Field Evaluation of Affordable Low Global Warming Potential Residential Heat Pumps

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ABSTRACT

Electrification of space heating is considered one of the first steps toward a broader goal of decarbonizing the U.S. building stock. Heat pump technologies provide greater heating efficiency than gas furnaces while also emitting less greenhouse gas. Beginning in 2025, residential unitary heat pump systems in California must utilize a refrigerant with lower global warming potential (GWP) than what is commonly used today. This presents a new challenge for manufacturers and installers as heat pump installations scale up.

This paper describes the results from a project funded by the California Energy Commission Electric Program Investment Charge (EPIC) program aimed at developing and demonstrating affordable and efficient low-GWP heat pumps. Demonstrations of a new heat pump technology developed by Rheem Manufacturing were performed in 10 homes in California. The new heat pump technology combines a novel compressor drive that allows variable speed operation using lower cost components and utilizes R-454B refrigerant that meets the upcoming California Air Resources Board (CARB) requirement on GWP. These developments are critical for creating a heat pump market for the future that is competitive with gas furnaces on both equipment and operating costs. Results showed an increase in utility costs for many sites; however, the greenhouse gas emissions were reduced by 44-98% for the heat pump systems relative to the natural gas heating systems replaced in the project showing significant progress toward decarbonization. This paper also documents the contractor experience during the retrofit process which includes the handling of the new refrigerant, and the tenant experience with the new heat pump technology.

Introduction

Next-generation heat pump technologies have the potential to significantly reduce greenhouse gas emissions from buildings in the U.S. According to the U.S. Energy Information Administration, only 14% of homes in the Western U.S. use a heat pump as their main source of heating (EIA 2020). While heat pumps have been on the market for decades, the initial capital cost and operating costs of heat pumps have not been competitive with traditional natural gas furnace solutions. In order to meet California's aggressive energy and carbon goals, it will be necessary to find low-cost solutions for switching the primary fuel for heating buildings from natural gas to electricity, while also improving the heating and cooling efficiency of heat pumps.

This paper outlines the results from a project aimed at demonstrating a next-generation ducted air-source heat pump technology for achieving high-efficiency heating and cooling at a lower cost relative to similar performing equipment. The equipment demonstrated features an innovative, cost-effective compressor drive that offers the advantages of a variable capacity system using lower-cost components, thereby reducing installation costs relative to competing technologies. Additionally, this system was designed to accommodate a low-GWP (R-454B) refrigerant to comply with upcoming CARB regulations, which will mandate that refrigerants used in all new stationary residential air conditioning systems have a 100-year GWP value of 750 or less starting in 2025. The heat pump technology was installed in 10 homes in California to evaluate its performance. Surveys of participants and contractors were conducted to identify market barriers to the adoption of the heat pump technology, including considerations related to the mildly flammable refrigerant.

Background

Motivation

California is moving aggressively to electrify all energy sectors with a goal of being carbon-neutral by 2045. For the California buildings stock, the state is taking a stepwise approach requiring zero-net energy (ZNE) construction for new residential homes by 2020 followed by new commercial buildings by 2030 (CPUC 2011). Additionally, there is a target to retrofit 50% of the commercial building stock to meet ZNE standards by 2030. Decarbonizing heating in buildings will require replacing gas end-uses with electric alternatives including heat pumps for space conditioning and domestic hot water.

Heat pumps achieve much greater efficiencies than gas furnaces; however, this does not always translate to utility bill savings for the customer because of the misalignment between the relative cost of heating fuels and carbon goals. Evaluating the operating cost of a heat pump relative to a gas furnace is not straightforward for multiple reasons. The working principle of a heat pump results in performance changes as temperature conditions outside change. In addition, heat pumps often rely on auxiliary electric resistance heaters when conditions are very cold, for defrost operations, or when demand for heat is high, changing their performance characteristics. Lastly, time-of-use electricity rates are becoming more common and impact the cost-effectiveness of operating a heat pump.

The project team estimates that, based on electricity and gas rates in 2020, a heat pump must achieve an efficiency rating higher than the minimum required by the Department of Energy in order to achieve a lower operating cost compared to a minimum efficiency furnace in many California climate zones. Advancing heat pump adoption in California through a market-based approach requires the development of technology that is cost-competitive with gas furnaces in both upfront capital and operating costs.

Another significant motivator for this project is the recent regulation by CARB, which mandates that all new stationary air conditioning equipment must utilize a refrigerant with a GWP of less than 750 starting in 2025 (CARB 2019). The commonly used refrigerant today, R-410A has a GWP of 2,088. The new refrigerant mandate will require changes to the design of equipment which must be considered when developing new heat pump equipment for California, and the U.S. broadly due to similarly aligned regulations by the Environmental Protection Agency.

Project Approach

The primary goal of this project is to develop and demonstrate a heat pump technology that achieves higher efficiency at a lower cost relative to other high-efficiency systems, while also using a refrigerant that complies with the upcoming CARB regulations. The development phase involved rigorous laboratory testing of the equipment to verify the heating and cooling capacities and power consumption under various operating conditions. Following the laboratory tests, 10 field sites in California were selected for demonstrating the real-world performance of the new heat pump technology. This effort included both baseline monitoring of the existing equipment and post-retrofit monitoring after the installation of the new heat pumps. To gain comprehensive insights, participant surveys were conducted to gather feedback on their experience with the installation and operation of the new equipment. Additionally, installation contractors were interviewed to understand any changes in installation procedures, particularly regarding the handling of the new refrigerant, R-454B, which, like many low-GWP refrigerants, is classified as an A2L (mildly flammable) fluid.

This thorough approach ensured that the new heat pump technology was tested not only in controlled laboratory conditions but also in diverse real-world scenarios, providing a holistic understanding of its performance, user satisfaction, and any potential market barriers related to adoption.

Technology Description

The next-generation heat pump developed for this project is designed as a standard split-system air-source heat pump. The indoor unit consists of a variable-speed blower paired with a heat pump refrigerant coil. Depending on the application, the indoor unit would also contain an electric resistance backup heater for maintaining comfort during defrost and providing additional capacity at low ambient temperature conditions. The outdoor unit consists of the variable-speed compressor, refrigerant coil, and fan.

