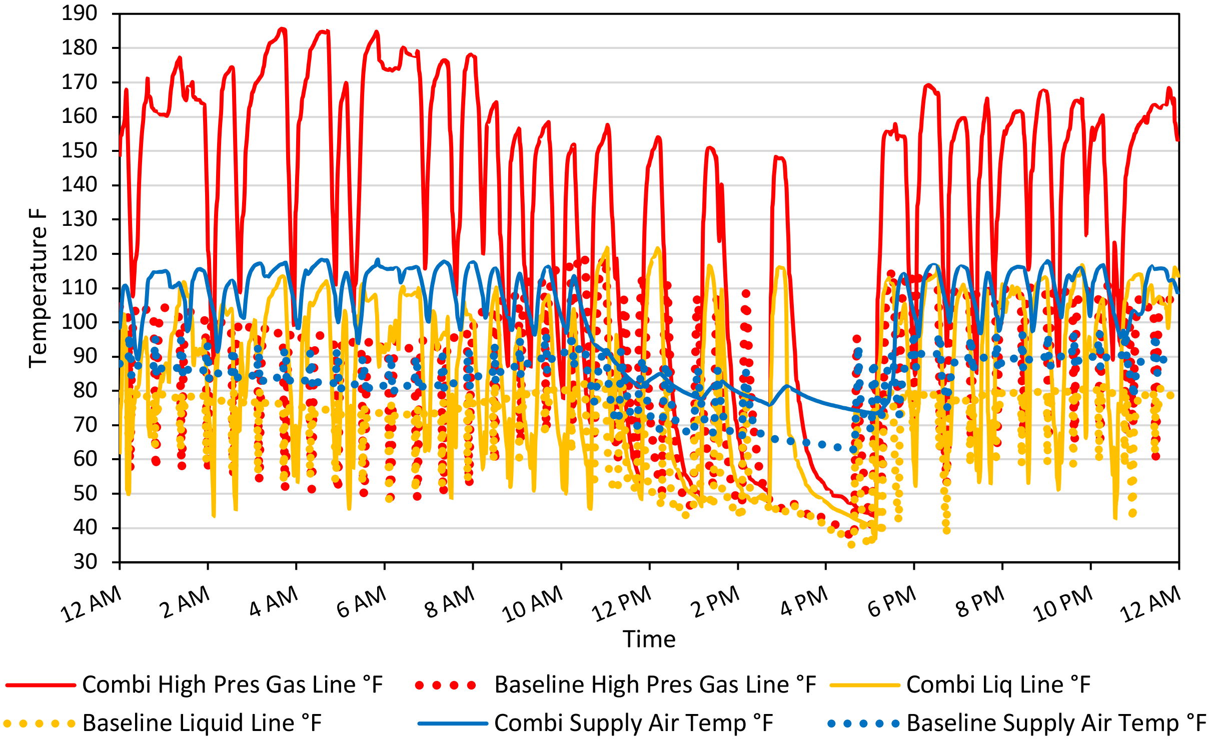

Figure 6. Heating season refrigerant temperature comparison.

First Summer Cooling Season Results

During the summer cooling season, the combi system also demonstrated no energy savings and in fact on average used 53 percent more energy than the baseline home as shown in Figure 7 below.

