Field Assessment of Ducted and Ductless Cold Climate Air Source Heat Pumps

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ABSTRACT

Air source heat pumps (ASHPs) have become one of the most exciting options for energy and environmental advocates. With large fractions of the country relying on delivered fuels (propane, oil) and electric resistance as their primary heating source — and an ever "greener" grid that is making electricity even more attractive — cold-climate air source heat pumps are starting to deliver on the promise of energy efficiency, reduced emissions, and happy customers. Recent changes to the new generation of ASHPs allow heat to be transferred into homes from exterior temperatures below 0° F, which has improved the capacity and effectiveness of ASHPs for a greater portion of the cold-climate heating season, thus reducing electricity and delivered fuel use. This paper reports on the updated results from a seven-site field study of cold-climate ASHPs that were installed in Minnesota homes, along with detailed monitoring equipment, to collect data. Both ducted and ductless systems were installed and analyzed. The study included a newly available ducted unit with plenum booster that eliminates the need for flex fuel systems. Data analysis showed considerable cost savings for the homeowner, from 30% to 56%. For retrofits, paybacks will typically be longer than 10 years, unless equipment replacement is necessary. At either heating or cooling system failure, heat pumps paybacks drop to 5- 6 years. For the flex fuel systems, the increased COP reduced the total propane consumption by about 60%, for the majority of MN homes, which is less than 500 gallons of annual consumption. This limits the need for costly winter refueling, as 500 gallons is the typical residential storage volume.

Introduction

This paper reports on Center for Energy and Environment's (CEE) recently completed *Field Assessment of Cold-Climate Air Source Heat Pumps* (Schoenbauer, Kessler, and Kushler 2017) that was supported by a grant from the Minnesota Department of Commerce, Division of Energy Resources through the Conservation Applied Research and Development (CARD) program. Additional work supported by Great River Energy, the Electric Power Research Institute, and Xcel Energy is also included.

Air source heat pumps (ASHPs) use refrigerant vapor compression to transfer heat from one location to another, allowing the system to heat a home during the winter and cool it during the summer. ASHP systems consist of an outdoor unit that contains a fan, outdoor coil, compressor, and expansion value, and an indoor unit that contains an indoor coil and fan. In heating mode, the outdoor unit uses a fan to draw outside air across a refrigerant-filled heat exchanger, thereby absorbing heat from the outdoor air. The compressor warms the cool refrigerant vapor by increasing the pressure of the refrigerant in the system. The warm refrigerant runs through the heat exchanger in the indoor unit, where cooler air from the house absorbs the heat from the refrigerant before the system delivers that heated air throughout the house by the indoor fan. In cooling mode, the system runs in the opposite direction, removing heat from the indoor air and transferring it outside, like a traditional air conditioning system.

ASHPs transfer heat from one location to another and do not generate heat directly. This heat transfer process makes ASHPs an efficient form of space heating and cooling, outputting more heat energy than the electrical energy required to run the system.

ASHP systems have been widely used for space heating in climates with mild heating seasons, and with recent upgrades in ASHP technology, systems can now meet the majority of a home's heat load in colder climates, offering a viable high-efficiency solution for space heating in cold-climate regions. These systems have the greatest potential for adoption in cold-climate regions where natural gas is not available for space heating, as ASHPs can offset the use of more expensive delivered fuels; or for homes that use electric resistance heating as their primary heat source. Additionally, as more federal and state policies require renewable sources of electric generation as a step on the path to becoming less carbon intensive, ASHPs will be a good option that increasingly benefits carbon emissions reduction.

Background

The addition of inverter technology to ASHP has improved system performance substantially, making the systems better suited for cold-climate heating. The inverter-driven compressor allows the compressor speed to modulate and increase capacity during periods of colder outdoor air temperatures. The first steps in market growth and program development for inverter-driven heat pumps started with the Northeast Energy Efficiency Partnerships (NEEP) in 2008. Since then the capabilities and applications of this technology have only expanded. This project reports on several of these applications, including ducted flex fuel whole house systems, ducted all electric whole house systems, and ductless mini-split systems. Each of these system types is capable of meeting the cold climate specifications created by NEEP. These specifications were created to identify cold-climate ASHPs (ccASHPs) and include variable capacity compressor, coefficient of performance (COP) at 5°F ≥ 1.75 at maximum capacity, and a heat system performance factor (HSPF) ≥ 10 for ducted systems and ductless single-zone systems, and ≥ 9 for ductless multi-zone systems (Northeast Energy Efficiency Partnerships 2015).

