Challenges and Performance from Seven Ducted Mini-Split Heat Pump Retrofits

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ABSTRACT

Seven homes in Sonoma County, CA were retrofitted in 2019 with ducted mini-split heat pumps (MSHP) and ducts in conditioned space. The energy use and comfort provided by the existing systems (baseline) and ducted MSHP systems (retrofit) were monitored for six months and one year respectively. Energy use was monitored directly using power meters on the breakers dedicated to the HVAC system and comfort was monitored using a smart thermostat that logged indoor temperature, relative humidity, setpoint, operation mode, and occupancy. The mechanical system retrofit was combined with envelope load reduction measures (air sealing and increased attic insulation). Dwelling vintage ranged from 1956 to 2004, and condition space floor area ranged from 731 to 1850 sq. ft. Even without the load reduction measures, the original systems were generally oversized. The largest mini-split system installed was 1.5-tons and the smallest pre-existing system was 2-tons. In one case, an 1144 sq. ft. house had a 3-ton AC replaced with a 3/4-ton ducted MSHP. In addition to monitored performance, installations and commissioning test results were documented in detail, including costs, and occupants were surveyed post-installation. The average cost per retrofit was $26,000, with prevailing wage labor rates. Monitored performance and detailed cost data were used to calculate cost effectiveness and payback. Because of the mild climate, changes in behavior due to the onset of the COVID-19 pandemic, and other factors discussed, cost effectiveness was only positive at one site. However, occupant satisfaction with the technology in surveys was high.

Introduction

A heat pump is an “air conditioner” that also works in reverse to provide indoor cooling and heating. Air-to-air or “air source” heat pumps work by pulling energy from the outdoor air to heat the indoor space, or they release energy to the outdoor air to cool the indoor space. A “split” heat pump, as seen in Figure 1, is split into two primary components: an indoor unit and an outdoor unit. The outdoor unit contains a compressor and a refrigerant coil that releases or absorbs energy from the outdoor air using a fan. The indoor unit contains a refrigerant coil that releases or absorbs energy from the indoor air using a blower which circulates air from the indoor space across the indoor coil and through a duct system, which distributes the air heated or cooled by the coil through the house. Closed circuit refrigerant lines connect both systems.

A mini-split heat pump (MSHP) is essentially what the name describes: a split system that is smaller in capacity and more compact. Traditional heat pumps typically come in capacities of 2-tons of cooling or more, operate at a single speed and refrigerant flow rate, and use a central duct system with a single indoor unit. MSHPs are typically variable capacity heat pumps (VCHPs) which can vary compressor and fan speeds to adjust output to match the current load on the system. Compared to traditional heating and cooling systems, MSHP efficiency ratings tend to be much higher. The advantages of variable speed systems are that they may be more efficient at part loads and may reduce indoor air temperature fluctuations due to more constant circulation at lower airflow rates. Variable speed systems typically run longer, but at lower speeds than traditional systems, ideally decreasing the overall electricity usage when paired with properly designed distribution systems. (Wilcox 2016) The MSHP installations covered in this paper are VCHPs.

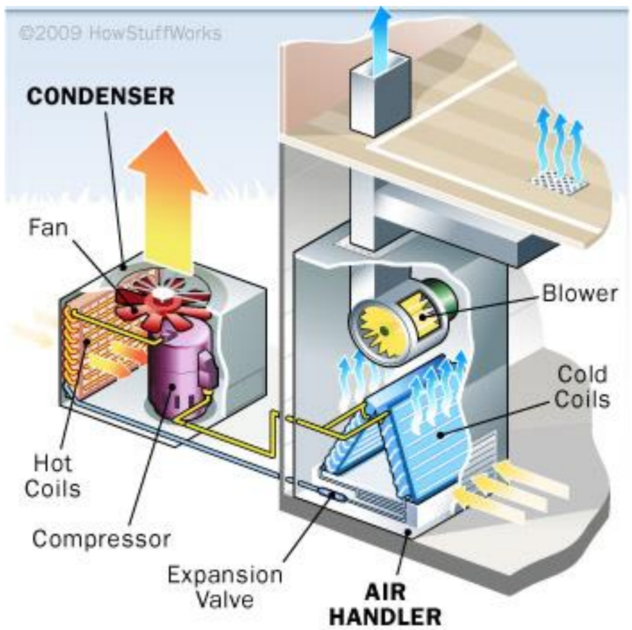

Figure 1: Split system in cooling. Image Credit: HowStuffWorks. (Brain, Bryant and Elliot 2011)

MSHPs can also be found in both ducted and ductless configurations. The MSHP installations covered in this paper are centrally ducted, with well-sealed ducts (≤ 12 CFM25) in conditioned space. Traditional ductwork located in attics and crawlspaces can waste 30 to 50% of heating and cooling energy through thermal losses and air leaks. Locating ductwork in conditioned space can significantly reduce these losses. Implementing thermal load reduction measures can translate to 20 to 30% energy savings depending on the application. (Hoeschele, et al. 2015)

However, it is important to note that energy savings do not directly translate to utility bill savings. Typical space heating systems found in most existing homes are natural gas furnaces while MSHPs are all electric. In California, the cost per unit of energy for electricity is much higher than for natural gas, to the point that, generally, heating using electricity costs more than using a natural gas furnace to meet the same load.[1] It is possible for the reduction in cooling costs, in combination with load reduction measures and through improved efficiency and reduction of duct losses, to be enough to offset the increased heating costs. (Mobley 2011) Though not part of this study, PV systems could also help offset electric heating costs.

