Business & Technology Report

February 2020

Space Heating in the Icebox of America:

Piloting Dual Fuel Solutions At Mountain Parks Electric Cooperative

NRECA
America's Electric Cooperatives

Business & Technology Report
February 2020

Space Heating in the Icebox of America:
Piloting Dual Fuel Solutions At Mountain Parks Electric Cooperative

Prepared By:

Katherine Dayem and Catherine Mercier
Xergy Consulting
(970) 459-4588 x102
www.xergyconsulting.com

NRECA Subject Matter Expert:

Brian Sloboda
Director, Consumer Solutions
Brian.sloboda@nreca.coop
(703) 907-5689

NRECA
America's Electric Cooperatives

Table of Contents

1. Executive Summary 1

2. Background and Motivation 3

3. ASHP Basics 4

4. Methodology 5

Equipment Selection 7

Participant Selection 8

Installation 9

Instrumentation and Monitoring 11

Baseline 12

5. Results and Lessons Learned 13

Thermostat Set Points and User Behavior 13

Fuel Usage and Cost Savings 13

Heat Pump Performance 16

Load Shapes and Demand 18

Emissions 20

Member Experience and Education 21

6. Implications for Program Design 22

7. Acknowledgements 26

8. References 27

1. Executive Summary

After a decade of declining or stagnant electricity sales, Mountain Parks Electric, Inc. (MPE), an electric distribution cooperative located in northern Colorado, is exploring electric space heating technologies that could increase electricity sales while decreasing members' space heating costs. Air source heat pumps (ASHPs) are an efficient electric heating option, and models that can operate in cold climates (ccASHPs) are now available on the market. In this study, we pilot ductless cold climate air source heat pumps to test their performance in cold conditions, their cost effectiveness relative to using propane as heating fuel, and their potential to increase MPE's electricity sales.

MPE is located in Granby, Colorado and experiences some of the coldest winter weather in the U.S., averaging 79 nights a year below 0 °F. Much of the rural area served by the co-op is outside of natural gas service, and members in those areas generally use propane furnaces to heat their homes. MPE previously piloted a central ccASHP sized to address the entire heating load of the study home that previously used electric resistance heating. The results of the study showed that the ccASHP can yield fuel cost savings relative to electric resistance heating, and also suggested that the ccASHP might yield savings relative to heating with propane. This study explicitly tests the benefits of ccASHPs against propane furnaces.

Usually, space heating studies are designed so that equipment under test addresses most, if not all, of the home's heating load. MPE had an additional constraint, however. Sensitive to the installation cost members would pay, MPE set out to test a solution that did not require member costs of more than $5,000. With this constraint, a dual fuel system utilizing a central ccASHP and the existing propane furnace was too expensive. The solution that did seem viable from a first cost perspective was adding ductless ccASHPs to offset part of the home's heating load.

The study team installed and monitored ductless ccASHP systems and existing propane furnaces in three Granby area homes and found mixed results. After the data collection phase of the project, the study team learned that occupants at one study home were using supplemental heating that was not metered during the study and corrupted the results. Of the two remaining homes, both saw fuel cost savings over the heating season, but only one realized enough savings for the initial investment to be cost effective (Table 1).

Table 1: Energy and cost savings of the ccASHP + furnace test case over the baseline propane furnace

		Home A	Home B
Energy savings	kBtu	18,400	36,400
	%	27%	38%
Cost savings	$	$170	$540
	%	11%	26%
Payback period		42	13
Cost effective		no	yes

The ccASHPs addressed about 43 to 46 percent of heating load over the heating season. At temperatures above 5 °F to 10 °F, the ccASHPs were less expensive to run than the propane furnace. Below that temperature, however, the heat pumps lose performance and use more electricity to keep up with heating demand. Consequently, the ccASHPs were most beneficial in the warmer months of the fall and spring, and less so in the cold winter months.

Member participants were happy with the ccASHPs and reported their homes were more comfortable with the heat pump systems. They reported more even and constant heat in the home when the ccASHPs were running. The only major complaint was increased electricity bills, which can be surprising to members if not compared to the related savings in propane costs.

The results show that with current equipment costs and fuel and electricity prices, ductless ccASHPs that address about half of the heating load of a home can be cost effective in some cases. Reduced initial costs and electricity rates and increased propane costs increase cost effectiveness. Any future ccASHP program would require careful consideration of rates and rebates to yield cost effectiveness to the consumer.

2. Background and Motivation

Mountain Parks Electric, Inc. serves the Fraser Valley and surrounding areas in northern Colorado. At an 8,500 of feet, the area averages 79 nights a year below 0 °F. Like many electric cooperatives across the country, MPE has witnessed stagnant and declining load over the past decade. One strategy MPE has identified to combat declining load is promoting electric space heating. Most of MPE's members use natural gas or propane as their primary fuel source for space heating, making electrification an attractive possibility to create new load, if it can save members money.

MPE has implemented an electric space heating program in the past to increase load. From 1990 to 2012, MPE promoted and offered time-of-use rates on electric thermal storage (ETS) systems. The program successfully grew MPE's load in off-peak afternoon and overnight hours. In 2012, MPE discontinued offering incentives for ETS because of concern that additional ETS units could impact wholesale peak demand charges.

Until recently, other electrified space heating came in the form of electric resistance, such as baseboard or electric forced air furnaces. Electric resistance heating is not cost effective for members compared to natural gas or propane heating. Air source heat pumps, however, move heat from outdoors to indoors, rather than produce that heat, making them a much more efficient electric space heating option. New advances in technology have led to heat pumps that can operate in sub-zero temperatures. If these cold climate ASHPs can maintain performance during MPE's cold winters, they could be a cost-effective space heating option for their members. Ductless ASHP have been tested with some success in cold climates, particularly Minnesota (Schoenbauer et al. 2017) and the Northeast (NEEP 2017).

MPE started examining ccASHPs in a small pilot conducted in 2017-2018. MPE installed two ductless ccASHPs that were sized for the heating load of the home,[1] totaled 5.5 tons of capacity, and were rated to maintain 100 percent performance at 5 °F and 90 percent at -13 °F in a 1,900 ft^2 study home. The homeowner used the ccASHPs as the primary heating source, and the existing electric resistance baseboard heating as back-up. The ccASHPs were able to address a large majority of the home's heating needs. Assuming that a propane furnace was used as a back-up heating system instead of electric baseboard, MPE estimated that at their electricity rate of $0.109 per kWh, if propane cost more than $1.92 per gallon, fuel costs for the ccASHPs and backup furnace would be less than for a propane furnace.

[1] Average high temperatures in the Fraser Valley are in the low 70s in the summer, and air conditioning is rarely needed. In this pilot, heat pump equipment was sized to fully (phase 1) or partially (phase 2) address heating load.

Propane costs in Colorado have been in the range of $2 per gallon over the past several years (U.S. EIA 2019). However, during the time of the pilot, a local propane distributor was offering prices between $1.40 to $1.70 per gallon with a minimum delivery requirement. The pilot results, therefore, did not provide conclusive outcomes on which MPE could base program decisions, but were compelling enough for MPE to further pilot ccASHPs.

During the heating season of 2018-19, MPE, in partnership with NRECA and its consultant Xergy Consulting, piloted ductless ccASHPs with back up propane furnace heating systems in three homes. These homes are in rural areas of MPE’s territory, where natural gas service is unavailable. The primary research question the study team examined was whether a ccASHP system with a propane furnace backup could save members money while providing additional kWh sales. In most pilots and programs, the heat pump system is sized to address most or all of the home’s heating load. This study is unique in that MPE started with an initial cost requirement: MPE aimed to test equipment that members could reasonably purchase in a future pilot.