Flex fuel heat pumps are a common name for a whole house ducted cold-climate heat pump that has a fuel-fired furnace (for this study, propane) as a back-up heating source. The system has an outdoor heat pump unit connected through a line set to an indoor heat pump coil. The indoor coil is installed in the house ductwork, just downstream of the furnace, and transfers heat from the outdoor unit to the home's ductwork. The interaction between the heat pump and the furnace is typically controlled via an outdoor air temperature sensor and a change point control. When temperatures are higher than the change point (set between 5 F and 10 F for this project) the heat pump meets the load. When temperatures are below the change point, the back-up furnace operates and the heat pump is turned off.

The all-electric heat pump has a similar set up to the flex fuel system, but there is no furnace burner. The indoor heat pump coil is installed just downstream of an air handler unit (with no burner). Downstream of the indoor coil is an electric resistance booster heater. There are several different methods for controlling the interaction between the heat pump and the booster system, but they all utilize the heat pump whenever it can operate. If the outdoor temperature and house heating load are such that the heat pump cannot meet the load, it runs at high output and is then boosted by the resistance heater. The mini-split system has the type of outdoor unit, but instead of connecting to a central duct system and air handler, the split connects to an independent indoor head. This indoor system has its own fan and indoor coil capable of operating independently of any other HVAC systems.

In Minnesota, more than 35% of homes do not have access to natural gas for space heating (U.S. Census Bureau 2010). Most of these homes are heated with propane, heating oil or electricity. These fuel types have traditionally been significantly more expensive than natural gas; this is especially true for propane, which has been susceptible to shortages and cost spikes, including during the 2013 and 2014 heating season when costs went from $1.67 to $4.61 per gallon (EIA 2010). The high efficiency of ccASHPs can help reduce reliance on delivered fuels for space heating in cold winter states such as Minnesota. During periods of very cold temperatures when ccASHPs do not have adequate capacity to meet heating load, a furnace or electric resistance heat can be used as backup.

Minnesota's Conservation Improvement Program (CIP) benefits Minnesotans by working to decrease emissions and reduce energy costs. Several utilities across the state offer rebates through CIP for ASHPs based entirely on their seasonal energy efficiency ratio (SEER) rating. However, the rebates do not reflect the full benefit of the heating capabilities of the new ccASHPs. Much of the savings from ccASHPs comes from replacing other space heating fuels that are less efficient, and these savings go unrecognized under state policy (that doesn't consider fuel switching). These current Minnesota regulations, with the exception of certain low-income customers, have no way to credit savings in deliverable fuels towards utility CIP goals. Furthermore, historically, CIP programs have not encouraged customers to switch fuel sources in order to achieve increased efficiency. While CIP provides an excellent policy structure for achieving electric and natural gas savings, Minnesota has no comparable structure or funding in place for achieving heating oil and propane savings. In Minnesota, as in other places around the country, renewable energy sources are increasing the capacity and impact on the electrical grid. As these enhancements continue, the discussion of beneficial electrification continues to grow. With significantly higher efficiencies and continually increasing capacities, ccASHPs are playing a major role in this discussion. Understanding the true potential of this technology is increasingly important as this discussion takes place.

Methodology

Field Characterization Cold-climate ASHP systems were installed in eight Minnesota homes. The ASHPs selected were designed for cold-climate operation with a traditional heating system as backup. The system was installed so that the ccASHP could be deactivated and bypassed, allowing the system to be run as either (1) a ccASHP with the existing heating system as backup or (2) an existing traditional system (just the baseline system, without the ccASHP). These two modes of operation were alternated through a full heating season to allow for a direct comparison of the two systems over the full range of outdoor conditions. This alternating mode method of testing has been used successfully by the Center for Energy and Environment (CEE) and many others for residential HVAC field characterization studies. At site was monitored for at least 16 month, allowing characterization of both the ccASHP and traditional system.

