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Can multi-function heat pumps with low-global warming potential refrigerant effectively decarbonize heating for low-income homes?

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ABSTRACT

Electrification of homes is a critical part of reducing greenhouse gas (GHG) emissions. However, space constraints, installation complexity, and the potential impact on energy costs slows the pace of retrofit electrification efforts. Also, the addition of electrical circuits for heat pumps and the increased household electrical demand often necessitates electrical panel upgrades, which increases costs and slows installation. Multi-Function Heat Pumps (MFHPs) use a single compressor to provide heating, cooling, and domestic hot water (DHW) – which represent the most intensive thermal loads of a home – and can ease the process of retrofit electrification. MFHPs are potentially more economical than typical split HVAC heat pumps (HPs) and heat pump water heaters (HPWHs), as they consolidate systems, require fewer circuits, streamline installation, and enable efficiency opportunities, such as recovering waste heat from cooling to heat DHW. The current study evaluates one MFHP product, a split HP with indirect water heater and ducted air handler, using a low-global warming potential (GWP) refrigerant (R454B). This MFHP has a unique defrost operation that pulls heat from the DHW tank instead of the indoor air, which avoids cold drafts on occupants. This allows for better thermal comfort without requiring an electrical resistance backup heater and costly panel upgrades. The MFHP was installed in two low-income apartments, evaluated for ease of installation, and monitored through the heating season to assess reliability, energy efficiency, and performance.

Introduction

Significant efforts in recent years have been geared towards reducing GHG emissions, largely under political directives to curb climate change. For example, the Biden administration in the United States has set goals for net-zero GHG emissions by 2050, with a push for 100% carbon-free electricity by 2035 (U.S. DOE 2022). Electrification of heating and hot water in the residential sector is a major step towards achieving that goal (Huismans 2023). In addition to reducing carbon emissions, electrification also offers health and economic benefits, such as improving air quality and reducing costs for equipment, maintenance, and energy use (Lee and Billimoria 2021, SMUD 2024).

HPs are an all-electric solution that can be applied to both water heating and space conditioning. In this regard, one of two configurations is possible: either (1) two separate HPs, one to provide heating and cooling, and another to provide DHW; or (2) a single, integrated MFHP to supply both space conditioning and DHW (Modera et al.). However, by combining the functions of air conditioners (A/C), furnaces, and water heaters into a single integrated system, MFHPs can further improve efficiency and comfort, and could reduce capital, installation, and maintenance costs compared to separate systems.

As illustrated in Figure 1, the MFHP in the current study is a split, centrally-ducted air-source HP with two refrigerant lineset pairs – one between the outdoor unit and the air handler, and another between the outdoor unit and the DHW tank. The outdoor unit comprises a single-speed compressor, refrigerant valves, and a finned tube refrigerant-to-air heat exchanger (ie: the “outdoor coil”). The air handler is a unitary centrally ducted vertical air handler with a single-speed fan, and an “A-coil” finned-tube refrigerant-to-air heat exchanger (i.e.: the “indoor coil”). The DHW tank holds 60 gallons of atmospheric pressure water, which immerses two spiral-coiled heat exchangers: one refrigerant-to-water heat exchanger, intertwined with a water-to-water heat exchanger for heating domestic water.

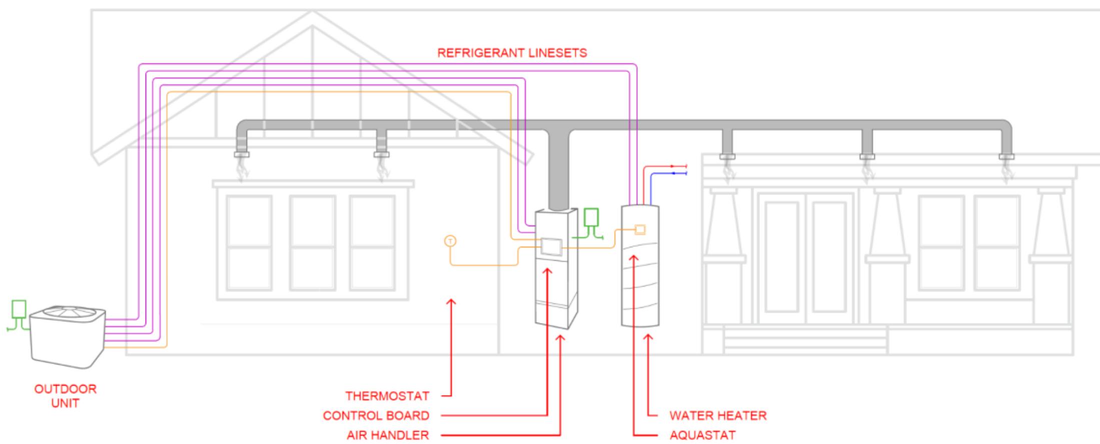

Figure 1. Split-ducted air-source multi-function heat pump (MFHP) system in a residential setting

This system design is advantageous for several reasons, including that it can directly replace the ubiquitous centrally ducted unitary A/C and furnace systems. Since the single compressor has sufficient capacity for space heating, it can satisfy DHW heating rapidly without the need for auxiliary electric resistance. Eliminating electric resistance backup heaters may eliminate the need for electrical service upgrades, by reducing maximum power requirements for the system. High upfront costs associated with electrical service upgrades is a major barrier to large-scale electrification, therefore further development of MFHPs can help advance residential electrification (Chakraborty, Challey, and Levering 2023, Deason et al. 2019).