Heat pumps resemble standard air conditioning units but have a refrigerant reversing valve which allows the refrigerant to flow in either direction. This effectively allows the evaporator and condenser to switch roles depending on whether the building is in need of heating or cooling. Space heating requirements are therefore satisfied using electricity without the need for fossil fuels. A major advantage of providing heat through the use of a refrigerant cycle is that the coefficient of performance (COP) can be greater than 1 meaning more heat is produced per unit of energy consumed by the system. This allows heat pumps to operate much more efficiently than gas furnaces or electric resistance heaters since those systems have a maximum possible COP of 1.

Standard efficiency heat pumps on the market today utilize fixed-speed compressors designed to operate on single-phase power, typically driven by Permanent Split Capacitor (PSC) motors (Goetzler, Sutherland, and Reis 2013). The novel compressor drive utilized in the heat pump developed for this project is a low-power inverter that operates the PSC motor at reduced speeds, similar to a variable-speed compressor driven by a brushless permanent magnet motor. Reduction in energy usage is primarily expected from the variable speed operation due to the ability of the system to modulate capacity to match the cooling/heating demand, without the need for cycling. Reducing the speed of the compressor and associated refrigerant flow also allow the heat exchanger coils to become more effective leading to higher efficiency.

The compressor drive is disabled during full-load operation; specifically, the compressor motor runs on supply power without intervention from the inverter. Thus, the full-load efficiency of the system remains unchanged. At lower operating speeds, the efficiency of the combination of the novel compressor drive, PSC motor, and compressor is lower than that of the combination of an electronic inverter drive, brushless permanent magnet motor, and compressor. Hence, the proposed technology has a lower efficiency than a conventional variable speed system but higher efficiency than a fixed-speed system. The cost of the PSC motor is less than that of a brushless permanent magnet motor. Since the novel compressor drive is only engaged during part-load operation, the components in the inverter drive are sized only for low-power operation. This strategy helps to keep the cost of the proposed technology lower than a conventional variable-speed heat pump system.

Field Demonstration

The field demonstrations aimed to provide a comprehensive technical evaluation of retrofitting existing HVAC systems with the next-generation heat pump in real-world scenarios. Ten detached single-family homes, constructed between 1976 and 2006, were selected for this study. The conditioned areas of these homes ranged from just over 1,000 to 2,600 square feet. These homes are situated in two California climate zones, specifically CZ02 (Santa Rosa, CA) and CZ12 (Sacramento, CA).[1]

Among the selected homes, eight utilized residential split air conditioning (AC) units for cooling, one home in CZ02 lacked cooling, and one in CZ12 already employed a heat pump. All but one of these homes utilized a natural gas furnace for heating. The cooling capacities of the existing AC units varied from 2 to 5 cooling tons (24 to 60 kBtu/yr), and the outputs of the gas furnaces ranged from 36 to 96 kBtu/hr. The retrofit heat pumps selected for this study had cooling capacities similar to the existing AC units.

To determine the appropriate capacities for the retrofit heat pumps, the research team conducted ANSI/ACCA Manual J load calculations for four of the homes. Additionally, all heat pumps included a 5-kW supplemental heater kit, except for one home in CZ12, where the existing panel capacity was insufficient to accommodate it. Table 1 provides a summary of the test site information and retrofit systems.

Table 1. Summary of Demonstration Sites and Retrofit Heat Pumps

Site	Climate Zone	Year Built	Conditioned area (ft^2)	Existing System	Retrofit Heat Pump
1	02	1993	1,100	Single zone split AC w/natural gas furnace AC: 2-Ton, 10 SEER Furnace: output 58,000 Btuh , AFUE 80%	3-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
2	02	1976	2,007	Single zone two-stage natural gas No cooling Furnace: output 97,000 Btuh , AFUE 90%	2-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
3	02	1996	1,400	Single zone split AC w/natural gas furnace AC: 3-Ton, 10 SEER Furnace: output 56,000 Btuh , AFUE 80%	3-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
4	12	2005	2,652	Two zone system AC (Natural gas furnace AC: 4-Ton, 10 SEER Furnace: output 68,000 Btuh AFUE 80%	4-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)

[1] The city selected in Climate Zone 02 has a 0.5% dry bulb cooling design temperature at 96°F, and cooling degree days of 456, the Winter Median of Extreme at 24°F and heating degree days of 2,980. The city selected in Climate Zone 12 has a 0.5% dry bulb cooling design temperature at 100°F, and cooling degree days of 1,470, the Winter Median of Extreme at 21°F and a heating degree days of 2,653.

5	12	1985	1,036	Single zone split 2-Ton heat pump with 5 kW supplementary heater kit, efficiency unknown	2-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
6	12	2004	1,588	Single zone split AC w/natural gas furnace AC: 3-Ton, efficiency unknown Furnace: output 40,000 Btuh AFUE 80%	3-Ton with no supplementary heater kit (16 SEER2, 8.1 HSPF2)
7	12	2003	1,801	Single zone split AC w/natural gas furnace AC: 4-Ton SEER 13 Furnace: output 71,000 Btuh	4-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
8	12	2006	2,121	Two zone split AC w/natural gas furnace AC 3-Ton, SEER 13 Furnace: output 68,000 Btuh AFUE 80%	3-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
9	12	2003	1,857	Single zone split AC w/natural gas furnace AC: 3.5-Ton, SEER 13 Furnace: output 71,000 Btuh AFUE 80%	4-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)
10	12	1990	2,336	Single zone split AC w/natural gas furnace AC: 5-Ton, 10 SEER Furnace: output 80,000 Btuh	5-Ton with 5 kW supplementary heater kit (16 SEER2, 8.1 HSPF2)

Measurement and Verification Method

Field Data Collection. The research team implemented a comprehensive monitoring system to gather data continuously over a period exceeding two years, from August 2021 to May 2024. One year into the data collection process, the installation of the next-generation heat pump marked the division of data into pre- and post-retrofit monitoring periods. Throughout the entire metering period, the following real-time data were collected at one-minute intervals, meticulously stored, verified, and analyzed at each of the ten sites. The collected data included:

- HVAC natural gas consumption (limited to the baseline period)
- HVAC electricity usage (fan, compressor and auxiliary use)
- HVAC air flow differential pressure (DP)
- Zone temperature and relative humidity
- HVAC supply and return temperature and relative humidity
- Outdoor air temperature and relative humidity

Moreover, the research team documented the HVAC air flow rate as a function of power and DP, which were used to determine cooling and heating outputs. Subsequently, the measured data were utilized to calculate annual energy consumption and to characterize both equipment efficiency and thermal comfort conditions.