[1] In 2020 for California, PG&E average energy costs were $0.012 and $0.076 per kBtu for natural gas and electricity, respectively. (PG&E 2022) Meeting the same load, a heat pump would need to achieve an efficiency ratio (usable heat divided by energy input, analogous to COP) greater than 5 to achieve the same cost as a furnace with an efficiency ratio of 0.8. At present, installed efficiencies of 3 are difficult to achieve with heat pumps.

This study retrofitted seven single-family homes in Sonoma County, CA in 2019 with ducted mini-split heat pumps (MSHP) and ducts in conditioned space. Ducted mini-split heat pumps were selected because the loads in larger homes generally exceed the capacity of ductless systems and more uniform temperature distributions can be achieved. (Wilcox 2016) In addition to the MSHPs, the retrofit package also included several load reduction and indoor air quality measures, to ensure building loads were within the capacity range of the MSHPs and to reduce the increased operating costs associated with switching from natural gas to electric heating. Detailed installation costs were collected, along with thermostat data, equipment submetering data, and occupant survey data, to evaluate the performance, comfort provided, homeowner satisfaction, and cost-effectiveness of the retrofit for each test site.

This study was one of fourteen different technology evaluations conducted as part of Sonoma Clean Power's Lead Locally program and funded by a grant from the California Energy Commission. (Hendron, et al. 2022)

Field Test Overview

MSHP systems were installed at seven single-family home test sites. An overview of these sites, including vintage, conditioned floor area, the baseline system, the retrofit system, and the reduction in ACCA Manual J calculated heating and cooling load is provided in Table 1. The conditioned area of the homes used varies from 731 ft^2 to 1,850 ft^2. All test sites had central heating and cooling pre-retrofit, with ducts located in a vented attic or crawlspace. Heating for all homes pre-retrofit was provided by a gas furnace, except Site 4, which had an existing ducted package heat pump system. Though this unit had electric resistance strip heat installed, the heat strips were not connected to power. Site 6 was the only test site with an existing PV system.

Table 1. Overview of Ducted MSHP Test Sites

Site #	Year Built	Cond. Area (ft^2)	Baseline System	Retrofit System	% Reduction in Man. J Load	
					Heating	Cooling
1	1989	1144	60 kBtu furnace 3-ton AC	0.75-ton Fujitsu	54%	42%
2	1956	731	80 kBtu furnace 2-ton AC	1-ton Mitsubishi	46%	40%
3	1991	1612	90 kBtu furnace 3-ton AC	1.5-ton Mitsubishi	30%	28%
4	2004	1100	2-ton package heat pump	1-ton Fujitsu	41%	39%
5	1976	1086	44 kBtu furnace 3-ton AC	1-ton Mitsubishi	50%	39%
6	1972	1570	92 kBtu furnace 4-ton AC	1.5-ton Mitsubishi	35%	45%
7	1970	1850	92 kBtu furnace 3-ton AC	1.5-ton Mitsubishi	40%	46%

As seen in Table 1, the installed outdoor and air handling units were manufactured by Fujitsu or Mitsubishi Electric. The size of each unit was selected to meet the calculated post-retrofit loads for each house. The units installed in this study had a rating of either 9,000 Btu/hour (0.75 ton), 12,000 Btu/hour (1 ton) or 18,000 Btu/h (1.5 tons). The average reductions in heating and cooling load were 42% and 40%, respectively. Site 1 had the most significant reduction in heating load (19,668 to 8,966 Btu) and third most significant reduction in cooling load (17,296 to 10,012). The existing AC was also 108% oversized according to the pre-retrofit Manual J calculations. (All sites had oversized equipment.) For Site 1, the retrofit MSHP was a 75% decrease in nominal equipment size from the existing AC.

Figure 2. Pictures of the seven houses in the Lead Locally program retrofitted with MSHP.

Installation

All existing HVAC equipment and duct work were removed and replaced with a new centrally-ducted MSHP at all test sites. These installations were also coupled with load reduction and indoor air quality measures. The following aspects were incorporated into each design:

- New R-8 ducts within the thermal envelope, either using furred or dropped ceilings, or by sealing and converting attic or crawlspace space into indirectly conditioned space.
- Engineered supply terminal devices for optimum room air mixing and quiet delivery.
- Increased the return air filter grille size and area permitting the use of higher efficiency filters (2” thickness) and longer filter service life.
- Single-part gun foam sealing of the ceiling plane from the attic side to seal all gaps around penetrations and the wall plate-to-drywall interfaces (Figure 3).
- Full attic perimeter eave block sealing with gun foam and installation of insulated vent baffles extended above full insulation depth to prevent wind washing.
- New cellulose blown-in attic insulation to a minimum of R-50.[2]
- Replacing all bathroom exhaust fans with new variable speed exhaust fans that provide ASHRAE 62.2 compliant continuous ventilation to maintain indoor air quality.

[2] The homeowner at Site 7 insisted on keeping their fiberglass batts. This was challenging to the retrofit effort.