The MFHP can operate in 5 discrete modes: water heating (WH), space heating(SH), space cooling (SC), simultaneous space cooling and water heating (SIM), and defrost (DEF). The air handler fan can also operate independent from compressor operation, and includes a fan runtime delay. Table 1 outlines how the different MFHP system components operate in each mode. The schematic in Figure 2 illustrates the complete refrigerant circuit, including all reversing valves, liquid line solenoid valves, and check valves which enable the single compressor to operate in various modes.

Table 1. MFHP operational modes

Mode	Evaporator	Condenser
Water Heating (WH)	Outdoor Coil	DHW tank refrigerant-to-water Coil
Space Heating (SH)	Outdoor Coil	Indoor Coil
Space Cooling (SC)	Indoor Coil	Outdoor Coil
Simultaneous Space Cooling and Water Heating (SIM)	Indoor Coil	DHW tank refrigerant-to-water Coil
Defrost (DEF)	DHW tank refrigerant-to-water Coil	Outdoor Coil

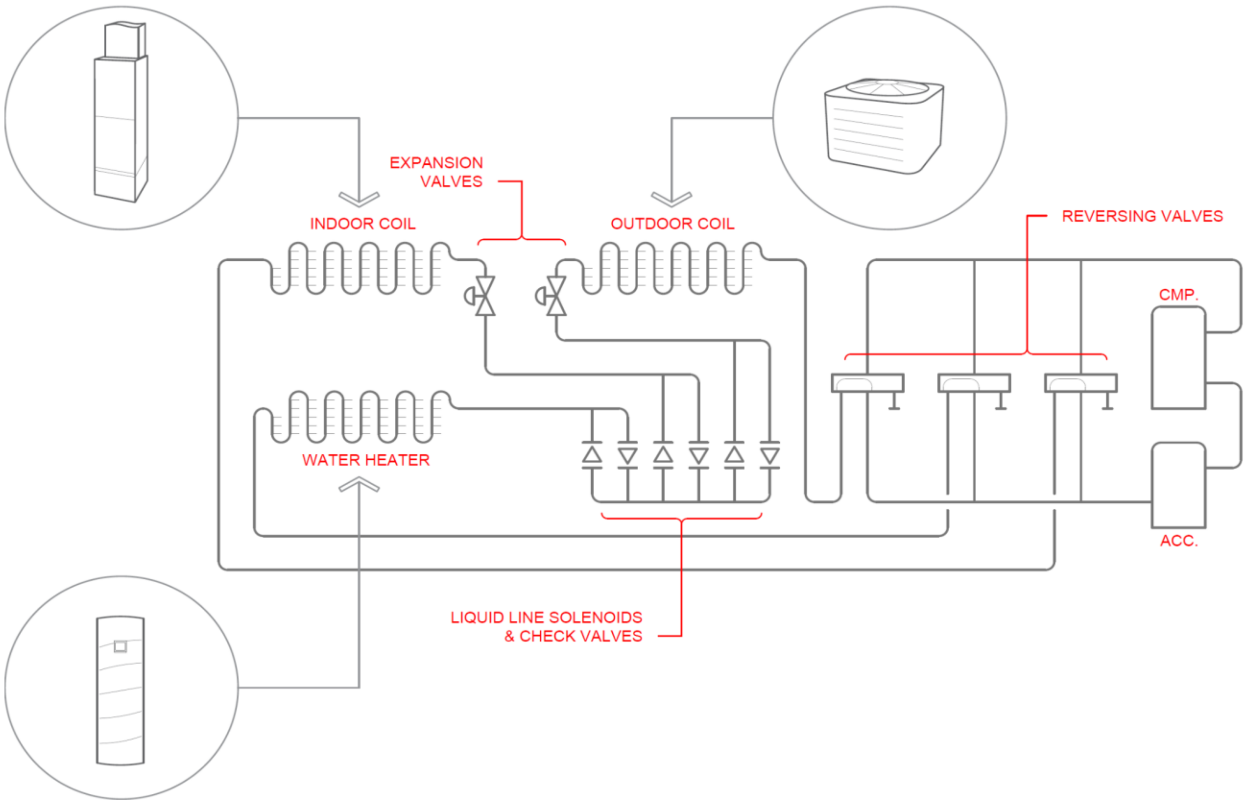

Figure 2. Schematic of refrigerant system for the MFHP

As with other heating and cooling appliances, one major concern regarding HPs is the pollutant properties of refrigerants. Traditional refrigerants tend to have high Global-Warming Potentials (GWPs) and Ozone Depleting Potentials (ODPs), and though the appliance envelopes are sealed, leaks are common during maintenance operations and as a consequence of regular wear on the system. As such leaks have a negative impact on the environment, recent works have investigated alternative low-GWP refrigerant options. However, many low-GWP refrigerants have significantly lower volumetric capacities and are consequently much less efficient than traditional refrigerants. To be considered viable alternatives, low-GWP refrigerants would ideally offer higher volumetric capacities, shorter lifetimes in atmosphere, and higher efficiencies (Uddin et al. 2018). One refrigerant commonly used in HPs is R410A. While R410A has 0 ODP, it has 4715 GWP_{20}. Meanwhile, R454B only has 1854 GWP_{20} and has been found to be a suitable drop-in alternative to R410A (Smith 2021). Both refrigerants are PFAS substances (ECHA 2023). Recent studies investigating the drop-in performance of low-GWP alternative refrigerants have found that R454B lowers HP heating and cooling capacity slightly, but also offers similar or slightly superior EER and COP (Sieres 2021).

This study compares pre- and post-retrofit data to analyze the economic benefits, energy efficiency, installation convenience, health and safety, grid benefits, and maintenance benefits of the MFHP system. Economic benefits are considered both in terms of upfront costs for equipment and installation, and its impact on energy costs. The post-retrofit MFHP equipment will operate on low-GWP R454B refrigerant.