HVAC Energy Use. The research team used International Performance Measurement and Verification Protocol (IPMVP) Option B (retrofit isolation with all parameter measurement) to quantify normalized annual HVAC energy use for the baseline and retrofit systems. Annual energy use was calculated using daily energy consumption data before and after the retrofit. The hourly energy use data were then input into a change-point regression model using the time-of-week-and-temperature (TOWT) regression method for each site. This model was selected to account for variations in energy use as heating and cooling systems are engaged. The developed models were subsequently applied to typical meteorological year weather files, normalizing the measured energy use to consistent weather conditions. The normalized energy use was then computed for the entire year, separately for the heating and cooling operation periods.

The comparative analysis also included an evaluation of the HVAC equipment efficiency. For both the existing AC units and the next-generation heat pumps, the coefficient of performance (COP) was characterized using measured cooling load, heating load, and electrical input data. The intent of the analysis was to validate the field performance of the next-generation heat pumps, acknowledging that field installation conditions differ significantly from laboratory conditions.

Utility Cost. The utility cost analysis sought to quantify the financial implications of the retrofit across the residential properties. Following the guidelines outlined in California Public Utilities Commission (CPUC) policy (CPUC D.15-07-001), the three major investor-owned utilities (IOUs) in California transitioned their customers to a default Time-of-Use (TOU) schedule in 2019. For this study, the research team scrutinized the energy costs associated with the post-retrofit system, as well as the calculated baseline for all homes, utilizing the PG&E TOU-C rate (PG&E 2024), as outlined in Table 2 below. Note that a baseline credit of $0.1073 is applied to baseline use.

Under the TOU rate plans, the utility imposes a fixed price per kWh based on both the time of day and the time of year. Notably, late afternoon and evening periods are subjected to higher rates compared to other times of the day, with summer season rates surpassing those of the winter season. To compute the baseline gas energy cost, the baseline allocation for each home was determined and the Tier 1 rate ($2.15 per therm) for usage was applied.

Subsequently, we applied the applicable rate to the normalized energy consumption for both pre- and post-retrofit systems to calculate costs, which were then summarized annually, including a breakdown for heating and cooling expenses.

Table 2. Electricity rate for PG&E TOU-C

Electricity ($/kWh)	Peak (4 p.m. to 9 p.m.)	Off Peak
Summer (June - Sept.)	0.63	0.54
Winter (Oct. - May)	0.52	0.49

Note: Baseline credit of $0.1073 is applied

Environmental Impact. The environmental impact assessment focused on quantifying the reduction in GHG emissions by leveraging the hourly GHG emission factors published by California Energy Commission (CEC 2022). These factors estimate the environmental benefits of transitioning to electric heat pump systems for residential space heating by converting predicted site energy ise to long-run marginal GHG emissions. The hourly factors vary by location, time of day, and season. For this analysis, the average grid GHG electricity emission factor was 0.1988 lb CO2e /kWh, and the average natural gas GHG emission factor was 13.29 lb

CO2e/therms. These multipliers were applied to the annualized gas and electricity use in both the pre-retrofit and post-retrofit scenarios to determine the differences in GHG emissions.

Preliminary Assessment Results

Measured HVAC Operation. The research team conducted an assessment of HVAC energy utilization for both pre- and post-retrofit periods. In the context of this paper, winter spans from December to February, while summer encompasses July to September.

Figure 1 depicts the hourly electricity and natural gas usage of the HVAC system, presenting a simultaneous comparison between the pre- and post-retrofit monitoring periods for a residence located in CZ12 (Site 7). The graph includes a line representing a 10-day rolling average of the data. During the cooling season of pre-retrofit systems, the HVAC system's electrical consumption predominantly stems from the operation of the air conditioner and fan. Conversely, in the heating season, the electrical usage primarily comprises the supply fan alone, which closely aligns with the natural gas consumption of the furnace. In contrast, post-retrofit systems exclusively utilize electricity, employed by the heat pumps for both cooling and heating purposes. It is noteworthy that there were instances of missing gas usage data for December during the pre-retrofit period, underscoring the significance of utilizing normalized energy data for direct comparison.