- New bathroom fan occupancy sensors for efficiency and indoor air quality.
- Single master switch for all ventilation fans for occupant control during local outdoor air quality events (such as wildfires).
- New seam-sealed 15 mil poly vapor barrier installed on crawlspace dirt floor, sealed to concrete perimeter stem walls.
- Air sealing the crawlspace perimeter, connecting it to the conditioned space above and moving the enclosure pressure boundary from the floor to the crawlspace perimeter.
- Installed minimum crawlspace mechanical exhaust ventilation as required by code.
- Relocated attic accesses from interior ceilings that penetrated air barrier to exterior access hatches above full depth insulation level (gable ends, exterior patios, wherever possible).
- Corrected or replaced any existing electrical work deemed unsafe before blowing in new insulation.

Figure 3. Examples of air sealing the attic side of the ceiling plane.

The installation at Site 7 also included a power vent water heater because of an existing atmospheric vent natural gas storage water heater within the conditioned space. Air sealing measures and the addition of ASHRAE 62.2 compliant ventilation made the existing water heater too hazardous to leave in place.

Images of an example installation are provided in Figure 4 and Figure 5 from Site 1. At this site, a dropped ceiling in a central hallway was used to house the return, a “slim duct” style MSHP air handler, and all supply ducts. Also, the air handler was effectively installed inside the return itself, providing full access to equipment for maintenance and service needs by removing the return air filters.

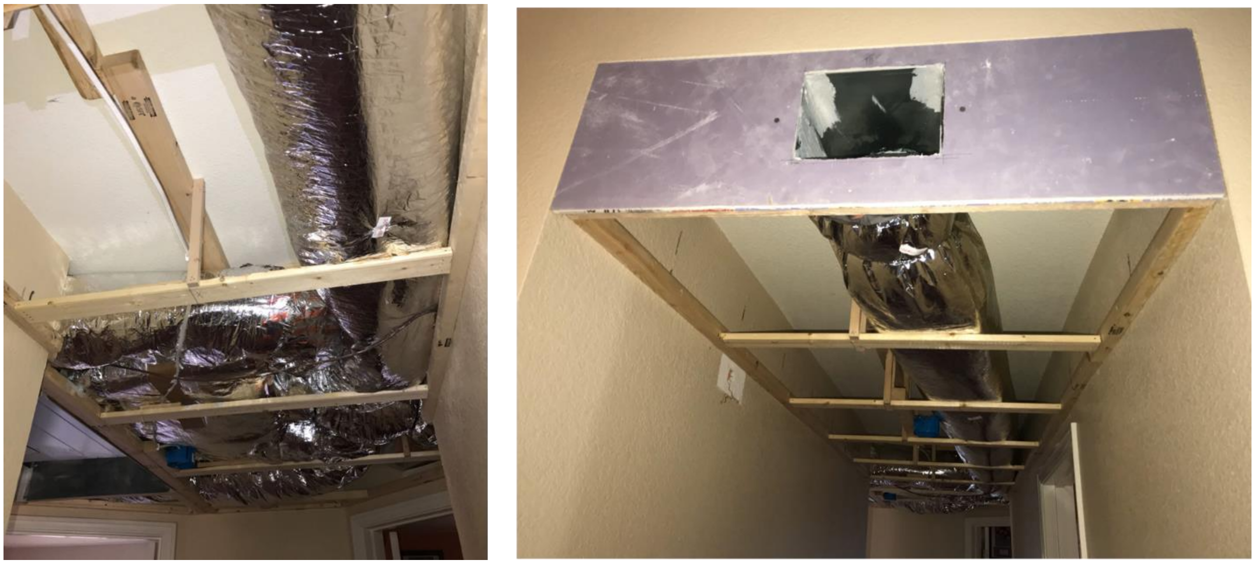

Figure 4. Example install of ducts in conditioned space (Site 1).