Installation Pre- and Post-Retrofit

The MFHP was installed in two adjacent, single story residences at a low-income apartment complex near Merced, CA. Apt-1 is a 4-bedroom, 2-bathroom unit occupied by 5 people. Apt-2 is a 3-bedroom, 1-bathroom unit occupied by 3 people. One MFHP system was installed for each apartment to provide heating, cooling, and DHW.

Prior to the retrofit, these apartments had split-unitary central ducted air-source HPs for heating and cooling, and unitary tank hybrid HPWHs for DHW. These existing HPs were only two years old, and had previously replaced split-unitary centrally-ducted A/Cs with gas furnaces and gas water heaters. This series of system retrofits allowed us to directly observe the practical differences between the different system types. The pre-retrofit HP was a 2.5-ton split-unitary system with a centrally-ducted air handler (HSPF 9.5, SEER 16, EnergyStar). The pre-retrofit water heating system was a 50-gallon unitary tank HPWH (UEF 3.5, FHR 67 gallons).

Figure 3. Pre-retrofit heat pump and heat pump water heater

The MFHP system consists of a 3-ton outdoor unit and air handler – with paired efficiency ratings of HSPF 8.5 and SEER 16 – and a 62-gallon DHW tank. As illustrated in Figure 1, the system includes two separate refrigerant lineset pairs, connecting the outdoor unit to the air handler and water heater, respectively. In addition to the compressor and the outdoor coil, the outdoor unit houses a proprietary refrigerant valving manifold – illustrated in Figure 2 – which is controlled to distribute and meter refrigerant to the indoor coil and DHW tank, to achieve each of the operating modes described in Table 1. The water heating component for the MFHP comprises a coiled refrigerant pipe, intertwined with a coiled domestic water pipe, submerged in an atmospheric pressure water tank. A thermostatic mixing valve is installed at the outlet of the DHW tank to maintain safe distribution temperatures, and to allow load flexible controls which may heat water in the tank to higher temperatures (~150°F).

Control sequencing for the system – its brains – is conducted by a proprietary control board. This control board receives signals from an Aquastat (water heating thermostat) measuring water temperature in the DHW tank, from a conventional 24V thermostat measuring air temperature in the apartment, and from other sensors in the system. Then, the controller determines the appropriate system operating mode and dispatches low voltage signals to operate the compressor, outdoor fan, air handler, and refrigerant valves. The MFHP can operate with any conventional 24V thermostat, but we installed new communicating programmable thermostats to support monitoring and to facilitate test of demand flexible controls.

The components of the MFHP systems were installed in the same place as their pre-retrofit counterparts. Specifically, the outdoor units used the 240V 30A circuits and the air handler used the 240V 20A circuits already in place. The 240V 20A circuits for the pre-retrofit HPWHs were abandoned in place, as the DHW tank does not include electric resistance and all thermal input is sourced from the outdoor unit. The new air handlers also connected to the existing central ducting. Since the pre-retrofit equipment was all-electric, the MFHP did not require additional electrical work.

Figure 4. Instrumentation installation and wiring

Installation of the MFHP systems took longer than expected, because this was among the first installations for this product and the systems were installed as part of a research demonstration that required coordination between multiple collaborators, which included additional work beyond the scope of this paper. The MFHP system for Apt-2 was installed on September 5-8, 2023, and for Apt-1 on October 10-11, 2023. In each case, the monitoring instrumentation was installed at the same time. Each installation started with removing the existing equipment, then the outdoor unit, air handler, and DHW tank were installed. Then electrical circuits and refrigerant line sets were installed. After all of the major pieces were in place, installation proceeded with connecting the ductwork, plumbing, and refrigerant piping, filling the DHW tank and coil, testing and charging the refrigerant system, installing controls, and commissioning the system. The same personnel were involved in both installations and, with the experience and lessons learned from the first installation, the team was able to complete the second installation much quicker and more smoothly than the first. Co-location of the mechanical systems made some things easier for this project; however, it also meant that all three trades – HVAC, plumbing, and electrical – were working on top of one another in a very small space, and sometimes had to wait for each other to complete work. Through these installations, it became clear that it is important to have coordinated leadership (ie: general contractor) on-site to facilitate the sequence of work for all trades. This need could also be addressed by a well-practiced and integrated installer team, but the greatest challenges for this installation were simply a lack of coordination and communication between different entities, and the designated individuals responsible for organizing workflow were not present or immediately available to address issues as they arose. Realistically, with improved practice, organization, workstream sequencing, and centralized leadership of trades, we expect a team of two to four workers could complete one system retrofit per day.

Figure 5. Completed MFHP system installation with all three components

System Performance Monitoring

Instrumentation and data acquisition equipment was installed during the system retrofit process to monitor system states and behaviors, to characterize performance and efficiency, to inform commissioning, and to support ongoing troubleshooting. We used a data acquisition system with an internet-connected data analytics platform to record measurements from an array of sensors measuring temperature, humidity, water flow rate, thermal energy flow rate, air velocity, and electricity use. Additionally, one-time field measurements of airflow, duct leakage, and ventilation effectiveness were performed.