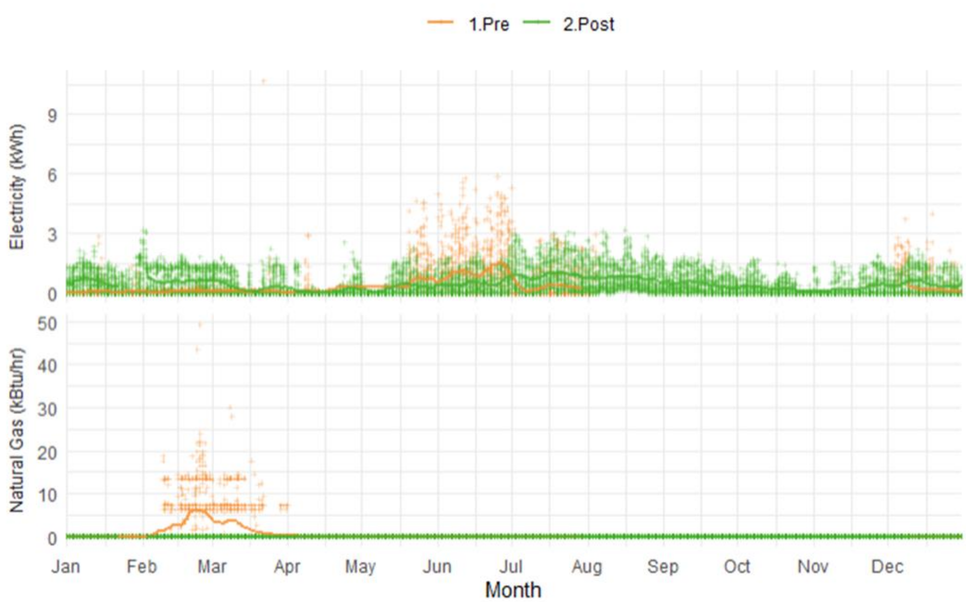

Figure 1. Measured Hourly HVAC Energy Use - Site 7

To compare the heating operation of the existing furnace with the retrofit heat pump, we analyzed the hourly profiles of electricity and natural gas usage before and after the retrofit. For instance, Figure 2 illustrates boxplots[2] depicting the energy use profiles during the winter

2 The lower and upper limits of each box in the boxplot represent the 25th and 75th quartiles, and the middle of the box is the median. The thin vertical lines, or "whiskers," show the range of temperatures from minimum to maximum, excluding outliers. Points were considered outliers if they were not within 1.5*IQR (inter-quartile range) from the lower and upper limits of the box, where the IQR is the distance between the 25th and 75th percentiles.

months for Site 7. Throughout most hours of the day, the heating equipment was active and operational. It is worth noting that the retrofit heat pump appeared to commence heating earlier in the morning compared to the furnace. However, this difference is likely influenced by the higher heating setpoint adopted during the post-retrofit period. Additionally, no operation of the electric heater kit in the retrofit heat pumps was observed.

Thermal comfort conditions before and after the retrofit at each site were assessed by comparing the measured zone temperature data. Although the retrofit heat pumps effectively maintained reasonable thermal comfort levels across all sites, changes in zone temperature distribution were observed during both summer and winter seasons at several demonstration sites. These changes are likely attributable to variations in occupant behavior, such as alterations in operating hours and thermostat adjustments for both cooling and heating. For Site 7, the variable-speed heat pump appeared to maintain the space temperature within a narrower range for both cooling and heating operations, as depicted in Figure 3. This finding aligns with the results of the occupant survey, wherein more than half of the respondents (n=7) indicated that the new heat pump better maintained setpoints than the old system, while the remainder reported no discernible difference.

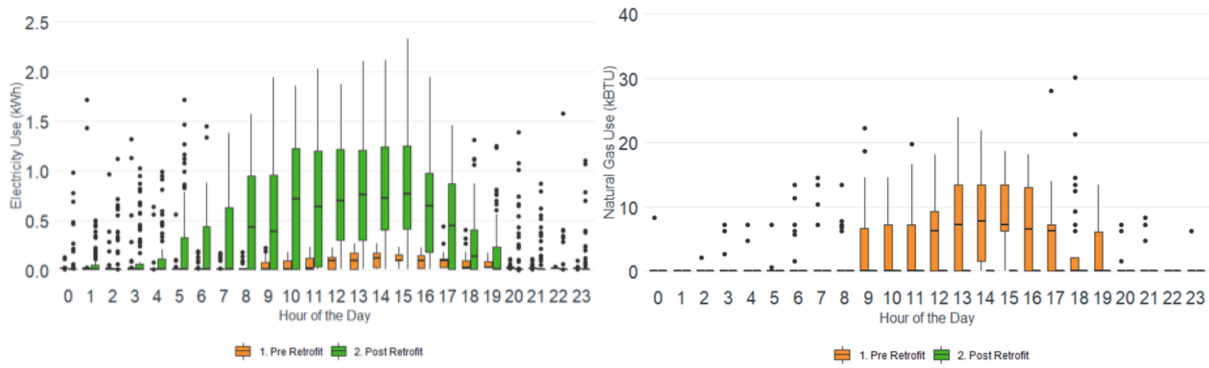

Figure 2. Boxplot of Measured HVAC Energy Use Hourly Profile during Winter - Site 7

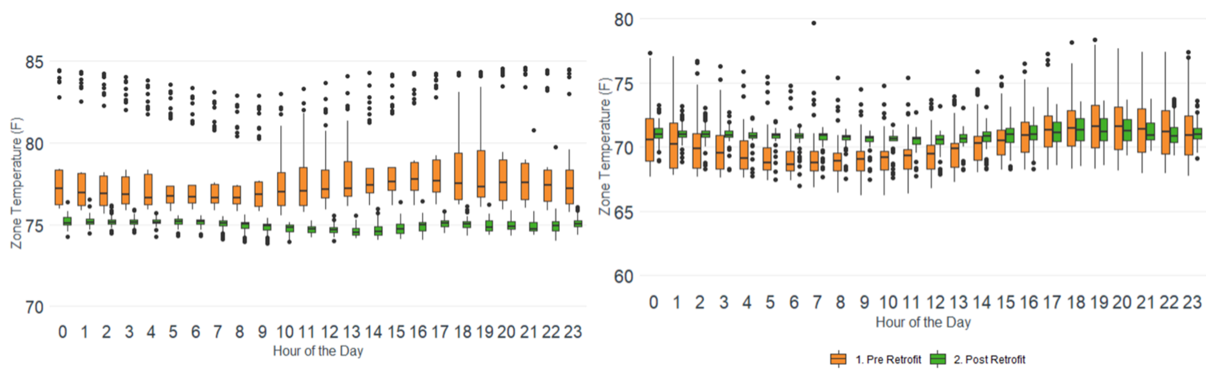

Figure 3. Boxplot of Measured Zone Temperature Daily Profile at Site 7: Summer (left) and Winter (right

To assess the energy efficiency of the heat pumps, our analysis concentrated on periods when the equipment was operating under steady-state conditions. During heating operation, we observed heating COPs ranging between 2 to 3 for most installations, particularly when outdoor air temperatures (OAT) fell within the range of 30 to 60°F. Conversely, for cooling, the retrofit heat pumps at most sites exhibited COPs ranging from 2 to 5. Figure 4 illustrates the HVAC efficiencies relative to outside air temperature for Site 7, serving as an illustrative example. The observed field performance aligns well with our anticipated expectations.