The research team worked to answer the following questions:

- How does installed equipment performance compare to manufacturer claims?
- What fraction of heating load is being met by ccASHP vs. propane furnace and under what conditions? What is the optimal outside air temperature to disable operation of ASHP?
- Can the ASHP meet member-specified setpoints?
- Is an ASHP program advisable for MPE and its members?

This report describes the pilot and its outcomes.

3. ASHP Basics

To heat a home, an ASHP absorbs heat from outdoor air and releases it indoors (Figure 1). In the heating cycle, latent heat energy is absorbed by vaporized refrigerant that runs through a heat exchanger coil in the outdoor unit. The refrigerant travels through conduit to one or more indoor units, where it is pressurized to release the latent heat and run through a heat exchanger coil. Indoor air is blown over the coil, absorbs the heat, and is released into the living space.

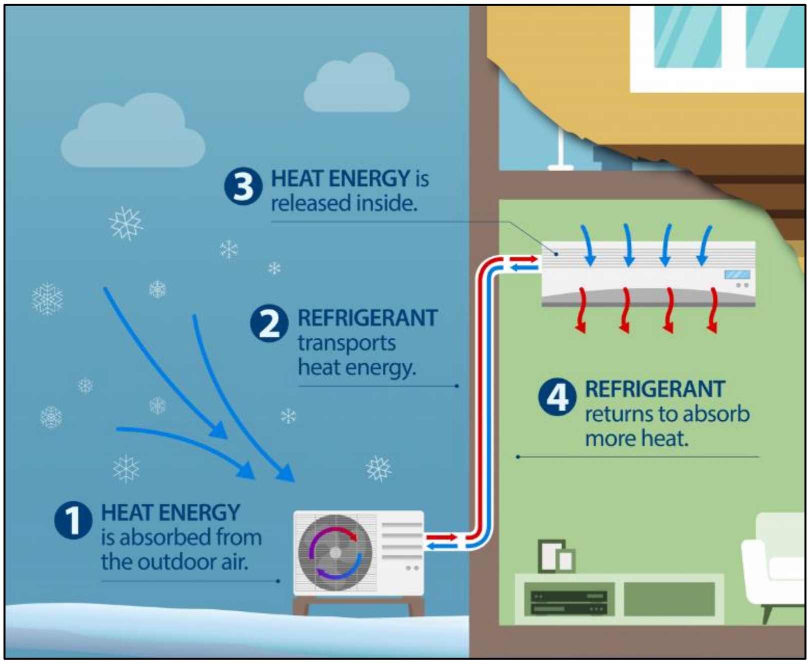

Figure 1: Illustration of a ductless ASHP in heating mode. Image from https://www.michigan-energy.org/heatpumps

The effectiveness of an ASHP in moving heat from outdoors to indoors is described by the coefficient of performance (COP), which is the amount of energy it delivers divided by the amount of electricity it consumes. In mild climates, ASHPs can achieve COPs of 3.5 or greater, meaning that they move 3.5 times energy than they consume. ASHP performance depends on temperature; COP decreases with outdoor air temperature, because the refrigerant cannot absorb and move as much heat. If temperature is cold enough, ice can build up on the outside of the outdoor unit's heat exchanger, further reducing its ability to move heat.

In recent years, more ccASHP models have become available on the U.S. market. These models can operate at full capacity in sub-freezing temperatures by using refrigerants that vaporize at very low temperature and variable speed compressors to better match refrigerant cycling with heating demand. In addition, these units include a defrost cycle, which allows the refrigerant to heat the outdoor coils periodically to prevent ice buildup. During the defrost cycle, the indoor space either does not receive heat, or is heated with electric resistance heat in the indoor unit. Although the length and frequency of the defrost cycle varies by manufacturer and product, the amount of time a given unit must spend in the defrost cycle increases as outdoor air temperature decreases. Field measurements in a pilot in Minnesota, for example, indicate that COP decreased by 13 percent at temperatures between 10 °F and 20 °F, by 11 percent at temperatures between 20 °F and 30 °F, and by 6 percent at temperatures between 30 °F and 40 °F due to defrost cycling (Schoenbauer et al. 2017). Although the defrost cycle reduces COP and increases electricity consumption, ccASHP units are often rated to maintain full heating capacity at outdoor temperatures as low as 5 °F.

4. Methodology

Pilot initiation consisted of two major phases: (1) equipment, site, and instrumentation selection; and (2) equipment and instrumentation installation. Our approach is discussed below.

Equipment Selection

CcASHPs with furnace backup can be sized in a variety of ways. Often, the systems are sized so that they can address most or all of a home's heating load on the coldest day of the year. For example, during the first phase of the pilot, MPE installed a 5.5 ton ductless system that could address most of the study home's heating load at a cost of almost $20,000. Realizing that most of their members could not participate unless initial costs were much lower, MPE took a unique approach in the second phase of this pilot: they set out to test a system that would cost participants of a future program on the order of $5,000 to install. **This constraint ruled out central or ductless systems sized to address all or most of the home's heating load.**[2]

MPE selected a Mitsubishi Hyper Heat ductless system, which consisted of one 2-ton (24,000 Btu) outdoor unit (model #MXZ-3C24NAHZ2) and two indoor units. The indoor units were 1.5 tons (18,000 Btu, model MSZ-FH18NA2) and 0.75 tons (9,000 Btu, model MSZ-FH09NA) highwall units. Specifications of the outdoor unit are provided in Table 2. The indoor units were installed to serve high occupancy areas of the home, and the remainder of the home would be heated by the existing propane furnace.

Table 2: Outdoor unit specifications.

Heating Capacity	24,000 Btu/hour
HSPF	10.0
Maximum COP	4.25
Heating Capacity at 5 °F	100%
Heating Capacity at -13 °F	90%
Note: HSPF is the heating season performance factor, a metric to measure performance of ASHP. It is a ratio that compares the heat output to the electricity consumed over the entire heating season.	

[2] Systems that are designed to address most to all of a home's heating load are often called "dual fuel systems," and operate only one heating component (the heat pump or the furnace) at a time. Due to the first cost constraint, the ccASHPs tested in this study were sized well below the home's heating load, and the heat pump and furnace were allowed to run simultaneously to adequately heat the house.

Participant Selection

MPE selected three homes for the study based on ideal building and occupancy criteria developed by the study team (Table 3). To allow the ccASHP systems to heat the most square footage of the study homes as possible, MPE sought 1,200–1,800 ft^2 single story homes with open floor plans. To additionally maximize the proportion of the heating load that could be addressed by the heat pumps, the study team sought out newer homes (built after 1980) that were likely to be better insulated and air sealed than older homes. Finally, the home must have a central forced-air propane furnace as its primary heating system, and participants must agree to not use any secondary heating, such as wood stoves or fireplaces.[3]

To participate, homeowners must have been full-time residents with consistent occupancy levels over the past few years. The participants also agreed not to sell their home for at least one year after the pilot, in case additional monitoring would be helpful after the pilot.

Table 3: Ideal study site characteristics.

Building Characteristics	Occupant Characteristics
▪ Single story ▪ Open floor plan ▪ 1,200 - 1,800 sf ▪ Post-1980 construction ▪ Primary heating system is central forced-air propane furnace	▪ Own and occupy the home; demonstrate consistent occupancy levels over the past 3 to 5 years ▪ Full-time residents ▪ Agree not to see home for at least one year after pilot ▪ Agree to use appropriate equipment during baseline and test periods.