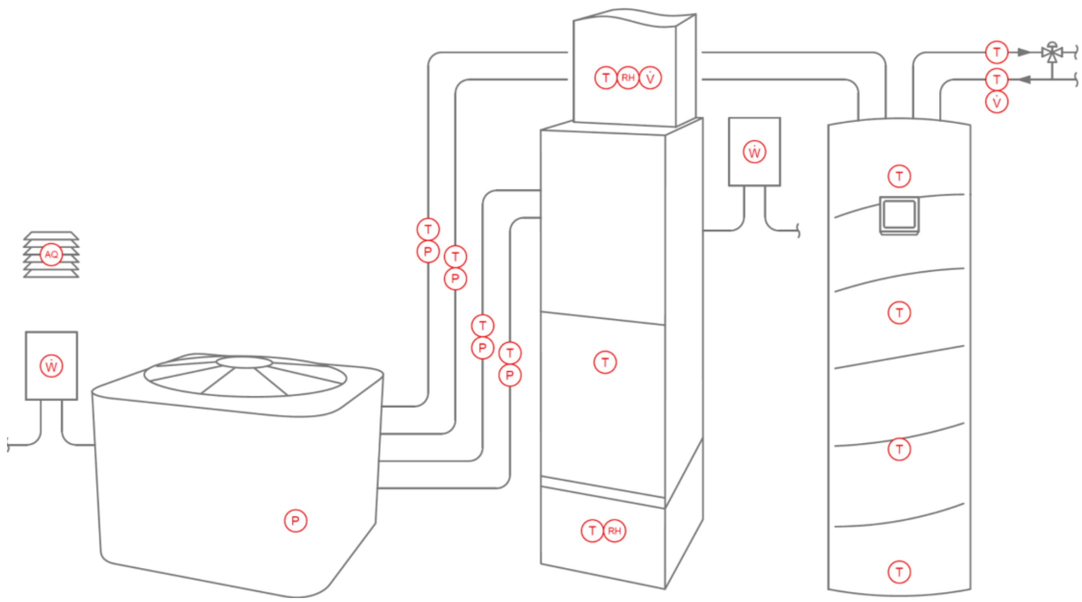

Figure 6. Monitoring schematic for MFHP system and sensor locations

Measurements and data acquisition system

The data acquisition infrastructure employed uses wireless mesh networking to communicate between a central internet-connected gateway and remote sensor nodes. The infrastructure is modular and easily configurable. It can integrate a wide range of third party sensors with different output signals (e.g.: 0-10V, 4-20mA, thermistor, pulse, Modbus), and thus facilitates collection of data for almost any measurement (eg: temperature, humidity, power, pressure, flow rate). The data acquisition hardware communicates to a web-based platform that facilitates system configuration, data analytics, and data dashboarding. All data is available through the web-based platform on a near-real-time basis and can be used for commissioning, diagnostics, system and sensor troubleshooting, and performance analysis. Figure 6 illustrates the location of all continuous measurements within the MFHP system. Not shown in Figure 6, we also used a packaged suite of air quality sensors to monitor temperature and humidity at two locations in each apartment, and at one shielded outdoor location. Table 2 describes each measurement and identifies the location of sensors.

Table 2: Instrumentation hardware and measurement variables

Measurement	Sensor	Sensor Location
Indoor air quality		
Temperature	Indoor Air Quality node	Living room and master bedroom
Relative humidity		
Outdoor air quality		
Temperature	Outdoor Air Quality node	Outside Apt 2's mechanical closet
Relative humidity		
MFHP System		
Electrical power	Power meter and Modbus bridge	In each apartment's mechanical closet
Outdoor Compressor		
Refrigerant Pressure – WH vapor line	0-10 V bridge	Pressure and temperature sensors installed on the refrigerant line next to outdoor unit
Refrigerant Pressure – WH liquid line		
Refrigerant Pressure – AH vapor line		
Refrigerant Pressure – AH liquid line		
Refrigerant Pressure – Shared Suction		
Refrigerant Temperature – WH vapor line	Thermistor bridge	
Refrigerant Temperature – WH liquid line		
Refrigerant Temperature – AH vapor line		
Refrigerant Temperature – AH liquid line		
Return Air		
Temperature and Relative Humidity	Vaisala HMP110, 0-10 V bridge	In the return air stream (entering the air handler)
Supply Air		
Air flow Rate	Vaisala HMP 110 0-10 V bridge	In the supply air stream (leaving the air handler)
Temperature and Relative Humidity		
Domestic Hot Water Tank		
Temperature bottom of tank	Thermistor bridge	Thermistors 2", 20", 40", and 60" from bottom of DHW tank, respectively
Temperature lower middle of tank		
Temperature upper middle of tank		
Temperature top of tank		
Domestic Hot Water System		
Post-mixing valve DHW supply temperature	Thermistor bridge	Return and supply water pipes of the DHW tank
Cold water makeup, hot water supply temperatures	BTU Meter RTD and Modbus bridge	
Cold water makeup flow rate		
DHW energy output		

One-time measurements

During commissioning of all systems, and in tandem with the installation of instrumentation and data acquisition equipment, a series of one-time, on-site measurements and field experiments were performed in the two apartments. A powered flow hood was used to perform a series of airflow measurements at the return registers and outlet diffusers for each ducted system, in heating, cooling, and fan-only mode. Since airflow measurements at inlet and outlet registers do not account for air leaks into and out of ducted distribution systems, CO_2 tracer gas airflow measurements were used to accurately determine the airflow rate across the indoor coil in each operating mode. These one-time airflow rate measurements were mapped to the continuous measurement of air velocity in the supply plenum to allow for continuous assessment of the airflow rate across the indoor coil, and for subsequent assessment of heating and cooling rates, and system COP. Calibrated duct leakage test equipment was also used to assess air leakage in each duct system. This involved pressurization and depressurization tests across a range of pressures to estimate the amount of leakage at normal operating pressures.