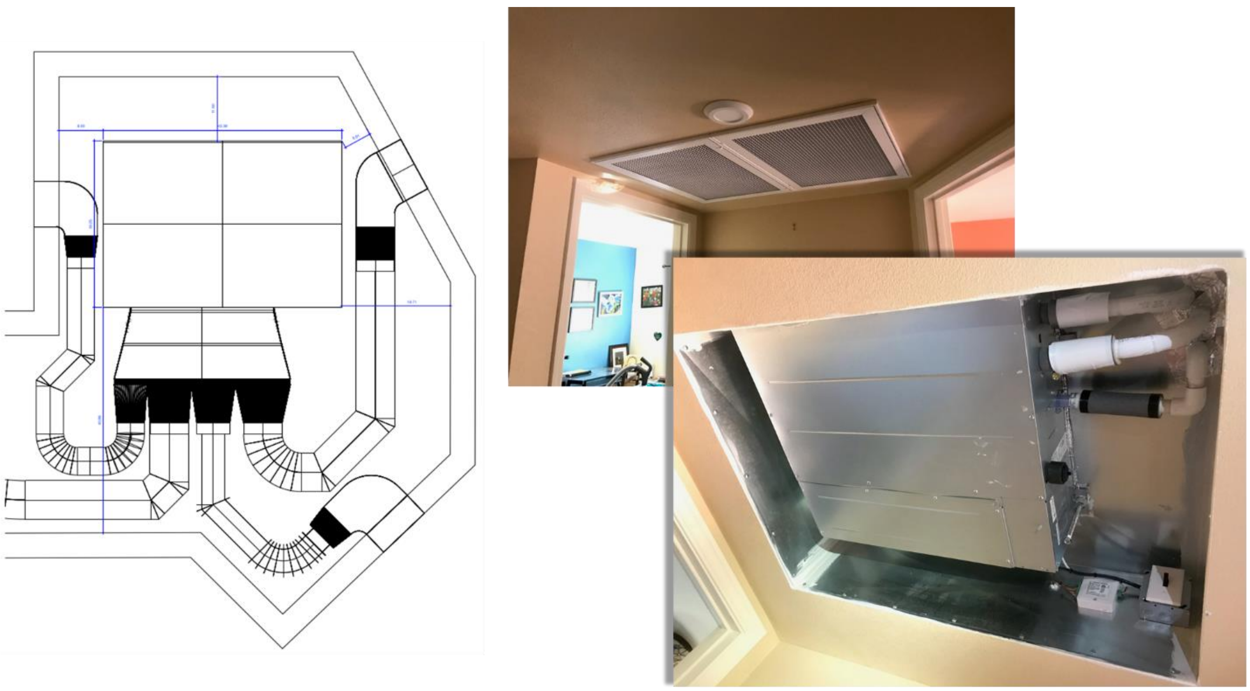

Figure 5. Example of MSHP air handler in conditioned space. Design (left) and finished install (right). (Site 1)

Commissioning

Commissioning data is presented in Table 2. The installations at each site utilized the "Measured Home Performance" best practices methods popularized by home performance contractor Rick Chitwood and others. (Chitwood and Harriman 2012) This process includes:

1. Walking the entire site and making measurements of the baseline condition using field diagnostic equipment (floorplans, fenestration area by room, enclosure leakage, duct leakage, etc.).

2. Incorporating this information into Manual J calculations of pre-retrofit load.
3. Developing a retrofit plan to address load and comfort issues for each room.
4. Incorporating these design goals with site data into new ACCA Manual J-S-T-D calculations.
5. Commissioning at multiple stages during the retrofit using the same field diagnostic equipment to ensure that design goals are met and equipment performance meets expectations.
6. Homeowner education to ensure correct expectations are set and maintenance requirements are known.

Table 2. Commissioning results by site. “LO” means the leakage is less than 10 CFM25.

Site	Final Blower Door (CFM50)	Blower Door (% Reduction)	Duct Leakage (CFM25)	Fan Efficacy (W/CFM)	Total Static (in. w.c.)
1	1036	29	LO	0.21	Unable to measure
2	684	38	LO	0.22	0.33
3	1021	45	LO	0.21	0.19
4	697	50	LO	0.21	0.18
5	535	42	LO	0.13	0.12
6	1060	39	12	0.22	0.33
7	1208	33	LO	0.20	0.27

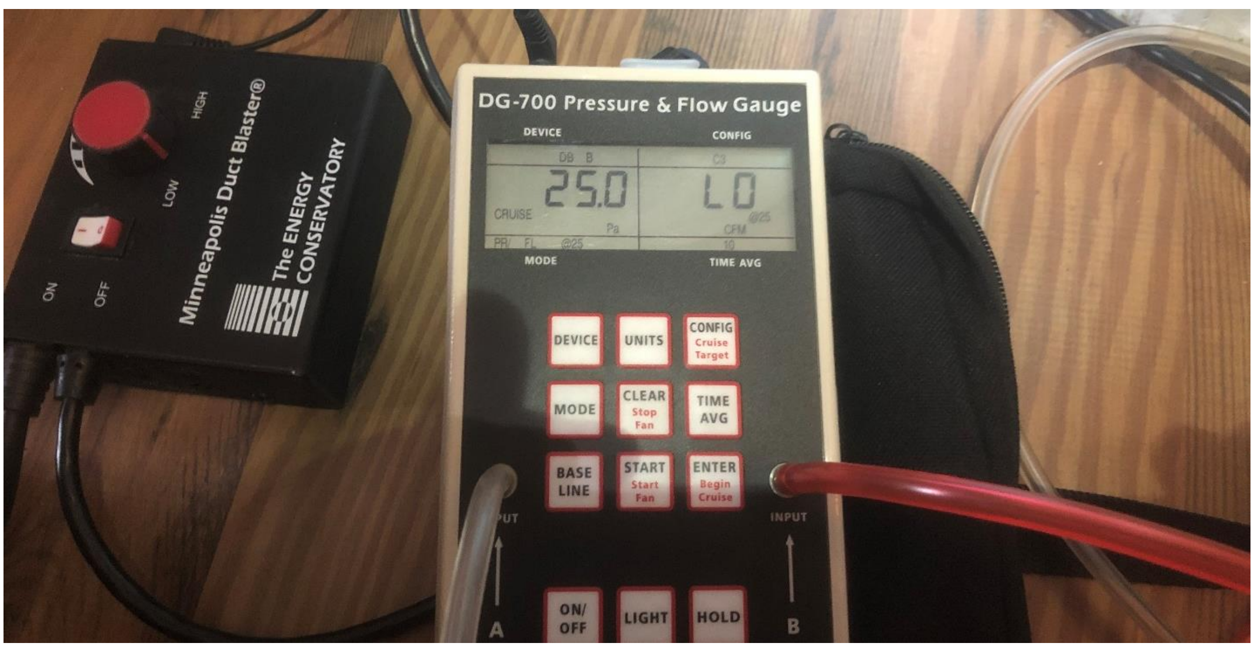

Figure 6. DG-700 digital manometer connected to a TEC Minneapolis Duct Blaster reading “LO”.