A large portion of the housing stock in MPE's territory is second homes, and finding participants who fit all the criteria above was challenging. Ultimately, MPE selected three study homes that met most of the building criteria, and whose owners met the occupant criteria. The homes were one or two stories and ranged in size from 1,200 to 2,300 ft^2 (Table 4). All study homes were built in the 1990s.

[3] Unfortunately, as we discuss later in this paper, one home violated this requirement and rendered its data unusable.

Table 4: Study home characteristics.

Home ID	Stories	Size (ft²)	Year Built	Furnace Output (Btu)	Furnace AFUE
A	1	1176	1997	67,500	92.1
B	2	2308	1993	Unknown	Unknown
C	2	1596	1994	91,000	92.0
Note: AFUE is the annual fuel utilization efficiency, a measure of the useful heating provided to the conditioned space divided by the energy consumed by the furnace over the heating season. Simply put, it is the season-averaged efficiency of the furnace.					

Installation

The study team and HVAC contractor NoCo Heating & Air, Inc. installed the ccASHPs and associated instrumentation (discussed in the next section) on October 29-30, 2018. Outdoor units were installed on or adjacent to each home in a location with good access to the indoor unit locations to minimize conduit runs (Figure 2). Refrigerant lines were run though conduit from the outdoor unit, through a small penetration in the wall, to each indoor unit.

Figure 2: Outdoor units and refrigerant line conduit of ccASHP installation. Left to right: study homes A, B, and C. Photos by Chris Michalowski, MPE.

Indoor units were installed in high occupancy areas of the study homes. The larger, 18,000 Btu indoor unit was installed in the main living space. The smaller, 9,000 Btu indoor unit was placed in a smaller high-occupancy area, such as a bedroom or office (Figure 3, Table 5).

Table 5: Indoor unit locations and furnace and heat pump set points for each study home.

Home ID	Furnace Set Point (°F)	Indoor Unit 1		Indoor Unit 2	
		Location	Set Point (°F)	Location	Set Point (°F)
A	68	Living Room	72	Master Bedroom	69
B	63	First Floor Living Room	72	First Floor Office	72
C	66	Main Floor Living Room	66	Downstairs Den	66
Note: Each indoor heat pump unit was controlled by a thermostat on the unit. Indoor unit 1 is 18,000 Btu and Indoor unit 2 is 9,000 Btu.					

Figure 3: Indoor units installed in study home B.
Left: Indoor unit 1. Right: Indoor unit 2. Photos provided by Chris Michalowski, MPE.

Remaining areas of each home would be served by the existing propane furnace. To minimize the heating impact of the furnace in areas served by the ccASHP, furnace registers were closed in these areas during the test periods of the pilot. In addition, the study team ensured that the furnace thermostat was located away from areas served by the heat pumps, and relocated the thermostat in one study home to do so.

The existing furnace would continue to be controlled through its existing thermostat. The thermostat on each indoor unit was set separately. The study team encouraged participants to set a lower furnace set point than the heat pump set point(s), but ultimately allowed them to use setpoints that made them comfortable.

The average price of equipment and labor was $7,200 after a rebate of $900 from Tri-State, MPE’s generation and transmission (G&T) co-op.

Instrumentation and Monitoring

The study team used an instrumentation approach similar to a previous pilot of ccASHP carried out in by the Center for Energy and Environment in Minnesota (Schoenbauer et al. 2017). The study team monitored energy use of the furnace and ccASHP, and air temperatures within the study homes (Figure 4). Each study home was instrumented with:

- One MPE AMI meter measuring electricity of the ccASHP. The meter was installed on the supply side of the outdoor unit and measured total electricity of the outdoor and indoor units combined.
- One gas meter to measure propane use of the furnace. The meter was installed next to the furnace, and only measured propane consumed by the furnace.
- Temperature sensors to measure supply temperature of each indoor unit.
- Temperature sensor to measure room temperature at the furnace thermostat.

The study team attempted to gather information that would allow COP estimates, including airflow out of each indoor unit, and current draw of each indoor unit. Unfortunately, the team's airflow measurement method of balancing air flow from the indoor unit with a duct blaster was too crude to make accurate measurements. In addition, current transducers installed on wiring from the outdoor unit to the indoor units did not provide reliable data. Therefore, the study team was unable to estimate COP.

With the exception of the electricity meter, which was connected to MPE's AMI system, data was transferred wirelessly within the study home to a router connected to the member's modem, which uploaded data to the monitoring equipment vendors' cloud. Data was monitored on a daily basis to ensure instrumentation was functioning normally and downloaded from the cloud service on a monthly basis. Hourly weather data was downloaded from a Weather Underground station in Fraser, near the study homes and at a comparable elevation.

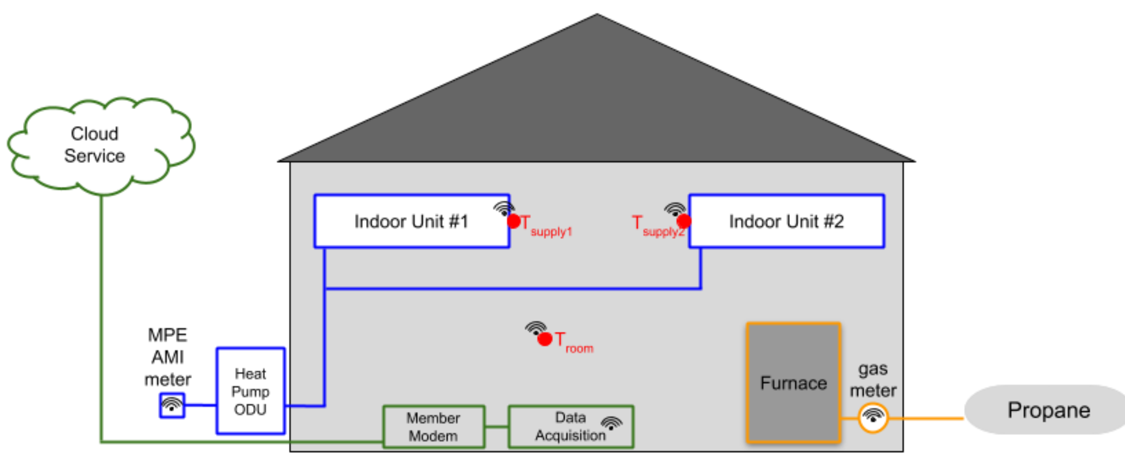

Figure 4: Illustration of instrumentation and data acquisition set-up.

Baseline

Because propane usage of the furnace in years prior to the study was unknown, the study team ran baseline periods during the pilot. Baseline periods were scheduled every six weeks and lasted 10 days each. At the beginning of each baseline period, participants turned off their heat pumps, opened the furnace registers that had been closed in areas heated by the heat pumps, and, in some cases, turned up the furnace set point to a comfortable temperature. The study team confirmed that heat pumps were off by reviewing the AMI data. At the end of the baseline period, participants returned the equipment to the test period conditions.

5. Results and Lessons Learned

Thermostat Set Points and User Behavior

In general, pilot instrumentation gathered data reliably, with the exception of one 2-day gap in gas data that resulted from an outage of the vendor's cloud. Weather data was reliably reported on a sub-hourly basis, with few missing days.

Although the study team made recommendations on set points, specifically asking that participants use a higher set points for the heat pumps than the furnace to give the heat pumps the best opportunity to offset the furnace, participants did have ultimate control over set points (Table 5). The set points are likely a main driver of fuel cost savings realized by participants, as discussed below.