Table 3. Example airflow measurements for MFHP in fan only mode for Apts-1 and -2

	Air Handler (tracer gas) [CFM]	Return inlet (flow hood) [CFM]	Laundry Exhaust Fan [CFM]	Bathroom Exhaust Fan [CFM]
Apt-1	1084	954	88	93
Apt-2	984	894	65	84

Calculated metrics

After monitoring setup, the data analytics platform was programmed to calculate several performance metrics in real time, including:

- Air-side sensible cooling/heating rate [kBtu/hr]
$$Q'_{sensible} = m'_{supply\ air} \cdot c_{p\ air} \cdot (T_{return\ air} - T_{supply\ air})$$
- Air-side total cooling/heating rate [kBtu/hr]
$$Q'_{total} = m'_{supply\ air} \cdot (h_{return\ air} - h_{supply\ air})$$
- Coefficient of Performance (COP) for space heating/cooling
$$COP_{space\ heat/cool} = \frac{Q'_{total}}{W'}$$
- Coefficient of Performance (COP) for water heating
$$COP_{DHW} = \frac{Q_{DHW}}{W_{DHW}}$$

Results and Discussion

Results presented in this section were derived from the system performance monitoring described above, and from assessment of electric utility meter data, which was used to compare pre-retrofit and post-retrofit energy consumption. Unfortunately, technical issues maintaining reliable Modbus communication between the data acquisition system, several meters, and the MFHP prohibited assessment of equipment level electricity use and DHW consumption during the 2023-2024 heating season, so the results presented in the paper provide only a partial view of equipment performance. Also, during the first several months of operation, the team encountered and addressed several technical challenges with MFHP operation and performance. As of May 2024, all challenges with the Modbus communications were resolved, and the equipment was performing reliably.

Data from the electric utility meters was used to compare the total apartment gross energy consumption in each apartment for the pre-retrofit and post-retrofit periods, fall through spring months of 2022-2023 and 2023-2024 respectively. The utility data was not weather-adjusted due to correlation issues with one of the apartments datasets. Apt-2 has one more months-worth of data due to its earlier installation date.

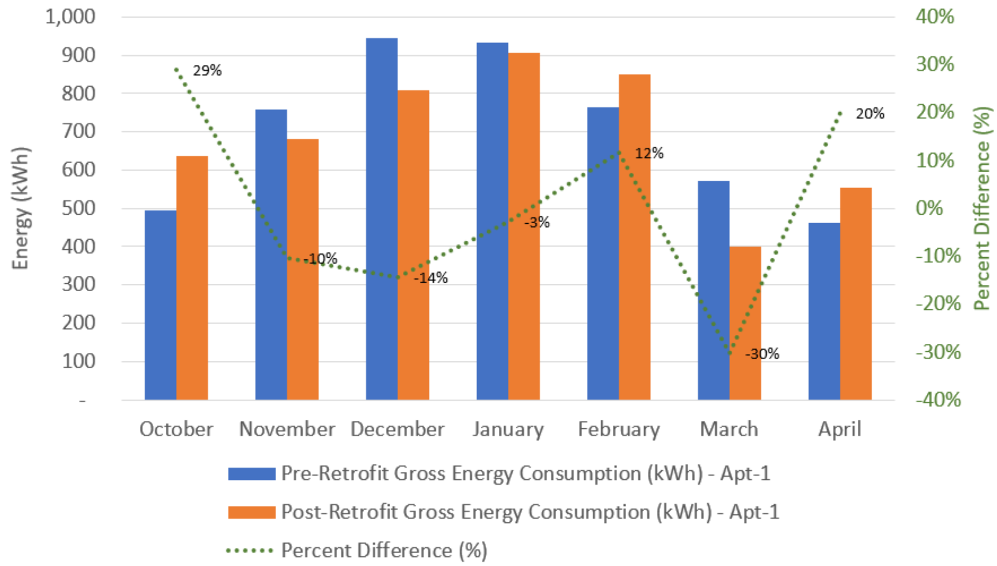

Figure 7. Comparison of actual pre-retrofit and post-retrofit energy consumption in Apt-1

The two apartments' electric energy consumption remained relatively consistent between the pre-retrofit period and the post-retrofit period, considering the electric energy consumption in Apt-1 was only 0.4% higher on average in the pre-retrofit period compared to post-retrofit and that in Apt-2 was 3.1% lower for the same time comparison. Weather and outdoor temperature are major factors affecting energy consumption, however. The post-retrofit monitoring period had 21% fewer total degree days with 24% fewer heating degree days, which likely resulted in a reduced HVAC load, specifically a lower heating load. It is also very difficult to know how differences in occupant behavior contribute to the differences in energy use between the pre- and post-retrofit periods; the utility data includes electricity use for the entire apartment, so any behavioral changes could contribute to the differences observed. The reasons and their relative impact for the differences in pre- versus post-retrofit energy consumption are unconfirmed and still under investigation. For example, it is not yet clear how the technical issues with the demonstration MFHPs, as described in more detail later on, have impacted energy consumption. As of April 2024, all monitoring for equipment-level electric power and thermal energy is online, which will allow continued work to assess COP for the MFHP in each operating mode and across a range of weather conditions.