Monitoring and Instrumentation

Monitoring included a pre-retrofit baseline period of six months and a one-year post-retrofit period. Start and end dates were slightly different for each site, but pre-retrofit monitoring generally began in March 2019 and concluded in October 2019. Retrofits were completed in late November and monitoring systems were recommissioned in December 2019. Wherever possible, the same monitoring equipment used in the pre-retrofit period was used in the post-retrofit period. Post-retrofit data presented in this paper covers the year of 2020. Key data points that were monitored both pre- and post-retrofit included:

- Indoor temperature and humidity.
- Outdoor temperature and humidity.
- System electricity use.
- Heating and cooling setpoints and equipment calls via smart thermostat.
- Furnace gas use (in the pre-retrofit period only).

Homeowners provided access to their utility data and were asked to complete surveys to provide feedback. Responses from the occupant surveys, as well as thermostat setting data were used to evaluate occupant behavior before and after the retrofits.

Additionally, detailed cost data was collected for each site, including permitting, labor by trade, and a detailed accounting of materials used at each site. After the yearlong data collection, simple payback for the installed ducted MSHP systems was calculated utilizing retrofit costs, energy costs, and energy use data.

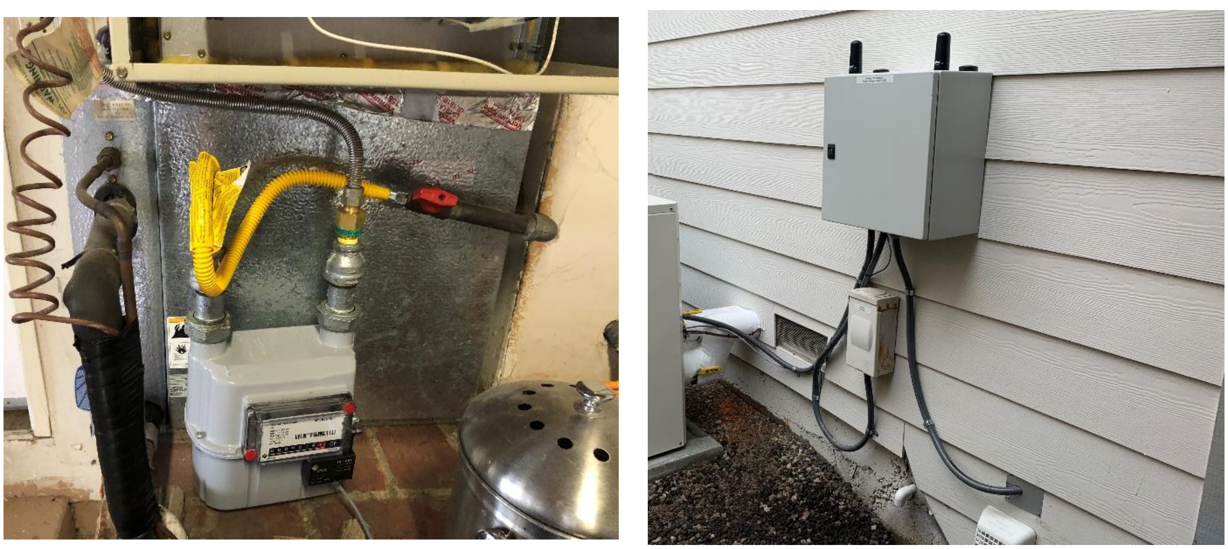

Figure 7. Example of the gas meter and main monitoring panel.

Results and Analysis

As stated previously, a direct comparison in energy usage pre- and post-retrofit will not directly reflect the performance of the new system. This is because gas is used for heating pre-retrofit and electricity is used for heating post-retrofit for six of the seven sites, and the price of natural gas in California is much less than electricity.

To account for the difference in monitoring period lengths and changes in outdoor conditions pre- and post-retrofit, total energy use during the two monitoring periods was normalized to the total cooling and heating degree days during the two monitoring periods.

Degree days were calculated using a base outdoor temperature of 60°F for heating, and 65°F for cooling. The total calculated degree days, total energy use for both gas and electricity, and the energy usage ratios, pre- and post-retrofit for each site, are shown in Table 3. For reference, the annual heating and cooling degree days for Sonoma County are 2901 and 386, respectively (both with a base outdoor temperature of 65°F). (ASHRAE 2021)

All sites show natural gas savings since they use electricity for heating instead of gas post-retrofit, except site 4 which already had electric heating pre-retrofit. Only three sites show positive electricity savings per degree day post-retrofit (sites 3, 6, and 7). The increases in energy usage may be caused by different thermostat set points pre- and post- retrofit along with changes in behavior due to the COVID-19 pandemic, further discussed later.

Table 3: Energy usage, degree days, energy usage ratios, and annual energy savings for the seven test sites, pre- and post-retrofit. Post-retrofit represents data collected during 2020.

		Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Avg.**
Actual Degree Days During Monitoring Period [DD]									
Heating	**Pre**	637	683	503	578	508	737	238	555
	Post	1,949	1,949	2,218	2,128	2,252	2,137	1,819	2,065
Cooling	**Pre**	770	0	886	637	597	896	1,360	858
	Post	1,351	1,351	1,389	842	1,034	1,086	0	1,175
Electricity Use [kWh]									
Heating	**Pre**	0	0	0	446.3	0	0	0	446
	Post	910.1	300.4	776	2,247	1,538	1,117	29.3	988
Cooling	**Pre**	0.2	0	1,454	73.5	273.5	1,214	32.3	508
	Post	29.6	137.7	1,733	9.5	547.5	636.6	0	516
Gas Use [kBtu]									
Heating	**Pre**	297	3,788	835	0	1,086	1,460	76	1,257
	Post	0	0	0	0	0	0	0	0
Electricity Usage Ratio [kWh/DD]									
Heating	**Pre**	0.000	0.000	0.000	0.772	0.000	0.000	0.000	0.804
	Post	0.467	0.154	0.350	1.056	0.683	0.523	0.016	0.479
Cooling	**Pre**	0.000	0.000	1.641	0.115	0.458	1.355	0.024	0.592
	Post	0.022	0.102	1.248	0.011	0.529	0.586	0.000	0.439
Gas Usage Ratio [kBtu/DD]									
Heating	**Pre**	0.47	5.54	1.66	0	2.14	1.98	0.32	2.26
	Post	0	0	0	0	0	0	0	0
Energy Use Ratio Savings (Pre- vs. Post-Retrofit)									
Heating [Gas]		0.466	5.543	1.659	0.000	2.137	1.981	0.319	2.265
Heating [Elec.]		-0.467	-0.154	-0.350	-0.284	-0.683	-0.523	-0.016	0.325
Cooling [Elec.]		-0.022	-0.102	0.393	0.104	-0.071	0.768	0.024	0.153
TOTAL [Elec.]		**-0.489**	**-0.256**	**0.043**	**-0.180**	**-0.754**	**0.246**	**0.008**	**0.478**

Comfort

Table 4 presents thermostat set points and deadband (difference between heating and cooling setpoints) for each site pre- and post-retrofit. A negative difference in value indicates that the thermostat setting called for more heating or cooling post-retrofit. Post-retrofit thermostat data was unavailable for Site 6 due to internet connection issues.

Table 4: Heating and cooling thermostat setpoints and deadband pre- and post-retrofit.

Thermostat Set Point [°F]		**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
Heating	**Pre-Retrofit**	68.7	64.6	64.9	62.5	67.5	71.5	61.5
	Post-Retrofit	69.2	67.3	64.4	71.5	66.4	-	60.0
	Difference	-0.5	-2.7	0.5	-9.0	1.1	-	1.5
Cooling	**Pre-Retrofit**	76.4	-	71.0	81.7	-	71.7	75.5
	Post-Retrofit	77.0	78.1	70.2	83.3	74.4	-	78.4
	Difference	0.6	-	-0.8	1.7	-	-	2.9
Dead band	**Pre-Retrofit**	7.7	-	6.1	19.2	-	0.2	14.0
	Post-Retrofit	7.8	10.8	5.8	11.8	8.1	-	18.5

Table 5 shows the activity rate (minutes of activity per day) for each site pre- and post-retrofit. This represents activity detected by the motion sensor built into the thermostat.

Table 5. Activity rate for each site, as seen by the thermostat motion sensor, pre- and post-retrofit.

Minutes/Day	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
Pre-Retrofit	125	147	231	223	244	276	112
Post-Retrofit	122	251	296	308	327	-	176
% Change	-2%	71%	28%	38%	34%	-	57%

Human comfort levels and preferences can greatly affect energy demand. In this study, no limits or restrictions were given to the homeowners regarding temperature range and they had free reign over their thermostat settings. Thermostat setpoints varied greatly across the test sites, but setpoints also varied within the same household pre- and post-retrofit. This change in behavior within a household may have resulted from spending more time at home during the COVID-19 pandemic. All sites except Site 1 saw significant increases in indoor activity from the pre to post retrofit periods.

Cost Effectiveness

Table 6 details the average cost to install the MSHP system, broken down into labor and material costs. The average cost for the MSHP system was $26,000 made up of $18,600 in labor costs and $7,400 in material costs.

Table 6: Cost of labor and material to install the mini-split heat pump system.

LABOR			
DESCRIPTION	**Hours**	**Cost Rate**	**Subtotal**
COMMISSIONING	14	150	$2,100.00
DRYWALL	21	150	$3,150.00
DUCTS	32.75	125	$4,093.75
ELECTRICAL	8	150	$1,200.00
FRAMING, FURRING, BACKING	2	150	$300.00
INTERIOR PROTECTION	8	150	$1,200.00
MECHANICAL (VENTILATION, DEHUMID)	22	150	$3,300.00
MISC	4	150	$600.00
PAINTING	8	150	$1,200.00
PLANNING	2	150	$300.00
PLUMBING	8	150	$1,200.00
		PROJECT TOTAL	$18,643.75
EQUIPMENT AND MATERIALS BREAKDOWN			
DESCRIPTION			**Cost with Tax**
MITSUBISHI 1 TON SYSTEM			$2,977
LINESET, COVER, HARDWARE			$325
ELECTRICAL WIRING, BREAKERS, DISCONN.			$162
PLUMBING PARTS, VENT PARTS (EXISTING)			$189
DUCTS, ELBOWS, TRANSITIONS, MASTIC, ETC			$379
SHEET METAL PLENUMS AND PANS			$541
PANASONIC FANS			$346
ECOBEE THERMOSTAT (EST)			$325
INTERFACE MODULE (EST)			$217
COLOR MATCHED PAINT			$81
PERSONAL PROTECTIVE EQUIPMENT			$217
DRYWALL, FRAMING, MUD, TAPE, ETC.			$271
HERS VERIFICATION			$487
PROJECT PERMIT			$271
SHOEMAKER CANS, RETURN AIR GRILLE			$325
ROOF AND SIDEWALL VENTS			$260
		PROJECT TOTAL	**$7,371.83**
		TOTAL COST PER SITE	**$26,015.58**