Six of the ASHP systems were centrally-ducted whole house units and two were ductless systems. All of the systems used variable speed compressors, often described as inverter-driven technology, allowing the system to change operation speeds and modulate capacity depending on temperatures and heating loads. This allows for increased capacities and effective colder temperature operation. For this study, four of the ducted systems were designed with a propane furnace as backup to meet the load of the home at the coldest outside temperatures. These systems are often referred to as flex fuel (or dual fuel) systems. The indoor coil of these systems was installed in the furnace duct-work, much like a traditional air conditioning system. The ducted systems relied on the furnace air handler fan to move air over the heat pump indoor coil to transfer heat to the ductwork and then the home.

The other two ducted central systems were designed with an air handler and an auxiliary electric resistance heat element set, which can provide additional heating capacity at colder outdoor temperatures. As is common for standard ASHPs, the booster heater provided supplemental heating to the home where the ccASHP was unable to meet the full load of the home. These systems were very similar in appearance to the flex fuel systems, but instead of a propane burner there is a booster heater in the ductwork downstream on the heat pump indoor coil.

The two ductless systems were designed and installed to meet only a fraction of the homes' total load; each home had electric resistance baseboard heat in addition to the ductless system. The ductless units were sized to meet the load of the room, or series of rooms, which has open communication with the ductless unit's indoor head. As would be the case for most DHP installs, where the DHP is intended to displace electric resistance heating in the main house living zone, both homes had bedrooms that were typically closed off to the main living zone, so the back bedrooms were primarily heated by the baseboards.

The equipment that was selected for installation is described in Table 1 (below). These systems were selected because the manufacturers are well established with large shares of the residential HVAC market and because the most local contractors are familiar with the systems. All systems meet the inverter driven requirements of ccASHPs and have heating ratings (HSPFs) in the highest levels available (at least 9.5 HSPF for all systems).

Table 1. ccASHP systems installed in 8 Minnesota homes

Site Number	ASHP System	Nominal Cooling Capacity	ASHP Type	Backup
1	Carrier Infinity with Greenspeed [25VNA048A003]	4 ton	Ducted	LP Cond. Furnace
2	Bryant Extreme Heat Pump [280ANV048]	4 ton	Ducted	LP Cond. Furnace
3	Carrier Infinity with Greenspeed [25VNA036A003]	3 ton	Ducted	LP 80% Furnace
4	Trane XV20i [4TWV0036A]	3 ton	Ducted	LP Cond. Furnace
5	Mitsubishi Ductless Hyper Heat [MUZ-FH18NAH]	1.5 ton	Ductless	Electric Resistance Baseboard
6	Mitsubishi Ductless Hyper Heat [MSZ-FH12NA] (2 units)	1 ton 1 ton	Ductless	Electric Resistance Baseboard
7	Mitsubishi Hyper Heat System [PVA-A30AA7]	3 ton	Ducted	Electric Resistance Plenum Booster
8	Mitsubishi Hyper Heat System [PVA-A30AA7]	3 ton	Ducted	Electric Resistance Plenum Booster

Cold-climate air source heat pumps were sized specifically for each home's heating load (as opposed to the cooling load). Sizing for heating typically increased the system size by one ton compared to sizing for cooling; this meant that where a home sized for cooling would install a two-ton heat pump, the same home sized for ccASHP heating would install a three-ton system. In cold climates, sizing the heat pump for a home's heating load is important in order to take full advantage of the system's variable capacity, thus minimizing the use of back-up heating. For ducted whole house systems, the design load of the entire home must be accounted for. In very cold-climate applications, much of Minnesota has a heating design temperature below -10 F, it is unlikely that the heat pump will meet the full load of the home at all temperature conditions — this makes the installation of a back-up heating source necessary in these climates (Schoenbauer, Kessler, and Kushler 2017).

Different types of heat pump systems have different types of controls. Flex fuel furnace systems typically have a changeover point where the heat pump can no longer meet the load of the home and operation switched completely to the furnace backup. For the systems in this study, the changeover points were typically set to 10 ^{0}F, one home was comfortable with a smaller safety factor and choose 5^{0}F. For systems with plenum booster heater backup the typical control strategy prioritizes the heat pump operation. The ASHP runs whenever there is a call for heat, and the auxiliary electric resistance heat boosts the delivered air temperature if the heat pump cannot meet the home's load. For ductless mini-split systems, the most common back-up system is electric resistance heat. For the ductless homes, the integration between these two systems was controlled by maintaining a higher conditioned space set point on the ductless thermostat and the thermostat controlling the back-up system, which effectively prioritized the ASHP.