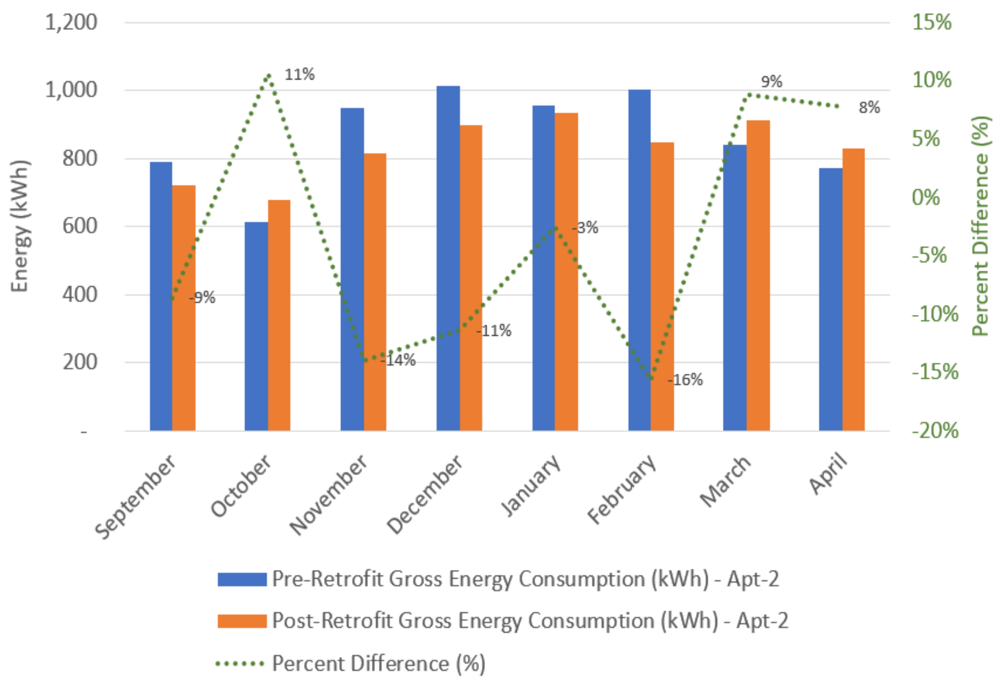

Figure 8. Comparison of actual pre-retrofit and post-retrofit energy consumption in Apt-2

Below are time-series analysis, space heating capacity, and COP characteristics for both apartments. The thermostats are in the hallways and two IAQ sensors (in the living room and master bedroom) also record temperature. Time-series of Apt-1 space heating are shown in Figure 9. The shaded region highlights the time when space heating was provided by the MFHP. As shown, during a space heating cycle, the thermostat temperature changes much less than the temperature in the living room or the bedroom. For example, the living room temperature increased by 3°F and the master bedroom temperature increased by 4.2°F, during the 40-minute space heating time period. The right y-axis shows the outdoor temperature, which was about 45°F during the space heating call.

The water heating and defrost mode response of the MFHP in Apt-2 is shown in Figure 10. The figure shows the DHW tank refrigerant pressures, refrigerant suction pressure, water temperatures at the top and bottom of the tank, and delivered DHW temperature downstream of the thermostatic mixing valve. The refrigerant pressures are used to discern the water heating and defrost modes. As shown, during the WH mode, the refrigerant liquid and vapor line pressures increase, suction pressure decreases, heat is transferred to the DHW tank, and subsequently, the water temperature in the tank rises. In the DEF mode, the refrigerant liquid and vapor pressures at the inlet and outlet of the water tank are equal to the suction pressure, indicating the DHW refrigerant coil is acting as the evaporator. Furthermore, the bottom tank temperature drops, indicating heat is extracted from the tank to defrost the outdoor coil. This unique defrost mode leads to a very quick defrost cycle (2-3 min) and does not require any heat extraction from the air handler or the indoor environment. Measurement of the DHW temperature downstream of the post mixing valve provides some indication of DHW draw events.