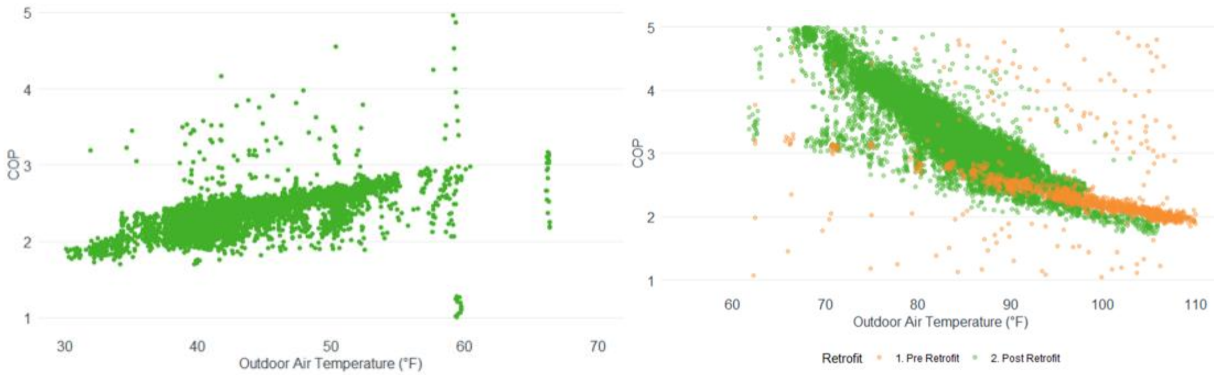

Figure 4. Example HVAC Efficiency: Next Generation HP heating COP (left) and Existing AC unit and Next Generation HP cooling COP (right) at Site 7

Normalized Energy Use

Annual HVAC energy usage varied significantly across sites due to factors such as occupant behavior, home vintage, and equipment efficiencies. Figures 5 and 6 present the annual electricity and gas usage density, normalized against TMY3 weather data, for both the existing and retrofit HVAC systems. It is evident that heating energy usage dominated for sites in CZ02 (sites 1 to 3), while the distribution between heating and cooling usage was more balanced for sites in CZ12 (4 to 10).

Upon comparing the pre- and post-retrofit periods, we observed electricity savings for cooling ranging from -41 percent to 68 percent across the sites. Although the heat pump systems demonstrated similar or higher efficiency compared to the old systems, the substantial variance in energy impacts among the homes can be attributed to occupant behavior. This includes changes in operating hours and thermostat adjustments, as reported in the Participant Survey.

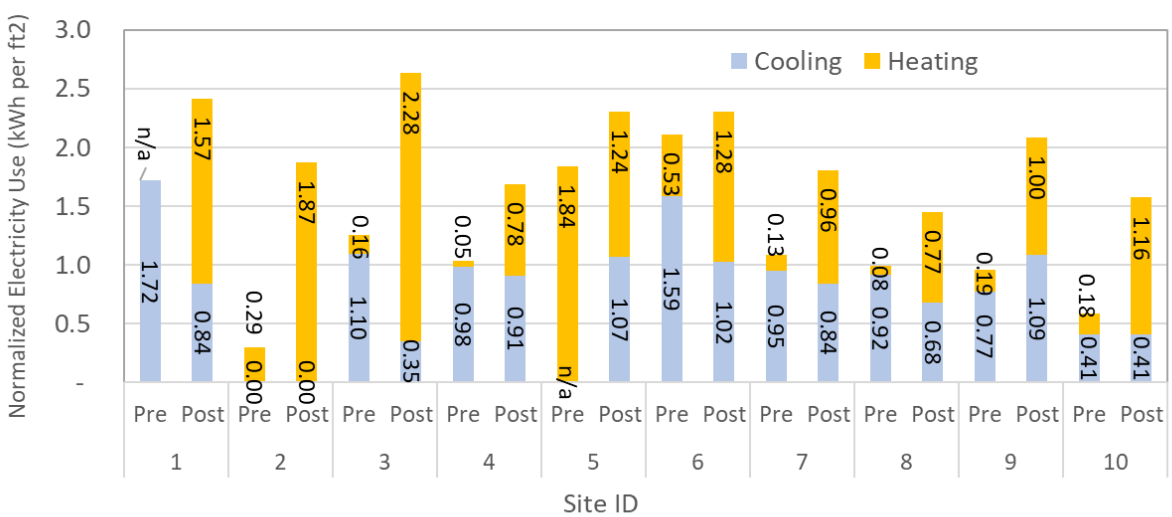

Figure 5. Normalized Annual Electricity Use Density for Pre- and Post-Retrofit Periods