Each home was fully instrumented with a residential HVAC data acquisition system. The system utilizes a Campbell Scientific acquisition system customized to collect HVAC data. Sensors were installed to monitor the energy consumption, runtime operation, and delivered energy of each system. The data collection interval was adjusted for high resolution (one second) data. This high resolution data allows for detailed analysis of the system performance. Additionally, data can be analyzed to understand the impacts and interactions of different parameters. Table 2 (below) details the data collection system used at each site.

Table 2. Heat pump data collection system

Measurement	Sensor	Location
Power	Watt transducer	Outdoor unit
Power	Watt transducer	Indoor unit
Current	Current transformer	Air handler fan
Current	Current transformer	Reversing valve
Air temperature	Thermocouple array	Supply duct
Air temperature	Thermocouple array	Return duct
Air temperature	Thermocouple	Mech. room ambient
Air temperature	Thermocouple	Conditioned space
Fuel consumption	Gas meter or watt transducer	Back-up system
Air flow*	TrueFlow ™	Air handler
NOAA data	Weather station	Nearest NOAA station

*Ongoing airflows were calculated from the direct measurement of fan power measurements that were calibrated to spot airflow measurements made at the installation, removal, and at least one mid-monitoring site visit.

Analysis

Annual Energy Use. The annual energy use analysis was based on creating a heating load performance characterization and a system performance curve for each site. These relationships were used with typical medological data to determine normalized annual performance. This approach has been used for many research projects in the past, including field evaluations of tankless water heaters, combined space and water heating systems, and other HVAC technologies. (For further discussion of this analysis model see Kessler (2016).)

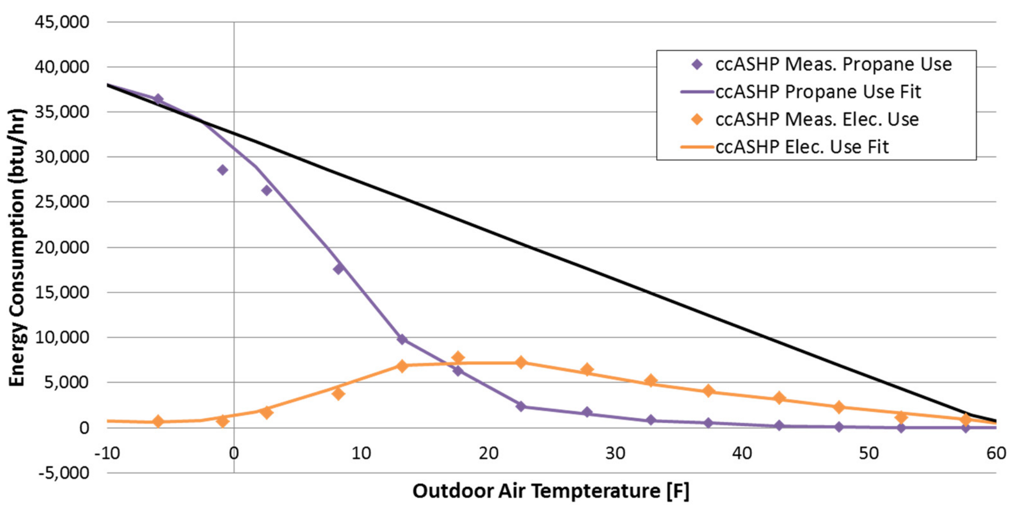
A system performance curve was developed for each site. Energy consumption data were measured directly at each site. The high resolution data were aggregated to daily values for this analysis. For ducted systems, both the electricity from the indoor and outdoor units, and the back-up propane use from the furnace, were measured. For the ductless systems, electricity was measured from the indoor and outdoor heat pump units, and also from the back-up electric resistance baseboards. The energy usage data were compared to the outdoor air temperature to develop the performance cuvre.

Figure 1 shows the system performance curve for the ducted systems at site_02. The model was created by averaging the energy use for each 5^0F outdoor air bin. Averages were taken for both the propane use (purple line in Figure 1) and indoor and outdoor unit electricity use (total electricity use shown in orange in Figure 1) per day during ccASHP operation. Additionally, the alternating mode methodology of the test allowed for data collection of furnace-only operation (black line in Figure 1), which was used as a baseline. As outdoor air temperatures approached the house balance point (typically between 55^0F and 65^0F) heating energy use approached zero for all modes of operation.