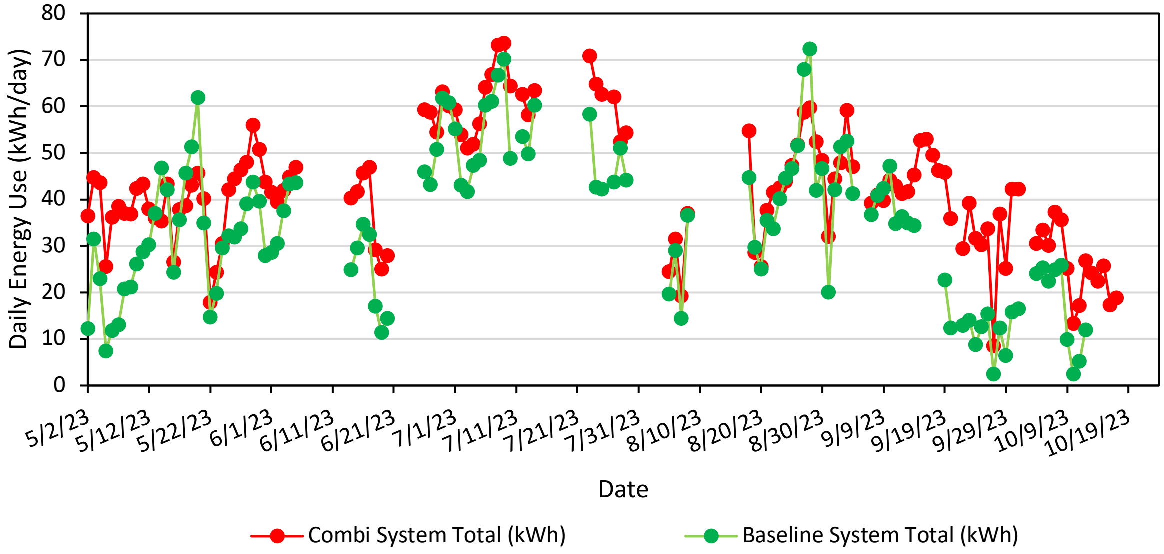

Figure 7. First summer, daily energy (kWh) usage, combi system versus baseline home's system. The daily total is the sum of all the HVAC + DHW equipment energy usage.

In addition to high energy usage compared to the baseline home, the combi system also exhibited unsatisfactory space cooling performance especially in the afternoon. High indoor ambient air temperatures during the late afternoon were recorded as a daily occurrence in the combi system lab home as shown in Figure 8 which is an overview of indoor ambient air temperature near the thermostat for the entire summer cooling period. The high indoor ambient air temperature in the combi system home is most evident when looking at data from a single day; June 30, 2023, was selected as a single representative/typical day as shown in Figure 9.

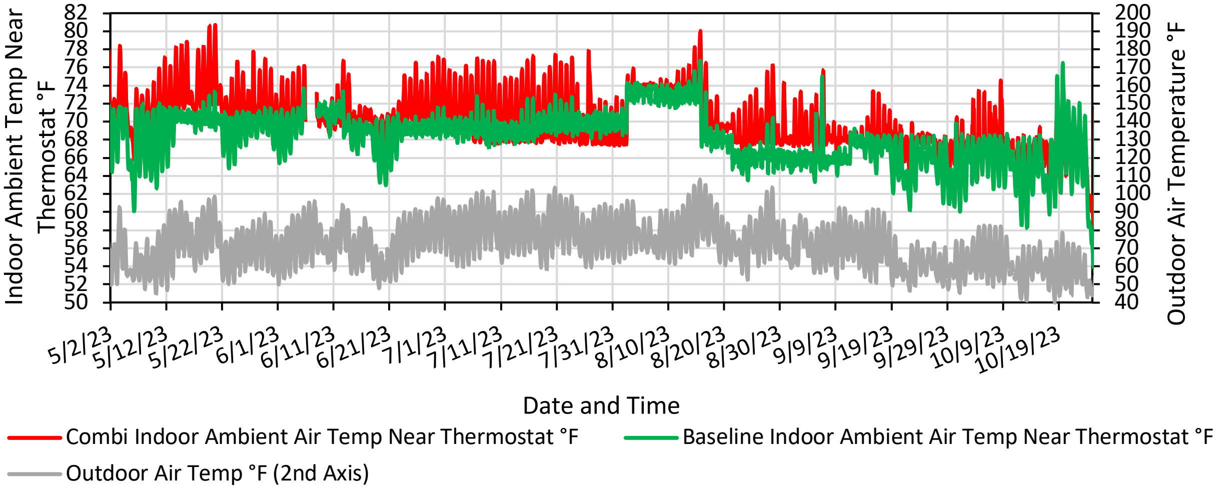

Figure 8. Summary of indoor ambient air temperature near the thermostat for the entire summer cooling period.