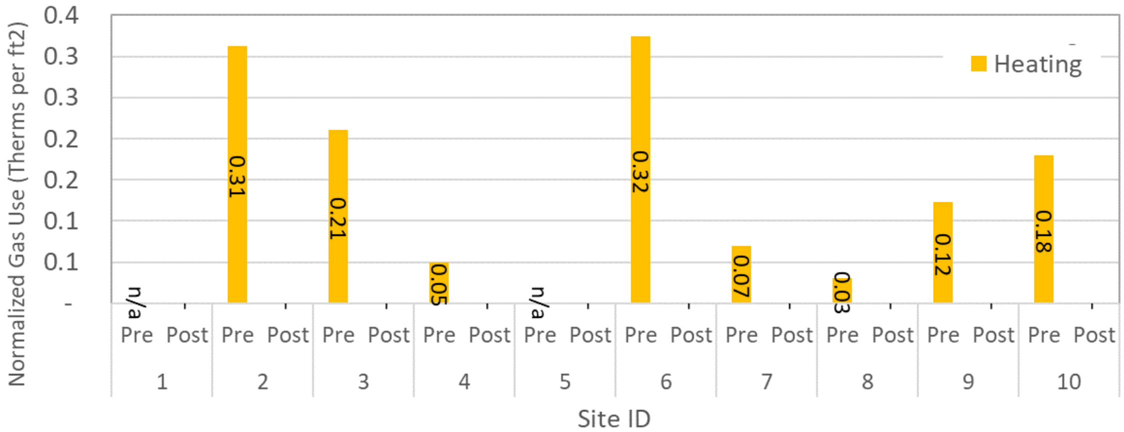

Figure 6. Normalized Annual Gas Use Density for Pre- and Post-Retrofit Periods

Utility Cost and Environmental Impact

Figure 7 illustrates the calculated annual costs for space heating and cooling in both the pre-retrofit gas scenario and the post-retrofit heat pump scenario. The percentage figures displayed atop the post-retrofit bar indicate the differences between the two scenarios, where a negative number signifies an increase in cost. The findings indicate that, based on the analyzed rate structure, operating the heat pump likely incurs higher costs compared to the baseline gas system. Specifically, there is an increase in energy costs ranging from 3 to 27 percent for 5 out of the 8 sites for which there is valid data. We observed 9 percent and 2 percent cost savings for Site 2 and 10 respectively. Site 6, which had a 46 percent cost savings, had a tenant switch during the monitoring period which could have impacted the result.

To put this in perspective, both gas and electricity rates and rate plans used in this analysis have experienced significant price increases. The average annual increase over a 15-year period has been 5.0% for gas and 7.2% for electricity, but in the past 5-year period the average annual increase has been much higher at 9.6% for gas and 13.8% for electricity. Based on an equivalent unit of energy delivered to a home, electricity was 7.3 times more expensive than gas with the 2024 rate, thus exceeding the cost savings potential of electric heat pumps over natural gas heaters even though they are 2 to 4 times more efficient from an efficiency perspective. If electricity prices continue to increase at a higher rate than gas prices, this will significantly impact California's electrification goals and reduce the pace of market transformation to electric heat pumps, especially in existing residential homes.

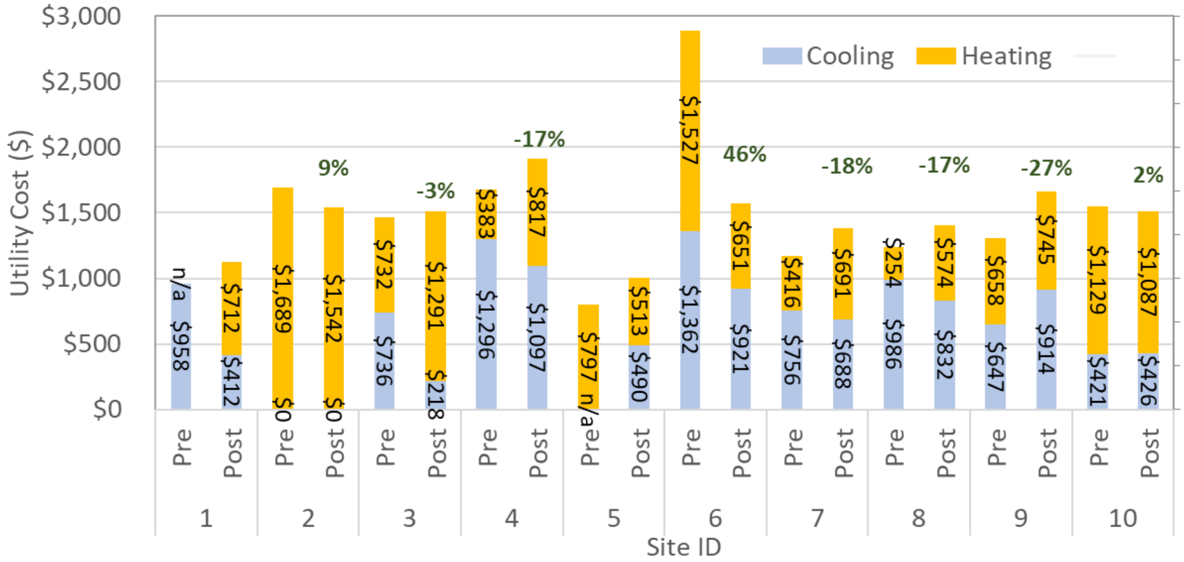

Figure 7. Annual Utility Costs for Pre- and Post-Retrofit System (reduction in cost shown as percentages atop post-retrofit result)

The California statewide grid hourly emissions factors, as provided by CEC exhibit variability throughout the day and across seasons. This variability reflects the GHG emissions associated with electricity and gas usage, which are expected to change over time as the state's grid transitions towards cleaner energy sources. For instance, during the winter months, average GHG emissions from electricity use may be 5-6 times higher than in months such as May or June, when demands are lower and renewable generation is more abundant.

The GHG emission impacts of the retrofit were found to align with this trend. Figure 8 illustrates that GHG savings ranged from 44 to 98 percent across the sites, with larger savings observed for sites in CZ02 compared to those in CZ12. This discrepancy can be attributed to the fact that heating constitutes a larger portion of energy demand than cooling in climate zone CZ02, as opposed to CZ12.