In moderate temperature conditions the propane furance still ran for freeze protection, but the electricity use from the heat pump mode was a larger fraction of the usage. As outdoor air temperature approached the changeover point (10^0F), propane usage increased. The difference in efficiency between the heat pump (with COPs greater than 1.5) and the back-up systems (with efficiency around 80% for propane backup and 100% for electric reisistance) meant that electricity delivered a proportionally larger amount of energy to the home when compared to the equivalent Btus of propane. For example, on a shoulder season day where propane accounted for about 25% of energy consumption (measured in Btus), the respective energy delivered from propane would be around 10% of the total energy delivered.

When temperatures were below zero at this site, the back-up propane use from the ccASHP was similar to the propane use in the baseline-only mode. Air temperature bins below the ccASHP system change point had some heat pump operation due to the range of daily temperatures. For example, a day when the average air temperature of 0^0F appears to prohibit heat pump operation because it is below the ccASHP change point of 10^0F, the maximum temperature of that day may have been above the change point, allowing the heat pump to meet part of the daily load.

Figure 1 . Energy Use for the ccASHP and the propane furnace backup at site 02



Additional Analysis. The level of monitored detail necessary for this analysis allowed for additional assessment of the systems. In addition to annual energy use, the analysis calculated system COP and delivered capacity. The COP and capacity of the ccASHP system was calculated from measured field data over the range of outdoor temperatures typically experienced in the field. The analysis determined how well the controls utilize the back-up system to minimize the fuel costs while meeting the thermostat heating set points.

High resolution data also allowed for analysis of each individual heating cycle. The cycle based analysis was used to determine the impact of various parameters on system performance. These parameters included system runtime, outdoor air temperature, capacity, and fan speed.

ccASHP systems that provide space heating at low ambient temperatures periodically required a defrost cycle. Frost can form on the outdoor coil surface at low temperatures and the amount of frost may be large enough to restrict air passage through the coil and limit heat transfer. Defrost cycles reverse the refrigeration cycle to melt the frost, but they also impact ASHP performance, by using energy for the defrost operation and reducing the availability of the ASHP and increasing auxilary heating. Collected data were used to measure the impact of defrost cycles.

Results

Annual Energy Use

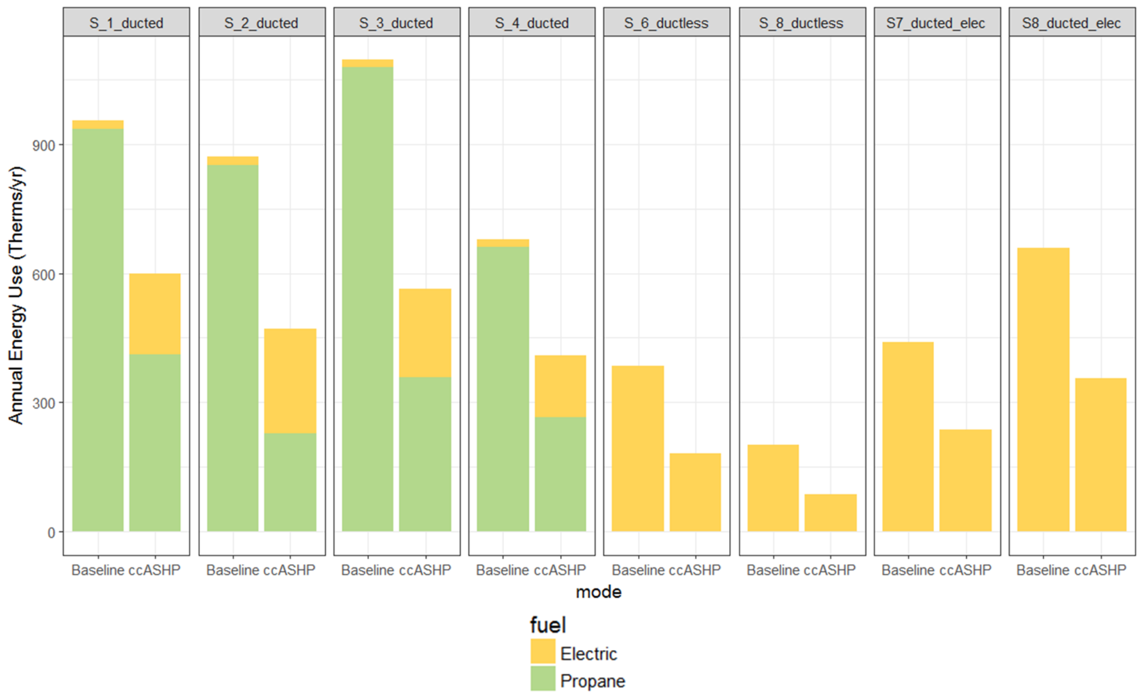
The system performance and annual energy use of each ccASHP and baseline system were analyzed using the methodology previously described. The following section summarizes the energy use and savings, reduction of reliance on delivered fuels, system COPs, and the ability of the ccASHP to meet the homes' load.