In 2020, the baseline electric rate for Pacific Gas &Electric customers was $0.26 per kWh and the average gas price was $0.012 per kBtu (PG&E, 2022). These were used with the energy usage ratios and degree days for 2020 given in Table 3 to estimate the annual energy costs for the pre- and post-retrofit systems with the same meteorological year and annual average energy cost. The annual savings are calculated as the difference between the pre- and post-retrofit annual energy costs. Dividing the total cost of installing the MSHP system by the annual savings provides a simple payback time, which was calculated for each site and presented in Table 7.

Table 7: Savings in cost of electricity for the seven test sites and simple payback time.

	Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
Heating (Gas)	$11.0	$130.7	$44.5	$-	$58.2	$51.2	$7.0
Heating (Elec.)	$(236.6)	$(78.1)	$(201.8)	$(157.2)	$(399.9)	$(290.4)	$(7.6)
Cooling	$(7.6)	$(35.8)	$142.0	$22.8	$(19.2)	$216.9	$-
Total	$(233.2)	$16.8	$(15.2)	$(134.4)	$(360.8)	$(22.3)	$(0.6)
Simple Payback[b] [years]	-	1549	-	-	-	-	-

[a] Based on 2020 average electricity cost of $0.26/kWh and natural gas cost of $0.0121/kBtu in 2020 (PG&E 2022).
[b] Average cost estimated at $26,000.

Energy and cost savings are seen for natural gas usage post-retrofit, as expected. However, the gas savings do not compensate for the increased electricity cost, except for site 2. The estimated total energy cost savings are negative for all test sites except site 2, ranging from a loss of about $360 to a gain of approximately $17 in annual savings. Likewise, site 2 is the only site with a positive payback time.

As previously noted, in California, the cost per unit of energy for electricity is so much higher than for natural gas that heating using electricity costs more than using a natural gas furnace to meet the same load. Meeting the same load, a heat pump would need to achieve an efficiency ratio (usable heat divided by energy input, analogous to COP) greater than 5 to achieve the same cost as a furnace with an efficiency ratio of 0.8. At present, installed efficiencies of 3 are difficult to achieve with heat pumps. This makes significant cooling season savings that more than cover the increased heating season costs the best hope to achieve cost effectiveness for these retrofits, but such cooling savings did not materialize for these sites.

This is also why incorporating load reduction measures when replacing furnaces with heat pumps is important, as these measures both decrease the amount by which heating costs will increase post-retrofit and augment cooling season savings.

Homeowner Feedback

Approximately a year after the MSHP systems were installed each homeowner was asked to complete a survey. The survey included questions regarding comfort, control, and quality of equipment. The homeowners were asked to rate their satisfaction on a scale of one to five, with a rating of one signifying "Very Dissatisfied" and five being "Very Satisfied". The consensus among homeowners was they were very satisfied or simply satisfied with the comfort levels related to temperature, feeling of drafts, perceived air quality, noise, and general comfort. Similarly, homeowners rated the HVAC system control as satisfactory. Some of the specific comments provided by homeowners were:

- “Missing option to run in “fan only” mode, or to adjust fan speed.”
- “System will not run in “fan only” mode even if selected at the Ecobee thermostat.”
- “Indoor air quality is easy to monitor and keep consistently great.”
- “Missing humidity control.”
- “Thermostats works as ’set it and forget it’.”

A few homeowners requested more information on the controls, which Frontier Energy and their contractors provided after the surveys were reviewed, addressing these comments.

Regarding indoor comfort, some homeowners complained about noise and some rooms not being conditioned or heated as effectively as others. Specific comments were as follows:

- “Quiet delivery of conditioned air without noises from furnace or fan.”
- “Outside unit noisy.”
- “One bedroom and office are consistently warmer/colder than other areas.”
- “Return air is noisy.”
- “I feel safer with electricity than gas.”

Additional comments received related to performance were, in general, very positive.

- “We love it!”
- “System works fast at providing warm and cold air.”
- “Less fluctuation in overall indoor temperature with the installed system. However, the bathroom has no supply air from the new system, resulting in much warmer indoor air temperature during the summer and requiring space heating during the winter. Bedrooms sometime fluctuate more in temperature too.”
- “No maintenance required as of yet.”
- “Energy and cost savings with new system.”
- “Glad that increased electricity usage (because of not using gas for heating) can be offset with PVs.”

Contractor Perspective

The clients and housing stock worked with on this project were very typical of all our past deep energy retrofit projects in Northern CA, except for a few notable things.