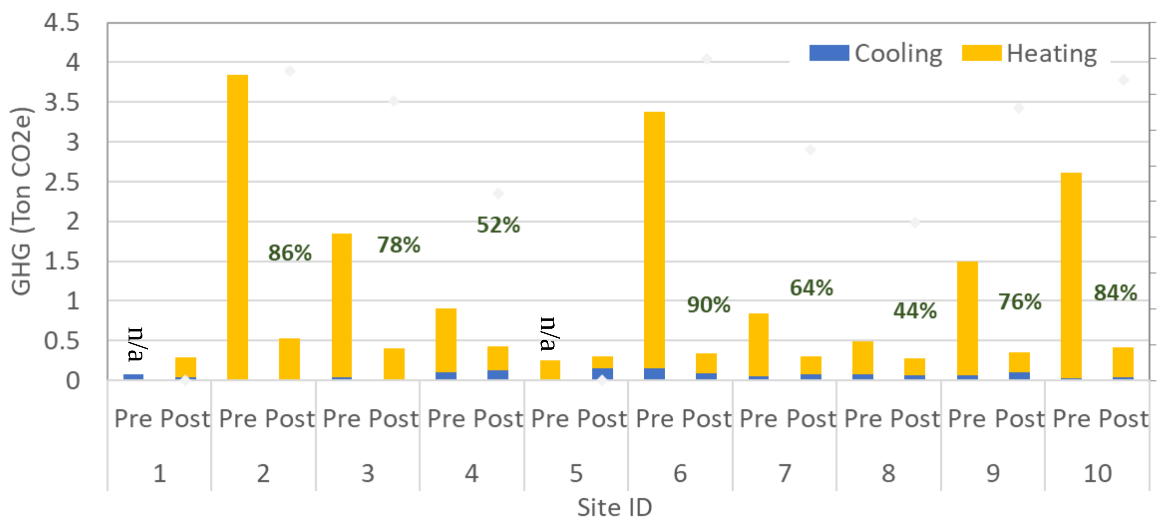

Figure 8. Annual GHG savings for Pre- and Post-Retrofit System (reduction in GHG shown as percentages atop post-retrofit result)

Discussion of Field Results

The field results generally validated the performance of the next-generation heat pumps in terms of both space cooling and heating functionality, as well as their energy efficiency, which was found to be comparable to that of other heat pumps on the market. Notably, at certain sites, we observed improved space temperature control attributable to the variable-speed capability of the new systems compared to the old single-stage systems.

During the cooling season, the COP for most installations exceeded 3 when outdoor air temperatures (OATs) were below 90°F. However, as OATs increased to 110°F, the COP dropped to 2. For heating, heat pump COPs ranged between 2 to 3 when OATs were between 30 to 60°F.

The assessment findings regarding energy usage, utility costs, and GHG emissions largely confirmed the anticipated impacts associated with replacing a split AC and gas furnace with a heat pump. With the analyzed rate structure, residents are likely to experience an increase in their utility bills. Moreover, regarding GHG emissions, the findings indicated a significantly positive impact showing reductions in GHG emissions in all cases with valid data.

Upon reviewing the space temperature profiles, variations in occupant behavior were observed, particularly concerning changes in HVAC operational hours and thermostat setpoints. For instance, some owners adjusted their heating setpoints lower, while others increased them during winter. Such behavioral changes can influence energy consumption patterns and should be considered in assessing the overall impact of the retrofit.

Market Assessment

One of the primary objectives of this project was to assess potential market barriers for low-GWP heat pumps installations. Surveys were conducted with both participants and installation contractors to document their experience with the installation and operation of the new heat pump systems. Nine of ten participants were replacing a natural gas furnace with a heat pump, and much of their feedback provided valuable insights into heat pump retrofits in general. While the focus of the project was on the installed R-454B heat pump, the feedback regarding the refrigerant used is generally applicable to other A2L refrigerants as well, such as R-32.

Participant Surveys

Surveys of the participants were conducted in the winter and summer during both baseline and retrofit periods. Most participants reported being comfortable with the temperatures delivered by the heat pumps in both summer and winter. However, there were mixed reports on the speed with which the desired setpoint was reached, with nearly half indicating that the system was “somewhat slow” to heat up in winter.

Five participants observed a decrease in electricity bills compared to the previous summer, while three noticed an increase. Those who reported an increase noted that the summer had been hotter than previous years, making it challenging to attribute changes in electricity bills solely to the heat pump. Additionally, electricity rate increases in one utility territory complicated pre- and post-retrofit bill comparisons. The perceived difference in heating costs varied widely: five participants noticed a decrease, three observed an increase, and two saw no difference. Comparisons of heating costs were complicated by the switch from gas to electricity in nine out of ten cases.

At no point during the project did participants convey any concerns about the flammability of the refrigerant used in the heat pumps. At the conclusion of the project, the experimental equipment will be replaced with (newly) commercially available heat pumps. Participants were given the option to elect between the same mildly flammable, low-GWP refrigerant used in the project (i.e., R-454B) or the current standard (i.e., R-410A, which is being phased out in January 2025).

Contractor Feedback

Two different contractors were used for the heat pump installations in this project. Both contractors noted that installing the heat pumps with R-454B refrigerant was not significantly different from installations with standard refrigerants. However, one contractor noted that installing R-454B refrigerant systems requires slightly more skill, effort, and time. As a precaution, the contractor kept a fire extinguisher nearby and ensured the area was clear of obstructions and flammable materials. Both contractors agreed that strict safety procedures must be followed to avoid problems when installing heat pumps with flammable refrigerants but acknowledged that there were no established procedures at the time of installation. At the time of installation, the manufacturer was still developing the guidelines for installing their R-454B heat pumps. Finalization of those guidelines will provide more clarity about what will be required to ensure safe installation and proper commissioning of their equipment.

Similarly, since heat pumps with R-454B refrigerant are not yet widely available, there is no standard requirement for installer training. Both installers had to identify appropriate resources to ensure their staff had the necessary knowledge and skills to install the heat pumps safely. One contractor did this by reviewing the information provided by the research team and the equipment's safety data sheets, reading about European installers' experiences working with the refrigerant, and watching YouTube videos about the refrigerant properties.

All participants were informed of the mild flammability of the refrigerant that would be used in the newly installed heat pumps during the consent process. None expressed concerns to either the researchers or the installers. In communicating with the participants, neither installer mentioned the refrigerant's flammability, feeling it would unnecessarily raise concerns.

Barriers to Adoption

The regulations that will govern low-GWP heat pump installations are currently uncertain. For example, safety protocols may need to be established. Due to increased flammability, A2L refrigerants may require special handling during transport, such as using compressed cylinder racks to hold the refrigerant on service vehicles. The Materials of Trade exceptions in the Code of Federal Regulations (49 CFR 173.6) exempt service vehicles transporting HVAC equipment from flammability signage requirements. Safety procedures related to installation also need to be developed, including whether standard "heat kits" used by HVAC contractors are adequate to mitigate the risk of fire.