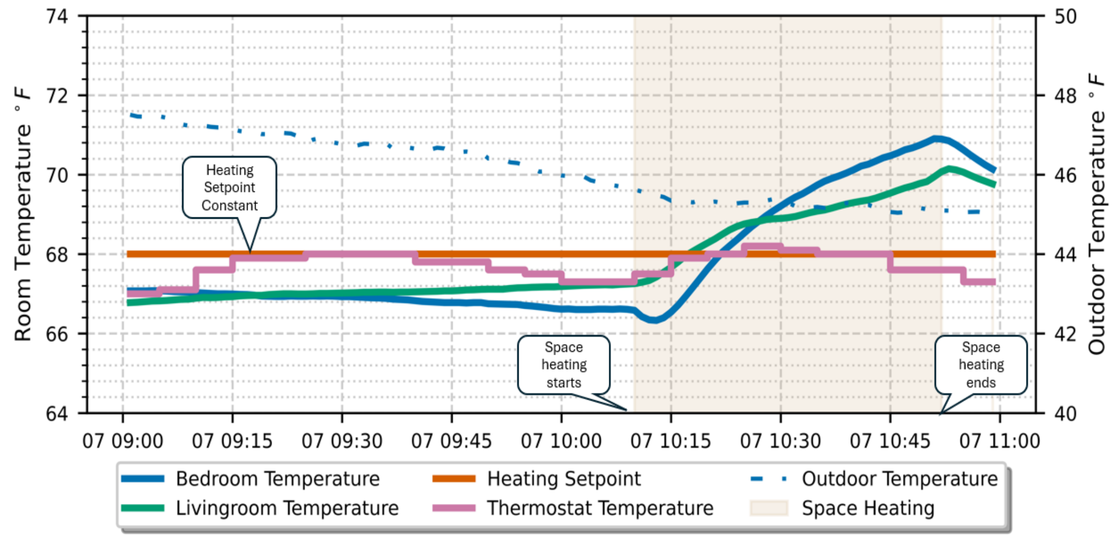

Figure 9. Example of time-series data for space heating in Apt-1 in winter

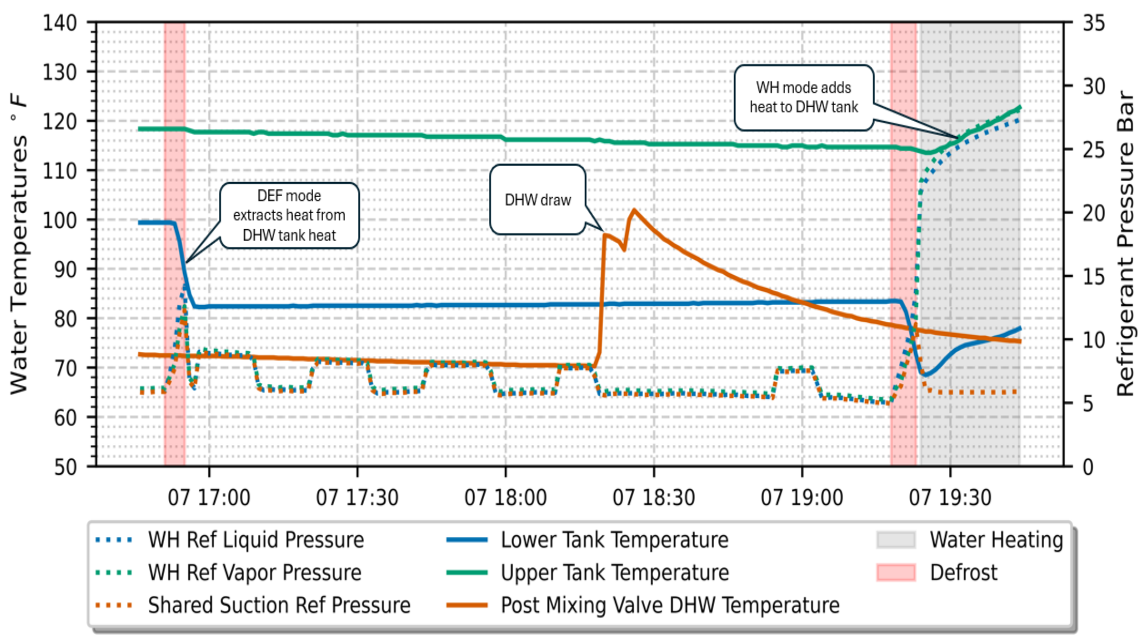

Figure 10. Water heating and defrost time-series graph for Apt-2

Figures 11 and 12 show the space heating (SH) capacities (left y-axis, red) and COP (right y-axis, blue) for each apartment as a function of the outdoor dry bulb temperature. The capacities and COP are calculated based on supply and return air conditions, from January to April 2024. Each red circle or blue triangle corresponds to a data point with one minute duration. Due to the Modbus communication issues, power measurement of the units started later in the winter season, which resulted in a smaller subset of SH COP data points (blue triangles) compared to SH capacity data points (red circles).

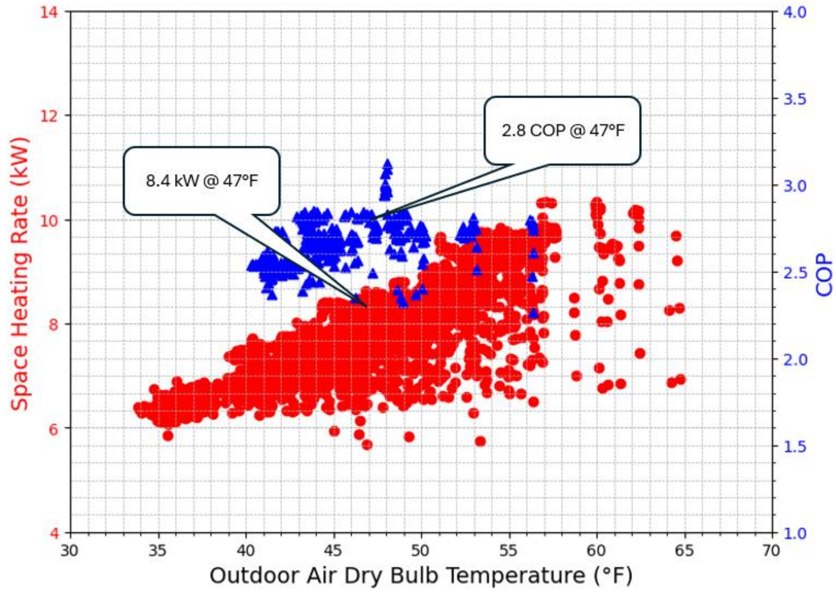

Figure 11. Apt-1 MFHP space heating rate (red) and COP (blue) with respect to outdoor dry bulb temperature.