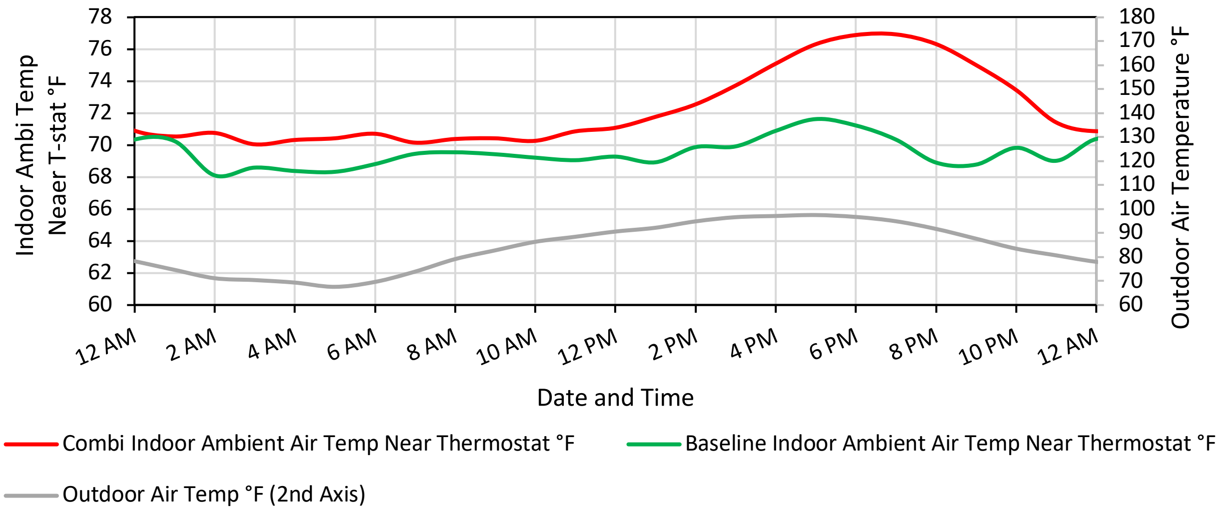

Figure 9. Example Summer Day, June 30, 2023, indoor ambient air temperature near the thermostat.

Examining the refrigerant line temperatures gives insight into why. In simultaneous heating and cooling mode, the system's control logic switches from low pressure target to high pressure target to prioritize the generation of high temperature hot gas as shown in Figure 10. The Hydro Kit creates high liquid line temperatures for reasons discussed in the winter section above. The high liquid refrigerant is much higher than the liquid line of the baseline home's heat pump. With elevated liquid refrigerant temperatures, even after changing temperature by changing to a low-pressure saturated liquid after the EEV in the AHU, the supply air temperature is still approximately 6-10 degrees °F hotter, as seen by the blue line versus the blue dotted line between the hours of 2 PM to 9 PM. The high liquid line temperatures during means simultaneous heating and cooling mode results in diminished cooling capacity which leads to high indoor ambient air temperatures.

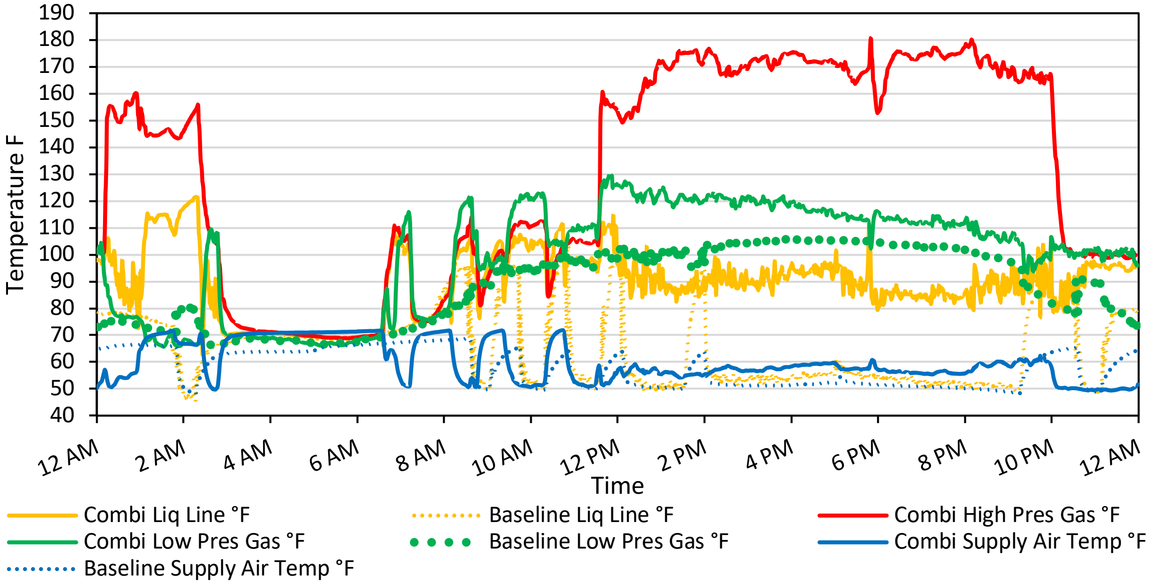

Figure 10. Cooling season refrigerant line temperature comparison, June 30 example day, between the combi heat pump system and the baseline home's heat pump.