On the technical side, R-454B cylinders currently require different adapters to connect to the gauge hoses. This small additional piece of equipment adds minimal cost and effort but no additional complication or risk. The installing contractors on this project expect that, eventually, the gauge hoses will be updated to connect directly to heat pumps with low-GWP A2L refrigerant.

Despite the special requirements noted above, neither installer on the project reported any problems or concerns about installing low-GWP heat pumps with an A2L refrigerant. One noted that the switch to low-GWP refrigerants is an inevitable part of the industry. They observed that the trade has been subject to many policy-driven changes over the last few decades, and the move to low-GWP refrigerants is no different from earlier changes. They expressed no concerns about the safety or customer appeal of A2L refrigerants and expect consumer demand to increase as the products become commercially available (and required by CARB and EPA regulations).

The biggest challenge the installers foresee in a widespread transition to low-GWP heat pumps is the ability to train HVAC installers at a pace that will keep up with the expected growth in demand. Training programs will need to be made widely available to ensure that new graduates and existing installers are able to obtain the needed training and certification. At this stage, it is unclear what installer training may be required, who will provide it, and how it will be funded. One option is to require certification for working with mildly flammable refrigerants. While this is arguably the best approach for ensuring safe installation, the added burden on HVAC installers could result in an inadequate number of installers receiving the required training on installing heat pumps with A2L refrigerants, thus hampering widespread market adoption. Funding to offset the expenses associated with providing training for installers could be made available through the Employment Training Panel, a state-run program established to support employers in upgrading the skills of their workers (https://etp.ca.gov/).

User and installer experiences in the field demonstration project suggest that heat pumps using A2L refrigerants do not pose significant challenges or barriers unique to residential heat pumps. Neither users nor installers had concerns about the flammability of the refrigerant, and the adaptations installers made to accommodate the refrigerant were minimal. This suggests that the market for heat pumps that use A2L refrigerants will be largely driven by refrigerant policy and the market for residential heat pumps in general. R-454B will be permitted as of July 1, 2024, and required as of January 1, 2025, for all new residential heat pump installations. Further reductions in the allowable level of global warming potential for refrigerants, for example to near zero, are under discussion but it is unclear if and when such changes may occur.

The initial cost of replacing a gas furnace with a residential heat pump is typically higher than installing a like-for-like replacement gas furnace and central AC.[3] Numerous financial incentives are available to California homeowners through utility programs, the statewide TECH Clean California program, and most recently through the Inflation Reduction Act. Much of the state funds have been earmarked for low-income customers, providing support worth up to 100% of project costs. Financial incentives for higher-income customers help defray the cost of heat pumps but do not typically create parity with gas furnaces. Additionally, the relatively high cost of electricity compared to gas in California investor-owned utility territories means that many customers will potentially face higher operating costs when moving from furnaces to heat pumps. The possibility of higher utility bills - and the uncertainty around that outcome - will be unappealing to many customers and unfeasible for low-income customers who are already energy-burdened (even if they can receive a heat pump for free). It is unclear how many California customers this will deter from installing heat pumps and what would be required to overcome such a barrier.

[3] The median total cost to install a natural gas furnace and 14 SEER central AC in California is roughly $4,000 (Opinion Dynamics, 2022) and $5,000-6,000 (Remodeling Calculator, n.d.). Estimates for installing a residential heat pump in California range from $10,000 (Opinion Dynamics, 2022) to $20,000 (TECH Clean California, 2024).

Finally, there is anecdotal evidence that California homeowners are finding the heat pump landscape very difficult to navigate. Those who follow the recommended practice to obtain three (or more) contractor quotes find them difficult to compare because the proposed system configurations often differ. In states like Maine and Massachusetts, third-party services have emerged to address this need, providing systematic quote comparisons and expert advice on which to select. Installers are also important resources for prospective customers who need basic heat pump education. This will require a workforce with knowledge and effective communication skills.

Heat pump adoption also seems to be hampered by the complicated incentive landscape in California. Difficulty navigating the application process deters some customers from the outset. For others willing to wade through the paperwork involved, the uncertainty around receiving a rebate can put heat pumps out of reach if they cannot afford to absorb the full cost. Here again, solutions are being offered through the private sector, with companies that will shepherd customers through the process and do the legwork to secure the incentives to which they are entitled. Financial incentives may be used to encourage the adoption of lower GWP refrigerants ahead of the mandates.[4] If that happens, customers' decision criteria will get further complicated.

Conclusions

Electrifying space conditioning systems is one of the first steps toward meeting decarbonization goals. This project documented the impact of installing a next-generation heat pump technology in 10 California homes. The heat pump installed was designed to achieve higher performance at lower market cost, while also utilizing a lower GWP refrigerant that meets the CARB regulation going into effect in 2025 (GWP <750). The installations highlighted some of the challenges of heat pump retrofits including electrical panel capacity limits and electrical upgrades required for the air handler. Surprisingly, the new refrigerant, which is designated as an A2L, mildly flammable fluid, did not represent a significant market barrier for the heat pump from the perspective of installation or user acceptance. The measured performance of the heat pump showed higher efficiency than the baseline systems but still resulted in increased utility bills of 3-27% for five out of eight homes due to higher electricity use in the winter. Some of these increases may have been a result of changes in occupant behavior (i.e. thermostat setpoints) as it was noted that the new variable-speed heat pump was able to achieve more stable temperature conditions in the home and warmer zone temperatures were observed at some sites in the winter relative to the baseline. While in many cases there was an increase in utility costs, the greenhouse gas emissions were 44-98% lower for the heat pump system relative to the natural gas heating systems used in the majority of baseline systems showing significant progress toward decarbonization.

[4] The Self-Generation Incentive Program encourages the use of heat pump water heaters with "low global warming potential" refrigerants, offering an additional $1,500 incentive compared to standard equipment.

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