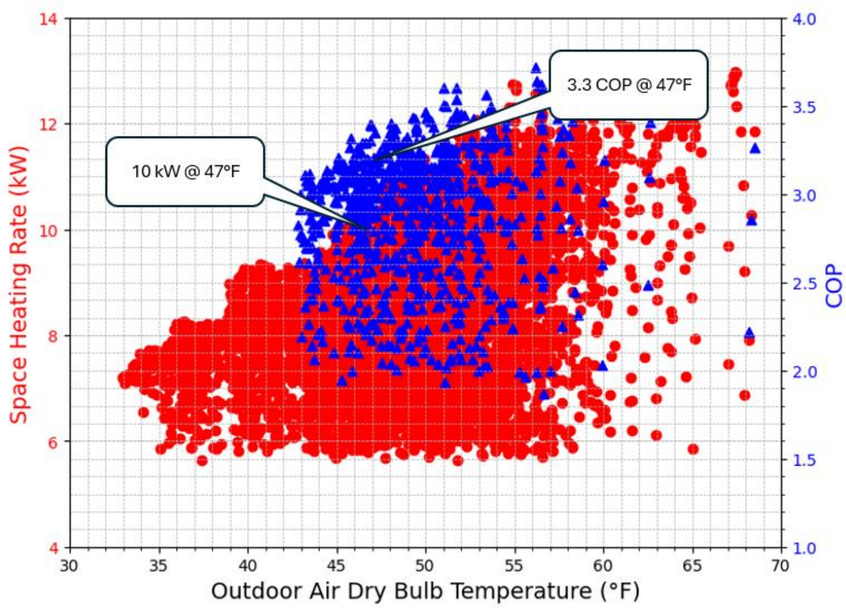

Figure 12. Apt-2 MFHP space heating rate (red) and COP (blue) with respect to outdoor dry bulb temperature.

The MFHP in Apt-1 shows lower heating capacity (8.4kW) than that in Apt-2 (10kW) at the 47°F rating condition. Since both MFHPs are the same model with the same rated capacity, this difference is likely due to suboptimal installation and commissioning of the unit in Apt-1. As of May 2024, further investigation is underway to understand and resolve the lower capacity observed for Apt-1. Possible explanations include lower refrigerant charge, refrigerant leaks, and improper tuning of the thermostatic expansion valves.

The Apt-1 MFHP is also seen to operate in SH mode less frequently than that in Apt-2 for the winter months. Additionally, the MFHP in Apt-2 is seen to have low to high SH capacity and COP for every outdoor temperature, which can be attributed to the frequent cycling of the compressor. Low capacity and SH data points for a given outdoor temperature are immediately after a compressor start during system transient operation. Since the Apt-1 system had a lower capacity, the compressor had lower cycling frequency and operated in a SH or WH mode for a longer duration to achieve the desired setpoint.

The two MFHPs installed had mixed success, with respect to reliability. For example, the Aquastat in Apt-2 failed the same evening the contactors concluded installation, necessitating an emergency replacement the next day to ensure the residents would have DHW. Since then, the Aquastat for Apt-2 has been replaced several times due to various issues, including corrosion, software complications, and unexplained failures. A number of complications with the software have also been identified, as well as functionality issues attributed to the control board that manages equipment operations. Consequently, the control board for both MFHP systems has been replaced several times. Other issues encountered have less certain explanations, and appear to have been addressed through ongoing controller updates, but it is not yet clear whether these changes have completely resolved the issues. For example, following a remote firmware update in March 2024, the MFHP in Apt-2 got stuck in WH mode for several days, during which time refrigerant vapor temperatures rose above 227°F, DHW tank temperatures rose above 207°F, and delivered DHW temperatures exceeded the safe operating range for the thermostatic mixing valve. Firmware updates following the event appeared to resolve the problem, but the root cause for this runaway WH event was never identified. As an emergency safety precaution, hard-wired high temperature cutoff switches were installed in the tank to disable the system if water temperatures are too high. In April of 2024, this emergency cutoff switch disabled the MFHP in Apt-2 on at least three separate occasions. On one such occasion, it was determined the switch had failed completely, so it was replaced. At the time of this publication, it appears the issue has been resolved – following several diagnostic visits and software revisions – and the system in Apt-2 has operated reliably for over a month. Notably, the MFHP in Apt-1 has not experienced the same runaway water heating issue, but all updates to the board and software have been deployed for the equipment in both apartments, for general system development.

Despite continued investigation into performance differences, and ongoing troubleshooting to address reliability and safety concerns, the two MFHPs have delivered sufficient heating, cooling, and hot water for several months, with only a few short periods of compromised functionality. The extended team of collaborators involved with this project – including the research team, manufacturer, controls contractor, installers, property manager, and residents – has been exceedingly cooperative and diligent in supporting the development and test of the MFHP technology. The detailed system monitoring and internet-connected data analytics platform deployed for this project has also been critical in facilitating preemptive solution management, rapid problem identification, remote diagnostics, and strategic coordinated response when issues arise.

Conclusions

This study evaluates a split, centrally-ducted air-source MFHP that provides heating, cooling, and DHW for residential applications. The MFHP was installed as a retrofit in two single-floor apartments near Merced, CA. This paper describes the system design, its functions, and its potential advantages compared to typical HPs and HPWHs. Then, it describes the design and deployment of a monitoring system to evaluate system performance, and discusses the installation process and challenges encountered. Installation of the MFHP system revealed clear advantages compared to installation of typical HP and HPWH strategies – especially with regards to equipment consolidation and reduced electric circuit upgrade requirements. Installation of the system encountered several challenges related to planning, coordination, and sequencing; however, we expect these challenges can be overcome for future installations through practice and strategic process management. A thorough suite of instrumentation was deployed with real-time remote monitoring capability that has provided exceptional insight into ongoing system performance, and has enabled rapid diagnostics and allowed the team to address problems preemptively. Unfortunately, challenges establishing reliable Modbus communications left several large gaps in data collected for the 2023-2024 heating season, but these issues have since been resolved. Analysis is conducted on an ongoing basis to understand energy consumption and performance – specifically, ongoing data analysis will reveal COP characteristics for the MFHP system in each operating mode, and with respect to outdoor temperatures. Analysis of the space heating capacity and COP for the MFHP systems reveals significant differences between the two, especially with Apt-1 system showing lower performance. There are also reliability issues with the control board and Aquastat which disrupted the proper function of the system in Apt-2. All these indicate there is need for continued investigation to understand the issues and resolve problems with the equipment and controls to achieve the highest possible performance.

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