First, every client in this project mentioned during our initial interviews that they barely used air conditioning during the summer, due to favorable topography that reliably brought in cool evening air off the nearby (20 miles) Pacific Ocean. They mentioned that when they did use AC, it was only for a few hours during the hottest parts of the day for maybe a 2 week stretch of time. This was very different than what we see much further inland at the northern tip of the Central Valley where we have performed this same package of retrofit measures many times with extreme savings and comfort benefits. (Mobley 2011)

Second, the clients did not hire us (like a normal project) and they weren’t selected on the basis of actually needing efficient heating and cooling systems (they weren’t chosen from high utility use, for example). They seemed genuinely pleased to receive the free retrofit and were willing to endure the inconvenience in exchange for the perceived value. However, had no other stake or reason to not change their behavior post-retrofit in ways that could affect cost effectiveness. It seems logical that, in a normal project, a primary motivation to maintain frugal behavior and setpoints following efficiency improvements is because the client spent a lot of money and desires to see savings and payback for their investment. Obviously, that was not the case here.

Finally, of course, as fate would have it, the post-retrofit monitoring period fell during a time of unprecedented home occupancy and working from home, further complicating any kind of efficiency comparison to pre-retrofit periods.

Conclusions

While this study was not able to demonstrate cost effectiveness in these seven test sites, this cannot be taken to be an indication that the measures deployed are generally not cost effective. Rather, several factors unrelated to the MSHP systems and load reduction measures themselves worked against cost effectiveness:

1. COVID-19 pandemic effects on occupancy and therefore on setpoint and use.
2. The climate where the sites were located is known for being very mild in the summer, limiting the effect of cooling energy use savings on net savings.
3. Because this was funded by a grant through the Energy Commission:
    a. Labor was required to be provided at prevailing wage rates, as opposed to normal labor rates typically charged by contractors. The average labor cost per site was roughly $18,600, which represents more than 70% of the average total cost.
    b. Materials were required to be sourced from distributors located within California. This effectively eliminated online and bulk purchasing options typically used by contractors.
4. The disparity between electricity and gas utility rates in California is too extreme to allow for cost effectiveness in switching from gas to electric heat, even if provided by a very efficient heat pump, without substantial cooling load savings. Electric rates are far above the norm seen in other states (nearly double the national average), and increasing faster than in other states. (Penn 2023)

However, this project did successfully demonstrate that combining load reductions measures with MSHPs has two important benefits:

1. **The size of the retrofit system can be significantly reduced from the existing system.**
   Most of the MSHPs were half the capacity of the existing air conditioners, a quarter of the size in the case of Site 1, and heating load was met without strip heat. All pre-retrofit heating and cooling equipment was oversized relative to pre-retrofit Manual J loads. Load reduction measures additionally reduced loads by an average 42% for heating and 40% for cooling. By using widely available diagnostic tools and best practices to correctly size equipment and implement load reduction measures, smaller capacity heat pumps can be installed, which translates to reduced peak demand and reduced strain on the electric grid.
2. **Load reduction measures often also improve indoor air quality and dwelling unit resiliency.**

a. All of the sites in the study are in a wildfire prone area of California. In fact, in 2019, the Kincade Fire came within 10 miles of Site 3, forced the evacuation of sites 3, 4, and 5, and delayed retrofit work.
b. Blown-in cellulose insulation, unlike fiberglass, does not need to be completely replaced if there is a fire.
c. Air sealing in general prevents the infiltration of wildfire smoke, and while ASHRAE 62.2 compliant continuous exhaust ventilation was installed at all sites, this included a single master switch so that it could be disabled in the event of bad outdoor air quality.
d. Moving ducts to conditioned space allows continued operation of heating and cooling while filtering the indoor air for the entire house, without the risk of smoke infiltration through leaky attic ducts. This is something that is difficult and expensive to do with furnaces due to flue exhaust and combustion air needs, yet relatively trivial for heat pumps, especially MSHPs.

The overall positive feedback from the homeowners also demonstrates that there is value to these measures beyond cost effectiveness. In all cases, comfort and air quality were improved, which was highly valued during the first year of COVID.

Recommendations

Retrofit programs such as this one can be expensive to implement. It would be interesting to see how well existing systems would perform had only the envelope improvements been done, perhaps in combination with deep HVAC system maintenance or “retro-commissioning” to improve the performance and usable life of the existing system. That may also prove to be more cost effective for low income and disadvantaged communities, where it is not typically possible to supplement incentive program dollars with homeowner dollars.

Future implementations of similar programs to the one discussed in this paper should consider site selection criteria that is based on need, such as through utility bill data review, to ensure the highest “bang” per program dollar. With such criteria, high cost effectiveness of this same retrofit would be likely.

Any retrofit program should also require contractors performing work under the program to follow the latest MSHP and VCHP best practices (Conant, et al. 2023) and proven “Measured Home Performance” methods (Chitwood and Harriman 2012). Measuring characteristics of the existing performance of the house enables accurate sizing calculation, duct design, and selection of replacement equipment. The process may also reveal other issues with the house that the homeowner may want corrected, saving them time and money by bundling work together. Measuring the same performance characteristics during post-retrofit commissioning helps hunt down difficult issues and reduces call backs This also provides verification and documentation that retrofit goals were achieved (or exceeded) giving the homeowner peace of mind, the tradesperson satisfaction in a job well done, and the general contractor a more irreproachable form of litigation protection than fine print on the back of a work order form.

All of this ensures the best value for the homeowner and the program, the best possible performance from all incorporated measures, more services to sell for the contractor, and high customer satisfaction (even in the event high savings do not materialize).

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