Unfortunately, during post-pilot participant interviews, the study team learned that home C ran a propane stove most evenings to supplement heating in the living room. Because stove propane use was not metered, we have little insight into the amount of heating that the stove delivered to the space. Consequently, we focus on results from homes A and B in the discussion below.

Fuel Usage and Cost Savings

Results were weather normalized by applying a linear fit to each home's heating load versus heating degree days (HDD).[4] Normal heating loads and fuel usage were then calculated for a typical meteorological year.

Weather normalized fuel usage of the baseline (furnace propane) and test case (furnace propane and heat pump electricity) are summarized in Table 6. For both homes with reliable data, energy use for space heating decreased when the heat pumps were in use. Over the heating season, home A's energy use decreased by 27 percent, and home B's decreased by 38 percent. The heat pumps addressed just under half of the homes' heating load: 46 percent in home A, and 43 percent in home B.

We note that the reported energy consumption does not include the electricity used by the air handler in the furnace. Future field studies should make efforts to meter this electricity use to more fairly compare total energy use of the baseline and test case systems. Air handler energy use will increase energy consumption in both the measure and test cases in Figure 6, but since the furnace runs more frequently in the baseline case, baseline

[4] HDD is a measure of a building's heating demand for a given day. HDD is calculated by subtracting the outdoor temperature from building setpoint: HDD = $T_{setpoint} - T_{outdoor}$.

energy use will increase more than test case energy with the addition of air handler electricity usage.

Table 6: Weather normalized fuel consumption and cost for baseline and test cases over the October to April heating season.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Home A</th><th colspan="2">Home B</th></tr>
<tr><th>Baseline</th><th>Test case</th><th>Baseline</th><th>Test case</th></tr>
<tr><td rowspan="5">Equipment</td><td>Furnace AFUE</td><td colspan="2">91.2</td><td colspan="2">Unknown</td></tr>
<tr><td>Furnace capacity (kBtu/hr)</td><td colspan="2">67.5</td><td colspan="2">Unknown</td></tr>
<tr><td>ASHP HSPF</td><td rowspan="3"></td><td>10</td><td rowspan="3"></td><td>10</td></tr>
<tr><td>ASHP capacity (kBtu/hr)</td><td>25</td><td>25</td></tr>
<tr><td>ASHP cost</td><td>7,200</td><td>7,200</td></tr>
<tr><td rowspan="7">Energy consumption</td><td>Propane (kBtu)</td><td>67,700</td><td>26,400</td><td>95,600</td><td>33,500</td></tr>
<tr><td>Electricity (kBtu)</td><td rowspan="2">0</td><td>22,900</td><td rowspan="2">0</td><td>25,700</td></tr>
<tr><td>Electricity (kWh)</td><td>6,720</td><td>7,520</td></tr>
<tr><td>Total (kBtu)</td><td>67,700</td><td>49,300</td><td>95,600</td><td>59,200</td></tr>
<tr><td>Savings (kBtu)</td><td rowspan="3"></td><td>18,400</td><td rowspan="3"></td><td>36,400</td></tr>
<tr><td>Savings (%)</td><td>27%</td><td>38%</td></tr>
<tr><td>Heating load addressed by heat pump</td><td>46%</td><td>43%</td></tr>
<tr><td rowspan="4">Energy cost</td><td>Propane</td><td>$1,480</td><td>$580</td><td>$2,090</td><td>$730</td></tr>
<tr><td>Electricity</td><td>$0</td><td>$730</td><td>$0</td><td>$820</td></tr>
<tr><td>Total</td><td>$1,480</td><td>$1,310</td><td>$2,090</td><td>$1,550</td></tr>
<tr><td>Savings</td><td rowspan="3"></td><td>$170</td><td rowspan="3"></td><td>$540</td></tr>
<tr><td colspan="2">Payback period (years)</td><td>42</td><td>13</td></tr>
<tr><td colspan="2">Cost effective</td><td>no</td><td>yes</td></tr>
</table>

Fuel cost was calculated assuming rates of $2.00 per gallon for propane (U.S. EIA 2019) and $0.109 per kWh for electricity.[5] Both homes saved on their total fuel costs for the heating season, but home B saved significantly more than home A (Table 6). This is likely due to a combination of factors, including overall space heating usage and set point selection. Home B is almost twice as large as home A, and therefore, has a larger heating load. In addition, the heat pump set points in home B were set 9 degrees higher than the furnace temperature, allowing the heat pumps to offset the furnace load as much as possible. Both indoor units were installed downstairs, where the occupants spent most of their time, and it is likely that the warm air rose into the upstairs space served by the furnace.

[5] At MPE, heat pumps are subject to its flat electricity rate of $0.109 per kWh. MPE has time-of-use rates for ETS systems only.

Fuel cost savings varies on a month-to-month basis, with maximum fuel savings in the shoulder seasons, and less savings during the cold winter months (Figure 5). This finding confirms that ccASHP performance decreases in cold weather. Even in the coldest winter months, however, operating the ccASHP with the furnace saves money compared to the furnace alone.

Lifetime cost effectiveness depends on initial cost and assumed lifetime of the ccASHP. The average install cost for sites in the pilot was $7,200 after a $900 Tri-State rebate. Lifetime of the ccASHP is expected to be at minimum 12 years (which is the length of Mitsubishi's warranty on the units) and average 18 years (Kolwey and Geller 2018). Assuming consistent annual savings, home A would not pay back the initial $7,200 investment within the lifetime of the product (payback is about 42 years). Home B would pay back the initial cost, however, in 13 years. Propane prices can change dramatically year over year and during the heating season, so payback periods may change, as discussed further in Section **Error! Reference source not found.**.

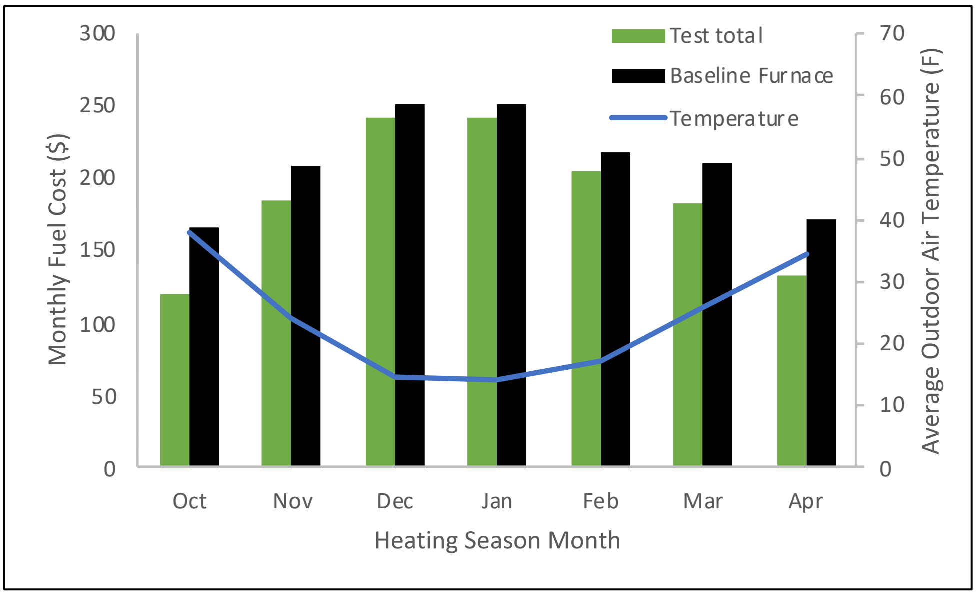

Figure 5: Monthly weather normalized fuel cost for baseline (black) and test (green) periods, and 30-year average monthly temperature (blue line) for Home A.