Second Winter Heating Season Results

Some control logic changes were made by the equipment manufacturer's research and development engineers on December 14, 2023, and additional changes were made on February 13-15, 2024. The changes have significantly reduced negative energy savings and showing some positive, 15%, energy savings on some days based on data spanning February 16 to May 15, 2024 as shown in Figure 11.

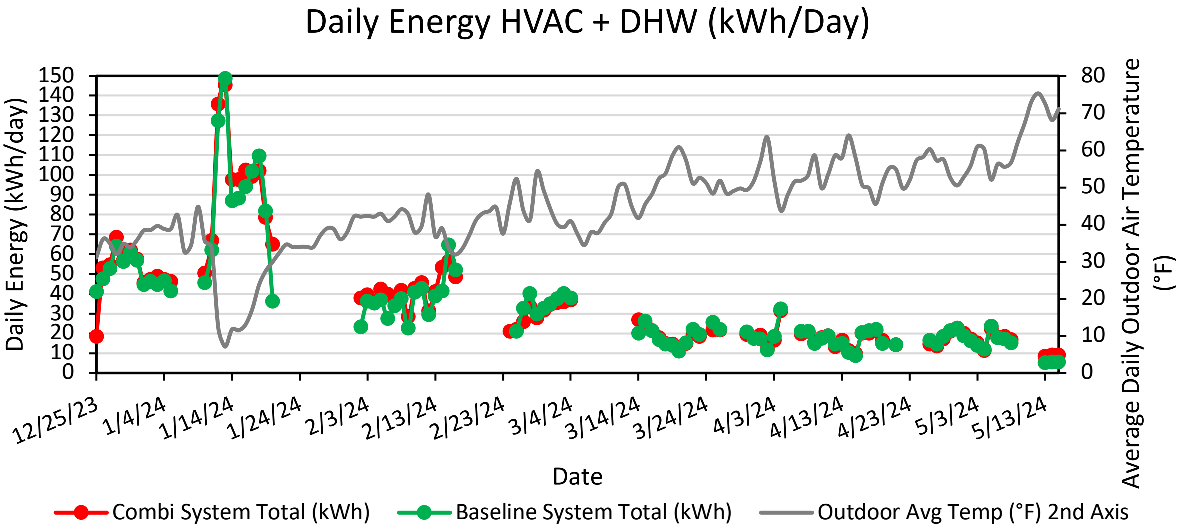

Figure 11. Second winter after firmware control logic updates, daily energy (kWh) usage, combi system versus baseline home's system. The daily total is the sum of all the HVAC + DHW equipment energy usage.

Discussion

The less-than-ideal performance from the combi heat pump system during the first winter and first summer can be attributed to several factors:

1. High default target pressures used by the control logic when in space heating mode or space heating mode with the Hydro Kit also calling for heat resulting in unsatisfactory system efficiency.
2. High refrigerant vapor usage rate at the start of a DHW heating cycle causing the compressor to speed up to a high energy state to maintain the high-pressure target. In tests done using large water draws, such as 3 GPM over 30 minutes for a total of 90 gallons, the cold water flowing through the Hydro Kit from a cold DHW tank can result in refrigerant consumption great enough to cause the AHU to not get enough refrigerant resulting in a short (~15-30 minute) period of reduced AHU supply air temperatures.
3. Lower efficiency due to DHW heat transfer at the end of a DHW heating cycle. This is due to two reasons:
   a. The diminished delta-T between water in the water tank and the water inside the closed heat exchanger loop when the thermal stratification of hot water reaches the elevation of the indirectly fired heat exchanger.
   b. The closed heat exchanger loop bringing back high return water temperatures resulting in high liquid line temperatures which inefficient.

4. In the summer, the default control logic for simultaneous heating and cooling uses high pressure target to control the compressor speed. Thus, for many hours of the day the low-pressure vapor isn't as optimized as it could be. Combined with the AHU being fed high temperature liquid refrigerant from the Hydro Kit together results in unsatisfactory cooling performance.
5. During a small number of test days ran with just the AHU running in cooling mode with the Hydro Kit turned off, the control logic mapping doesn't allow the ODU to modulate to a low enough energy state to result in energy savings compared to the baseline home. Additionally, the low-pressure target is too low which requires elevated compressor energy use to maintain.