The annual energy consumption for both the baseline (furnace only) and the ccASHP with back-up systems was determined with a binned analysis of the heating system energy consumption versus outdoor air temperature. Figure 2 shows the site energy use, in propane and electricity, for each site with the baseline (furnace or electric resistance) and the ccASHP. Significant site energy reduction, between 37% and 54%, was measured for all sites. The figure also illustrates the switch from a delivered-fuel dominated heating system to a primarily electricity-based system for the flex fuel sites. In baseline, furnace-only operation, 97% to 98% of site energy use was from propane. The air handler fan operation was the only electricity use, and this was a small fraction at 2% to 3%, of total site energy use. In the ducted flex fuel ccASHP system operation, between 48% and 69% of site energy use was electricity. While the air handler fan (the indoor unit) accounted for the same fraction of energy use, the addition of the outdoor unit (the heat pump) accounted for almost half of the total site energy use.

For the ductless systems and all electric ducted systems, it was assumed that the load met by the heat pump system would have also been met by an electric resistance heater in the baseline case. These systems saw a 46% to 56% reduction in electrical use with the ductless system. Along with these energy savings, there are substantial cost savings for the homeowner. There was an average cost savings of 33% for ducted flex fuels ccASHPs and 53% for all electric systems. Ducted systems saved between \$377 and \$764 per year and ductless systems saved between \$369 and \$610 per year.

Unlike the flex fuel systems, the all-electric ducted systems did not have a fixed temperature set point to switch to the backup-only operation. The all-electric systems allowed the heat pump to run wherever possible and boost the capacity with backup. The flex fuel system with fixed temperature control turned off the heat pump and switched to back-up at set temperature when the heat pump could not meet the full load. This was necessary due to the increased modulation and low output capability of the electric resistance compared to a furnace. This resulted in the heat pump meeting a larger fraction of the load in the all-electric systems. The annual COP was 1.9 on average for the all-electric systems compared to 1.3 for the flex fuel units.

Figure 2. Annual Energy Use data for baseline and ccASHP systems at each site



Detailed System Performance

Figure 3 shows the performance of individual heating cycles for a ducted flex fuel system. This figure shows the individual heat pump cycles, heating cycles that included defrost periods, as well as the efficiency of the furnace-only cycles. These furnace-only events were typically between 70% and 85% efficient, or 8 to 15 percentage points below the rated AFUEs for the condensing units. The non-condensing furnace was typically firing around 57% to 65%; these efficiencies were below the rated efficiencies due at least partially to the cycle length. Typical furnace events took more than 15 minutes for the instantaneous efficiency to reach the condensing level (>90%), and it didn't reach steady-state operation for an additional five to ten minutes. Most furnace cycles concluded before these transient start-up effects were made insignificant, and these effects degraded the estimated annual efficiency in the baseline mode as well as the efficiency of the back-up propane system for ccASHPs.

Note that it is very common for installed efficiencies to be lower than rated performance. This is because ratings are conducted at a specific set of operating conditions, which are often not directly recreated in the field. Additionally, the method of tests for HVAC equipment, including AFUE and HSPF, are intended to compare unit performance, and they are not intended to represent the installed efficiency of any specific installation. Figure 3 shows the rated COPs at 17^{o}F and 47^{o}F. The rated heat pump performance were with the measurement error of the field data at the 17^{o}F condition for all sites.