(See the next chart for data on Home B.)

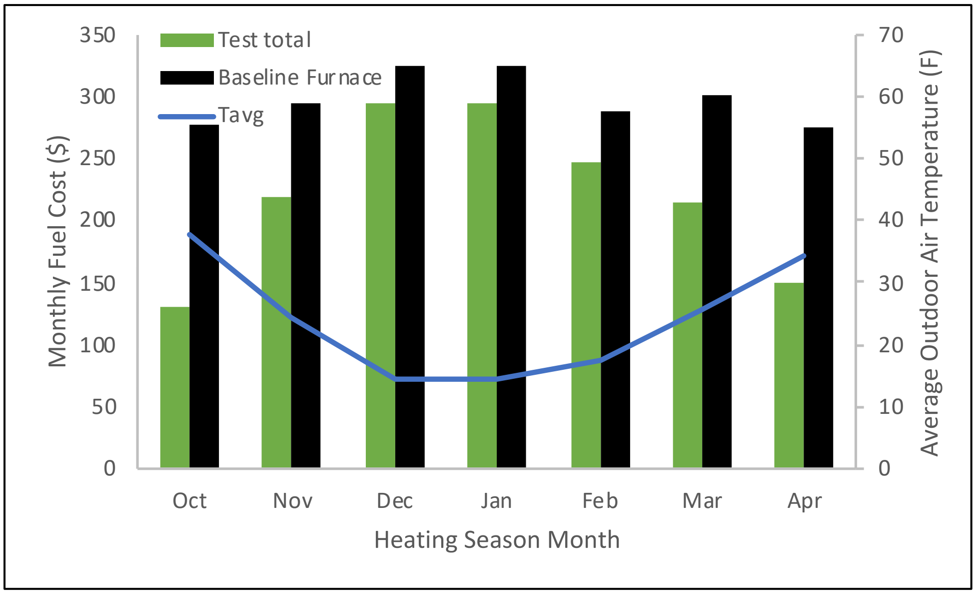

Figure 6: Monthly weather normalized fuel cost for baseline (black) and test (green) periods, and 30-year average monthly temperature for Home B.

(See previous chart for data on Home A.)

Heat Pump Performance

Heat pump performance is usually measured as COP, which can be calculated as:

$$COP = \dot{m}C_p(T_s - T_R)$$

where $\dot{m}$ is the mass flow of the air through the heat pump supply, C_p is the specific heat of air (in units of energy per degree temperature per weight), T_s is the temperature of air when exiting the heat pump (supply temperature), and T_R is the temperature of air entering the heat pump (often estimated using room temperature). Although we were not able to make the airflow measurements necessary to estimate the ccASHP's COP, we are able to infer relative performance from other observations, including:

- **Supply temperature:** Do the ccASHP maintain supply temperature as outdoor air temperature decreases?
- **Room temperature:** Do the ccASHP and furnace systems maintain room temperature as outdoor temperature decreases?
- **ccASHP energy use:** Does the ccASHP draw energy proportional to outdoor air temperature?

We found that in both homes A and B, heat pump supply temperature degraded slightly when air temperature dropped below about 0 °F, but that the room temperature (measured at the furnace thermostat), was almost always greater than the furnace set point. This indicates that the ccASHP + furnace system maintained expected room air temperatures, and when the heat pump performance degrades at low outdoor temperature, the furnace addressed lost capacity.

Hourly ccASHP electricity usage data also indicates decreased heat pump performance at low outdoor temperature (Figure 6). At temperatures above about -10 °F to 0 °F, the relationship between heat pump energy use and air temperature is approximately linear, indicating that the heat pump is able to supply heat to the space by increasing energy use. However, at lower temperatures, this relationship breaks down, particularly in home B.

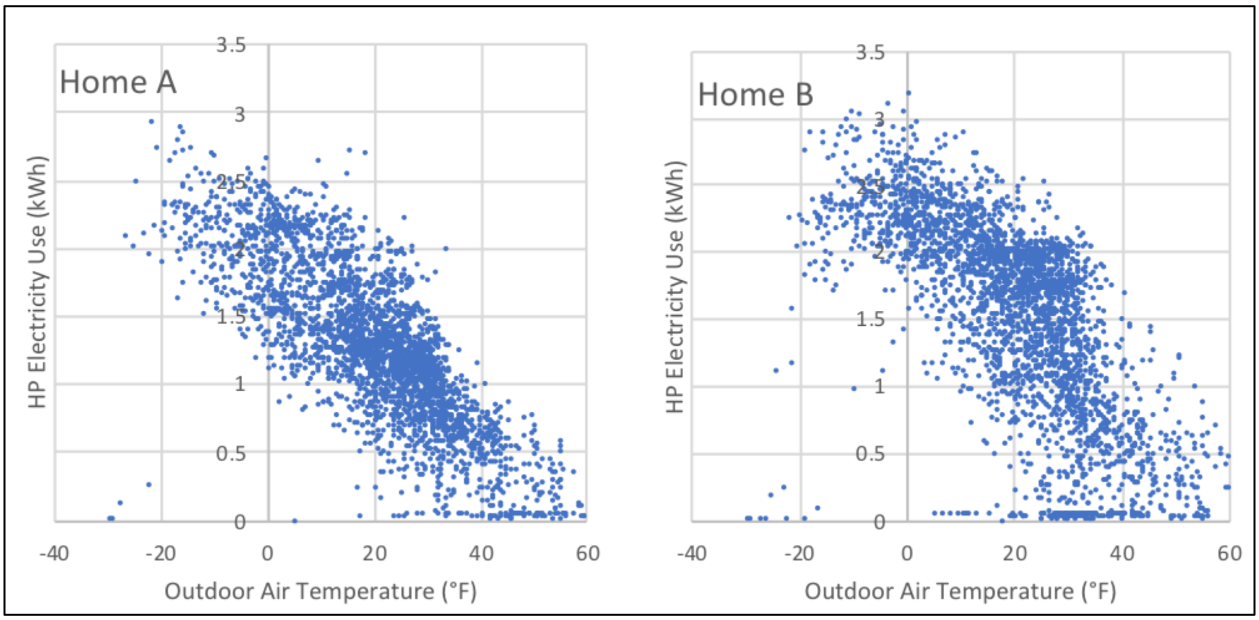

Figure 7: Hourly heat pump electricity use versus outdoor air temperature for study homes A (left) and B (right).

Daily fuel cost as a function of HDD (or outdoor air temperature) shows the cost optimal temperature range for operating the ccASHP (Figure 7). For both study homes A and B, it is less expensive to run the ccASHP + furnace system at HDD less than 60, or outdoor temperature of about 5 °F to 10 °F. Below 5 °F to 10 °F, it is cheaper to heat with the propane furnace.