The combi heat pump system's default logic produces very high temperature refrigerant vapor. The reason is because the ODU was designed to work in light commercial applications where line set lengths between the ODU and the furthest IDU can be as long as 984 ft. The default logic chooses compatibility and good user comfort experience over a wide range of applications over efficiency. With a high hot gas pressure target, the refrigerant will be hot enough to provide satisfactory heating performance even after accounting for heat loss from long runs. Additionally, the default ODU logic for when a Hydro Kit calls for heat is high target pressures to make high temperature refrigerant.

Solutions and Future Work

Heat pumps are extremely energy efficient when both high performance hardware and software are well-tuned for an application. None of the problems are unsolvable with today's technology. A way to solve the problem described in #1 in the previous section is to reduce the control logic's target high pressure value for single family residential home applications. The greatest energy efficiency is achieved when the target pressures are as low as possible to still result in temperatures high enough to provide adequate space heating or DHW heating, the lower pressures result in less compressor energy usage resulting in greater energy efficiency. A way to solve problem described in #1 in the previous section is to slow the water pump speed in the closed heat exchanger loop to reduce the rate of cold water reaching the Hydro Kit. This logic could run as soon as reduced hot gas temperatures are detected at the AHU, to ensure the AHU always has priority to for the hot gas. A way to solve problem number three with the current equipment setup is to use the heat pump to heat the DHW tank only until the tank reaches a lower water temperature such as 108 °F and engage the electric resistance heating element in the DHW tank, shown in Figure 1 above, to finish heating the DHW to the final desired temperature such as 120 °F. An alternative way to solve problem number 3 is to utilize a DHW tank with a better refrigerant to tank/water heat exchanger design that allow the refrigerant to more effectively release heat to result in a lower liquid line temperatures even when the tank is approaching the final desired tank temperature. An example of a better heat exchanger design is shown in Figure 10. Both solutions for problem number three would result in lower liquid line temperatures which would help the AHU achieve its designed cooling capacity during the summer. A way to solve problem number four is to switch the control logic for simultaneous heating and cooling to using low pressure target to control the compressor speed could result in improved cooling performance while still yielding acceptable heating performance for DHW heating. A way to solve problem number five is to expand the modulation range for the logic to utilize more of the hardware capability and to adjust the target low pressure value based on outdoor ambient air temperature.

Not all solutions to the observed high system energy usage and unsatisfactory cooling performance can be completely fixed via software changes, some require hardware modifications and changes. For example, water heating efficiency could be further improved, and system complexity and costs can be reduced by use of a water heater tank with a wrap-around heat exchanger on the outside of the tank or a tank with spiral refrigerant to water heat exchanger directly submerged in water as shown in Figure 12 below. Such a tank designs would be better than the DHW setup with the Hydro Kit connected to an indirect fire water heater tank because it would eliminate the inefficiency of having an intermediary heat transfer fluid. It also spreads the heat exchanger out across a wider vertical range of the tank to enable good heat exchange at various level of tank charge. Most importantly it has wraps located at the very bottom of the tank, this region of the tank will remain relatively cold even when the tank is fully charged due to thermal stratification and the location of the temperature sensors. This relatively cold tank region helps maintain low liquid line temperatures even when the tank approaches a fully charged state. This is important for efficiency because high liquid line temperatures equals energy wasted since that heat energy is lost when the refrigerant undergoes expansion into a low pressure low temperature liquid.