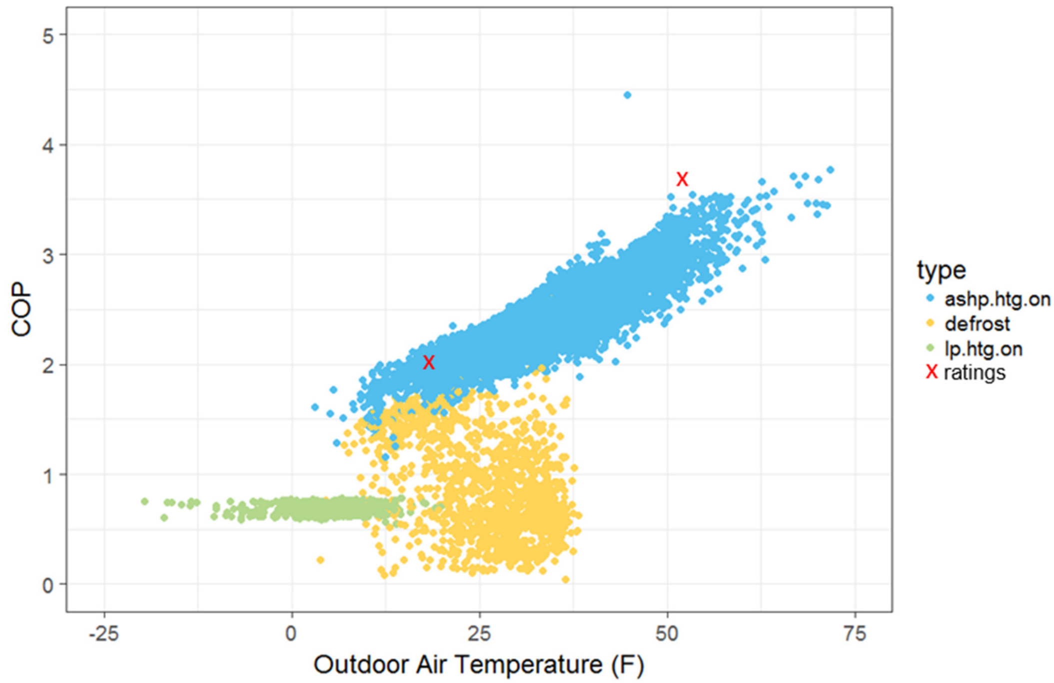


Figure 3.ccASHP performance data by heating cycle for a centrally-ducted flex fuel system

Figure 4 shows similar cyclical data for an all-electric heat pump system. This plot shows the heat pump-only heating events (in blue), the events where defrost was active (yellow), and events that required some electric resistance booster heat (green). The all-electric heat pump does not have the fixed switch over point to backup. Therefore, below 30^0 F outdoor temperature we see events that are heat pump-only as well as events that include auxiliary electric resistance. The booster auxiliary heat operates at a COP of 1, which is less efficient than the heat pump, but because the heat pump is prioritized and the booster is supplemental, even at the coldest outdoor temperature (around -7 ^{0}F) the system COPs are greater than 1.0. A small number of heating events had COP's less than 1.0, these events were typically very short and start up and cool down losses reduced the event COP. These events had only had a very small impact of the total system COP.