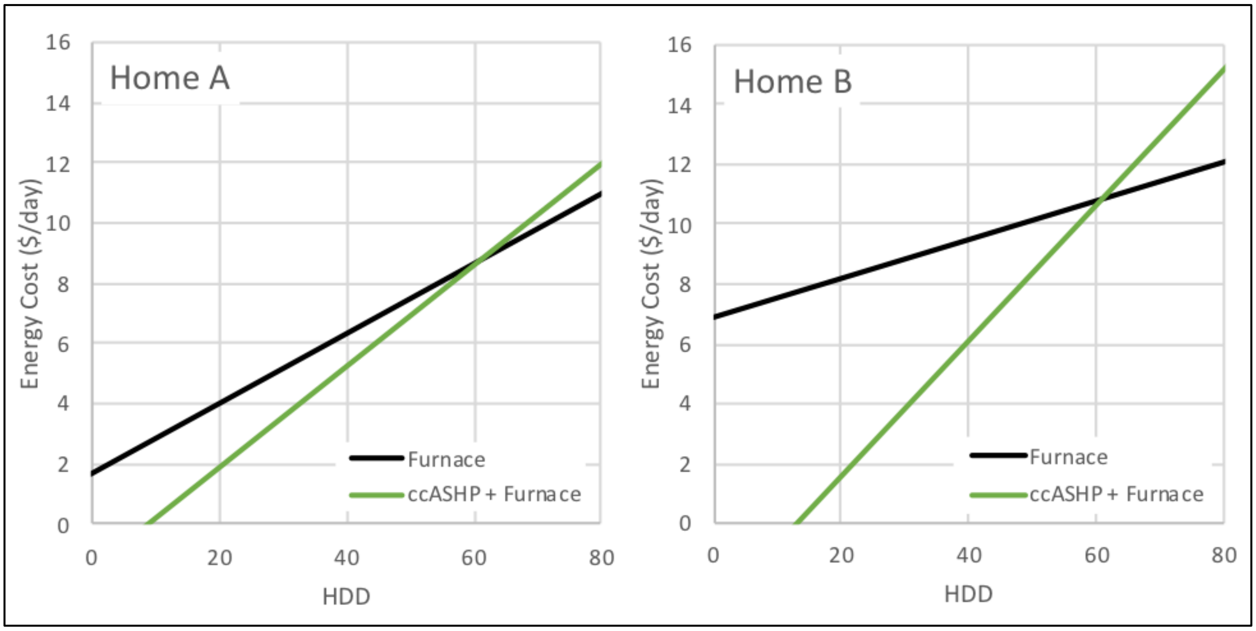

Figure 8: Daily space heating fuel cost versus HDD for study homes A (left) and B (right).

Load Shapes and Demand

Typically, ASHPs are run at a constant set point temperature, rather than set back during the day and night hours when occupants are away or sleeping. This is because the variable speed compressors in ASHPs are most efficient when they are using the middle range of their capacity to address heating load (NEEP 2017). When the ASHP must run at full capacity, performance decreases and electricity use increases (Foster et al. 2017). During the pilot, occupants could set their desired temperature on each indoor unit using a remote, and that temperature was maintained unless they changed it.

Because the set point remains constant, the ccASHP load shape tracks outdoor air temperature in a predictable way. CcASHPs draw maximum load during the overnight and morning hours, when temperatures are coldest (Figure 8). The ccASHP load decreases through the afternoon as the day warms up, and then ramps up again when it begins to cool down outside. In the winter, load peaks around 2 kW between midnight and 8 a.m. or 10 a.m. In the shoulder months of November and March, homes still have a significant heating load, and the ccASHPs draw about 1.7 kW overnight. By April, temperatures warm and heating load decreases to about 1.2 kW overnight.

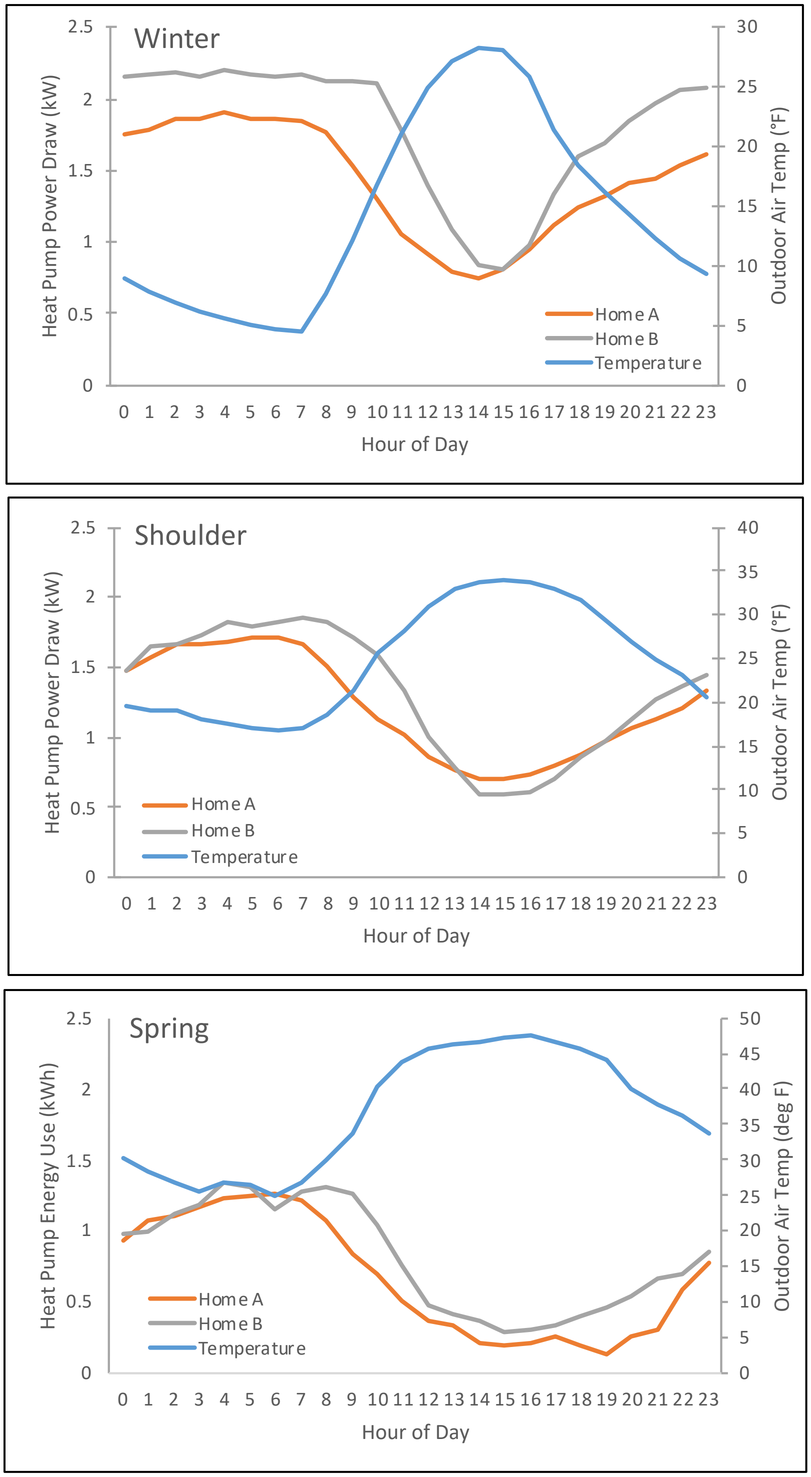

Figure 9: Seasonal load curves for winter (December through February), shoulder (November and March), and spring (April) seasons.

Maximum demand of the heat pumps is about 3 kW, and occurs at the lowest outdoor temperatures, which typically occur overnight (Figure 9). MPE is assessed demand charges for peak demand between the hours of noon and 10 pm. Depending on the time of day of the assessed peak, each home could contribute between 1.5 kW to and 2.8 kW to MPE's peak.