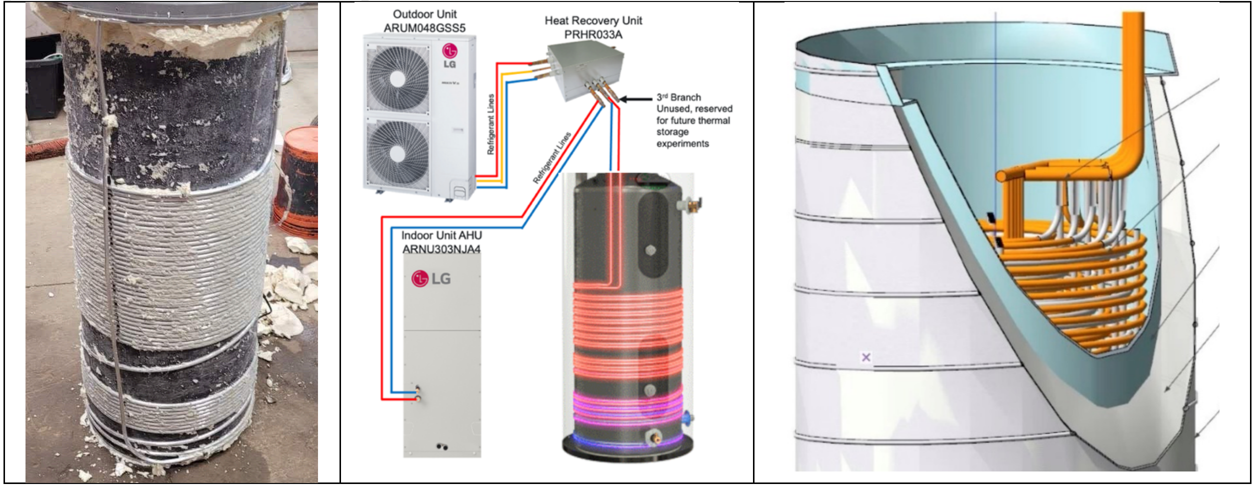

Figure 12. Left, picture of a water heater tank with a wraparound refrigerant to tank heat exchanger found in a typical unitary HPWH. Middle, rendering of what the combi heat pump system setup would look like if the Hydro Kit and indirect fire water heater tank were replaced with a water heater tank with a wrap-around refrigerant to tank heat exchanger. Left, a rendering of what a tank with a submerged spiral coil refrigerant to water heat exchanger running the vertical length of an insulated tank could look like.

The combi system can be further simplified if the DHW branch never needs to go into cooling mode. However, the PNNL project team would like to work with the manufacturer to better understand the magnitude of the cost savings of removing that feature versus the defrost benefits of borrowing heat from the DHW for defrost and maintaining space heating output during defrost.

Additional insights on how to make a combi heat pump that works efficiently across a range of operating states and temperatures can come from the research and development in the refrigeration space. Much literature has been published on how to efficiently operate a refrigeration system with multiple evaporators at different temperatures (e.g. freezer, vegetable cooler, and meat cooler) using a single compressor. The key component to making the system work is back pressure valves on the low-pressure vapor line to allow the different temperature evaporators to operate at different low pressures and therefore different temperatures. Electronic expansion valves could possibly be used to throttle the refrigerant volume to a condenser in a situation that would result in multiple condensers at different temperatures (e.g. space cooling mode, AHU acting at the evaporator, ODU acting as a condenser, and DHW tank acting as another condenser) with the desire to prioritize the hot compressor discharge gas going to the DHW tank. Currently with the combi system not having back pressure valves, the ODU fan spins very slowly or not at all to allow the hot gas to not be released to the outdoor air and therefore go to the Hydro Kit. If the ODU fan spins more the hot gas will automatically condense using the ODU heat exchanger because most of the time the outdoor air temperatures will make that heat exchanger more thermodynamically favorable. Electronic expansion valves could possibly be controlled to function as variable back pressure valves. Back pressure valves would enable a small amount of heat pump water heating to occur simultaneously with a significant amount of air conditioning load. The back pressure valve would allow the hot gas to remain at a high pressure needed for DHW while metering enough through so the ODU heat exchanger can reject enough heat maintain adequate air conditioning for the building’s heat load.

Conclusion

While not the original research goals of the project, this project is an example of how much the efficiency of a heat pump can be affected by hardware and software nuances, particularly what happens when a system designed for simultaneous heating and cooling of IDUs is applied to simultaneous heating and cooling with one branch being DHW and the other branch being space conditioning. In the case of this combi project in the PNNL Lab Homes, optimizing the control logic changed the energy savings from negative 34-53 percent to as much as positive 15 percent based on winter data from the second winter from Dec 23, 2023, to May 15, 2024. There are reasons why the manufacturers have not yet offered a widely available, highly energy efficient, combi heat pump that can provide residential space conditioning and DHW. Significant new control logics and hardware modifications are needed to arrive at a cost-effective, relatively easy to install, and energy efficient combi heat pump system that has the control logics optimized to work well across all likely operating conditions. It is not as simple has adapting a heat pump that can provide heat to a hydronic radiant floor and using it for DHW. The manufacturer has already produced new firmware versions to address some of the problems observed, the updated firmware is already showing some energy savings compared to the baseline home’s equipment. If additional funding can be secured for additional fiscal year(s) of research, the project seeks to work with the manufacturer to implement and test the performance of the combi heat pump additional software and hardware changes at the PNNL Lab Homes.

A working combi heat pump can enable homes where current unitary HPWHs would not work well to access high efficiency DHW heating thus expanding the number of homes that can benefit from heat pump water heating. A combi heat pump could also require fewer circuit breakers to operate, allowing some homes with small and 100% full panels to electrify without the cost of a panel upgrade.

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