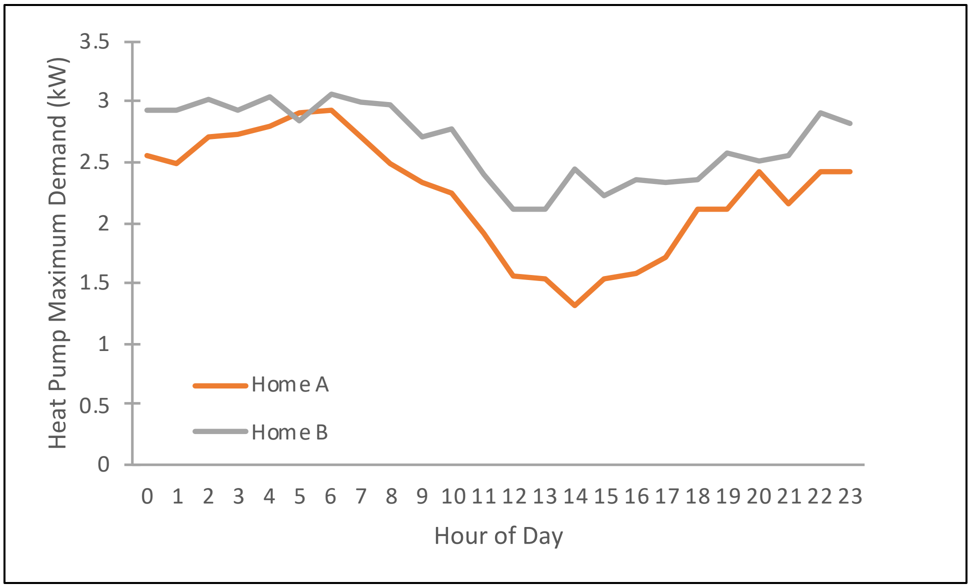

Figure 10: Maximum demand for each hour of the day over the heating season.

Emissions

In addition to cost savings, the impact of an electrification measure on atmospheric emissions is often evaluated. Although the annual emissions impact of a fossil fuel furnace remains constant (assuming climatic normal temperatures) over its lifetime, the emissions intensity of an electricity-using product such as a ccASHP will change as the electric grid resource mix changes. Electricity generation emissions can vary over the course of the day (as generation mix and demand vary), and over the years (as old and often coal-based generation is retired and lower carbon generation sources are commissioned). Current and future generation mix and emissions intensity varies from grid to grid.

To provide a rough estimate of whether or not the ccASHP + furnace system will yield emissions savings compared to the baseline propane furnace, we can calculate an emissions "tipping point." If the average emissions intensity of electricity used by the ccASHP over its lifetime (assumed to be 18 years) is less than this tipping point, the measure will reduce emissions.

Based on the electricity and propane usage of the study homes, we estimate that the emissions impact of electricity used by the ccASHP must *average* 800 lb CO_2/MWh and 1,100 lb CO_2/MWh over the lifetime of the ccASHP for homes A and B, respectively, to achieve emissions reductions with the ccASHP + furnace system. Even if heating season emissions of a particular grid are larger than 800-1,100 lb CO_2/MWh at present, a ccASHP may yield emissions reductions over its lifetime, if grid emissions decrease in the future. In some cold climate regions of the country, average grid emissions intensity is already low enough to yield emissions savings even in the first year of operation. These regions include New England and upstate New York (U.S. EPA 2016).

For most electrification measures, additional cost and emissions savings can be gained by controlling the end use to avoid operation during demand peaks, when costs and emissions are increased. Heat pumps, however, are most efficient when they operate at a constant set point rather than being set back (see previous section). Therefore, more study is needed to quantify the efficiency losses related to temperature setbacks versus the cost and emissions savings related to avoiding operation during peak hours to better understand the benefits of peak avoidance.

Member Experience and Education

Member participant feedback regarding the heat pumps was mostly positive. “We give it a big thumbs up on the heat pump.” They reported that their homes were warmer and more comfortable than they had been before the installation of the ccASHP. “We are loving this system so far, with a warmer house… since the [ASHP] system was turned on.” The members of one home had been using space heaters to provide supplemental heating before the pilot, but did not see any need for them after the ccASHPs were installed: “We are warmer with the combined systems and haven’t been using space heaters anymore.”

The only major negative feedback related to increased electricity bills. “That first electric bill shocked us!” noted one participant. This speaks to the need to educate and prepare members who install ccASHP that their monthly electricity bills will increase significantly, and that the savings they will see will be on their overall energy bills, and may not be appreciated without a look at the whole heating season.

6. Implications for Program Design

As the results above indicate, member characteristics such as thermostat settings and home heating requirements can influence how much savings can be achieved with a ccASHP + furnace system. The viability of a future ccASHP program also depends in part on whether or not members can realize enough savings to make the initial cost seem reasonable. The economics of a program can change due to changes in propane costs, electricity rates, and rebates offered to offset initial cost.

Propane price is the most volatile and least controllable economic variable of influence. Over the past 5 years, propane prices have ranged $1.64 to $2.43 per gallon (U.S. EIA 2019). Prices tend to be lowest in the fall, when members may be filling their tanks for the heating season, and higher in the winter, resulting in a more costly tank fill if the member needs to refill in the winter. Note that changing prices were not assumed in our analysis above. Depending on the amount of fuel used by a member, propane prices must be about $1.80 to $2.50 per gallon in order for a program with an initial cost of $7,200 to pay itself back in the lifetime of the product (Figure 10). Note that these figures do not include cost of capital or financing, which would further reduce cost effectiveness.

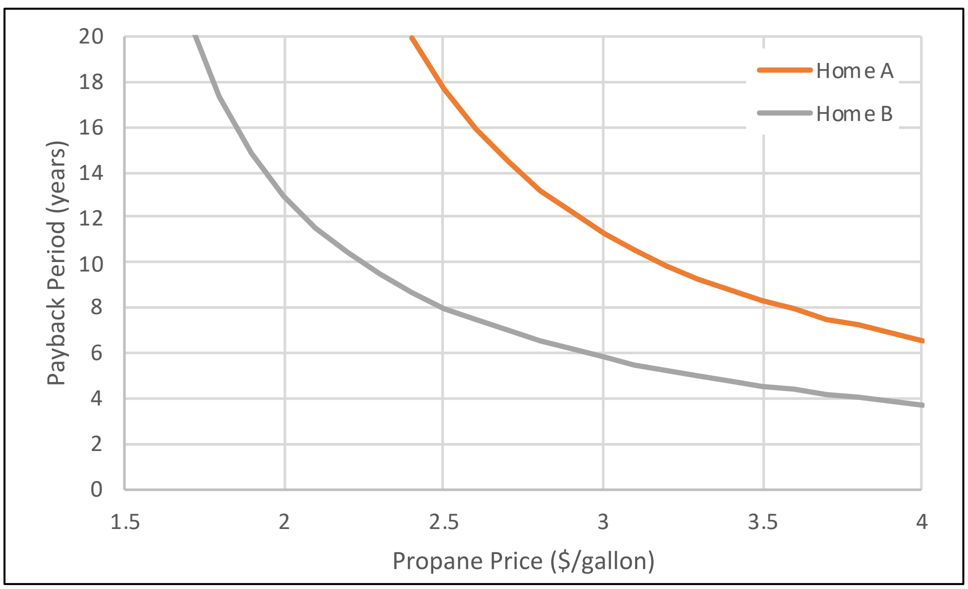

Figure 11: Payback period for a range of propane prices at study homes A and B. Calculations assume an electricity rate of $0.109/kWh and an initial cost of $7,200.

The co-op has more control over the other economic factors: electricity rate and rebates to reduce initial cost. Assuming a constant propane cost of $2.00 per gallon, reduced electricity rates can make the ccASHP cost effective to the member, if electricity rates are low enough (Figure 11). An electricity rate of about $0.05 to $0.07 per kWh would make the system cost effective for home A, while any rate below the current flat rate easily makes home B's system cost effective.

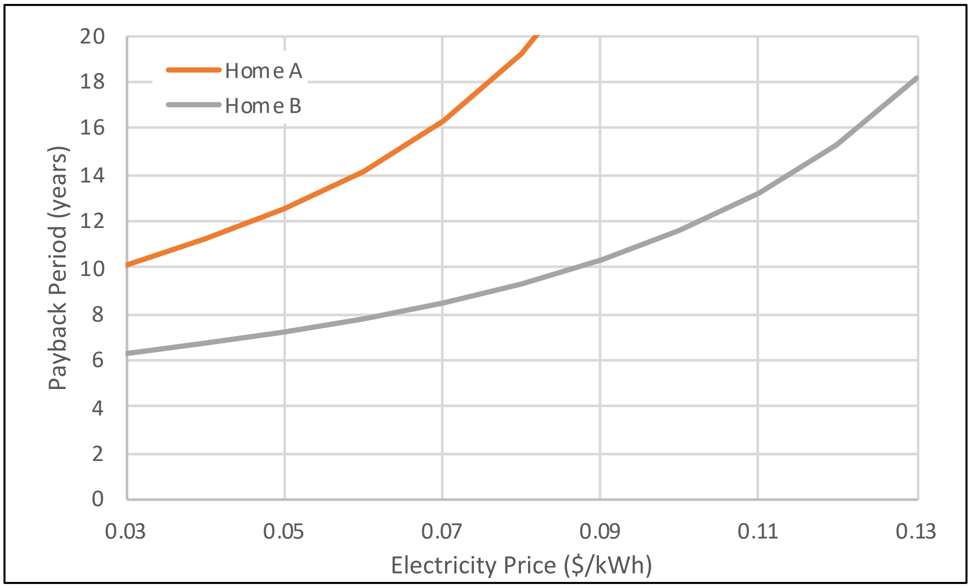

Figure 12: Payback period for a range of electricity prices at study homes A and B. Calculations assume a propane cost of $2.00 per gallon and an initial cost of $7,200.

Rebates to reduce initial cost can also make a potential ccASHP program more attractive to members. For the system to be cost effective for study home A, initial cost must be about $3,000 or less, given propane and electricity costs of $2.00 per gallon and $0.109 per kWh, respectively (Figure 12). Home B's system would be cost effective even without the $900 Tri-State rebate.

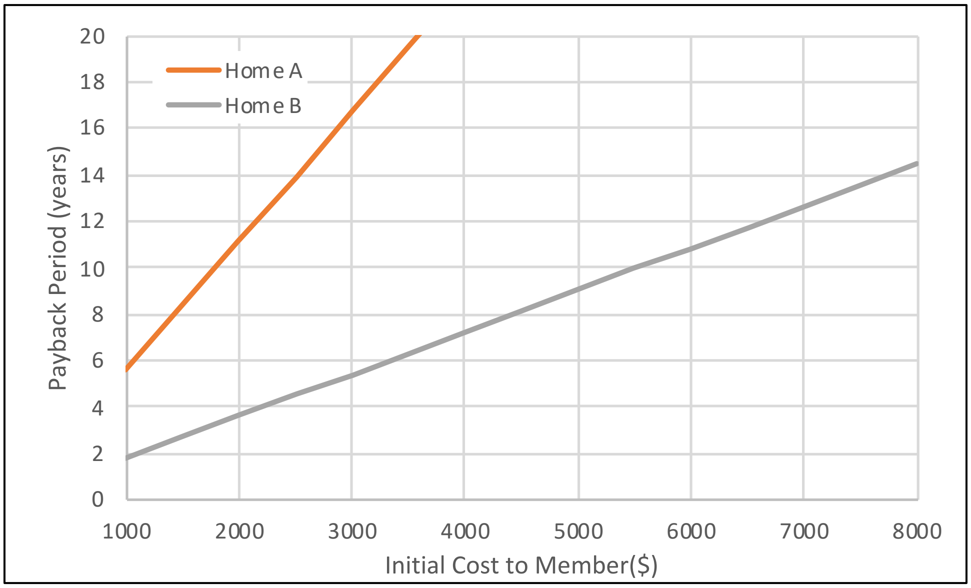

Figure 13: Payback period for a range of initial cost to member. Calculations assume a propane cost of $2.00 per gallon and an electricity rate of $0.109 per kWh.

The discussion herein indicates that there is a wide range of savings achieved by the study homes, and a wide range of program parameters that would lead to success for home B and not for home A. For a program to be successful, therefore, co-ops may focus on homes with large savings potential and seek ways to maximize savings realized.

Homes that have large savings potential generally consume more heating fuel and may use higher set points. More savings can be achieved in homes with a large difference in heat pump and furnace set points.

In addition, this study highlights the need for controls that can allow automatic switching between ccAHSP + furnace heating, and heating with the furnace alone. Central ducted systems can be controlled using a single thermostat that switches between heat pump and furnace operation based on outdoor temperature. We were not able to identify an analogous control technique for a ductless heat pump cassettes and a central furnace at the onset of this pilot.[6] If the systems could be optimally controlled, members could realize more savings by switching the heat pumps off at temperatures below about 5 °F to 10 °F, when fuel costs for running the furnace alone become lower than the combined system.

[6] In pre-pilot discussions with Flair, which makes wireless controls for ductless heat pumps, we learned that dual fuel control is theoretically possible with Flair's equipment and a smart thermostat. However, it was not an available feature of products on the market at the time of the pilot.

Finally, member education is important to make sure they use the heat pumps properly and set appropriate set points. Members also need to expect increased electricity bills and understand that savings is for total fuel costs.

7. Acknowledgements

We thank Chris Michalowski of MPE for his assistance and collaboration over the course of this project. Chris managed and carried out key elements of the pilot, including identifying and communicating with member participants, and assisted with instrumentation installation and troubleshooting.

8. References

Foster, S., S. Lyons, I. Walker, T. Thurnham. 2017. Hybrid Heat Pumps. Prepared for the United Kingdom Department for Business, Energy & Industrial Strategy by Element Energy Limited.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700572/Hybrid_heat_pumps_Final_report-.pdf

Kolwey, Neil and Howard Geller. 2018. Benefits of Heat Pumps for Homes in the Southwest. Prepared by Southwest Energy Efficiency Project.
http://www.swenergy.org/Data/Sites/1/media/documents/heat-pump-study-2018-06-11-final.pdf

NEEP [Northeast Energy Efficiency Partnerships]. 2017. Northeast/Mid-Atlantic Air-Source Heat Pump Market Strategies Report 2016 Update.
https://neep.org/sites/default/files/NEEP_ASHP_2016MTStrategy_Report_FINAL.pdf

Schoenbauer, B., N. Kessler, A. Haynor, D. Bohac, and M. Kushler. 2017. Cold Climate Air Source Heat Pump. Prepared for Minnesota Department of Commerce, Division of Energy Resources by Center for Energy and Environment.
https://www.mncee.org/MNCEE/media/PDFs/86417-Cold-Climate-Air-Source-Heat-Pump-(CARD-Final-Report-2018).pdf

U.S. EIA 2019. Weekly Colorado Residential Propane Price. Accessed August 2019.
https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=W_EPLLPA_PRS_SCO_DPG&f=W

U.S. EPA [United States Environmental Protection Agency]. 2016. eGRiD Summary Table. https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

Van Atten, C., A. Saha, L. Slawsky, C. Russell, and L. Hellgren. 2018. Benchmarking Air Emissions of the 100 Largest Power Producers in the United States.
https://www.mjbradley.com/sites/default/files/Presentation_of_Results_2018.pdf