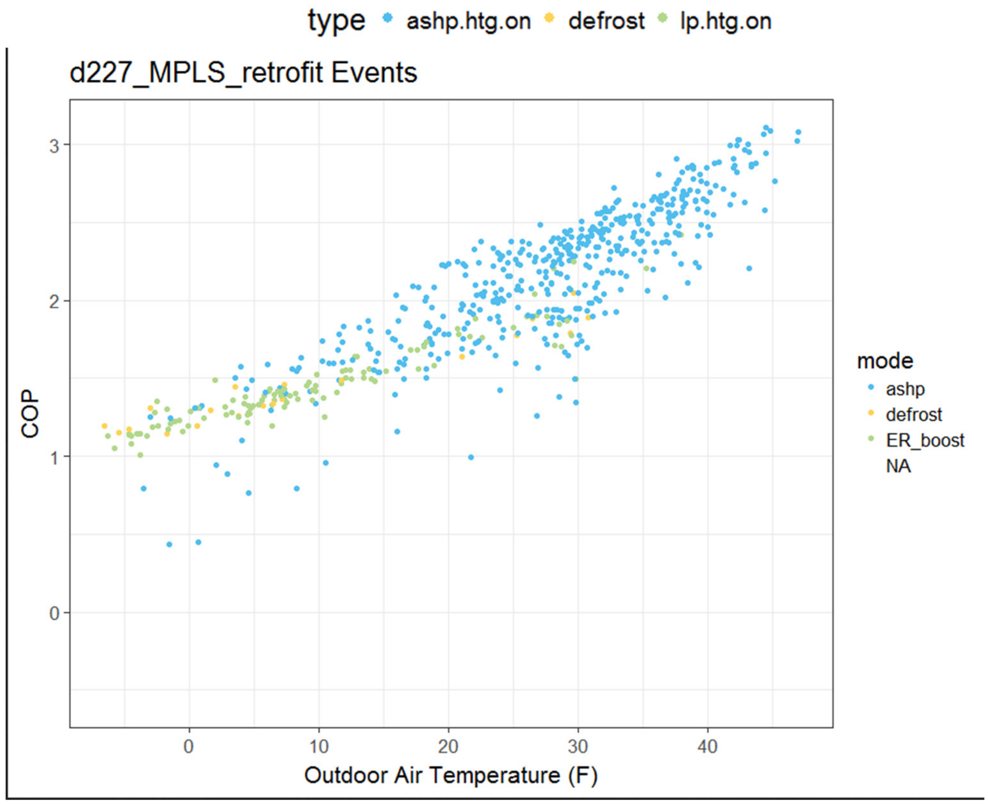


Figure 4. ccASHP performance data by heating cycle for a centrally-ducted all-electric system

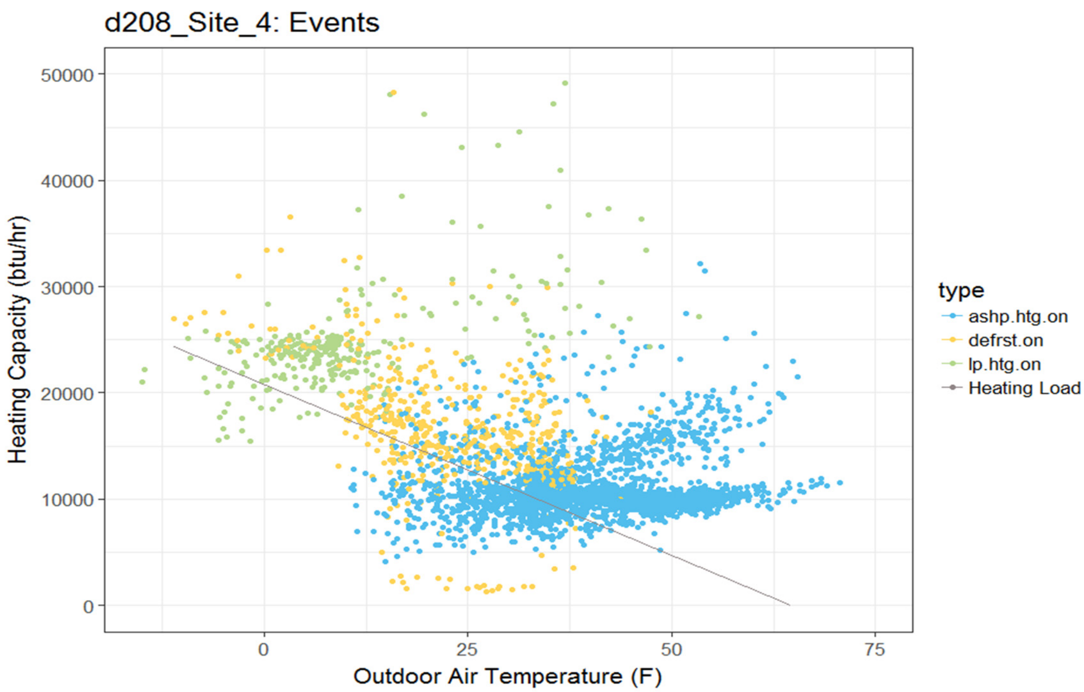
The capacity of each ducted ccASHP was compared to the heating load of the home. In general, the ccASHP ran at low capacity for long periods. Figure 5 shows the capacity of each ccASHP heating event compared to the daily heat load requirements for one flex fuel site; this was typical operation for the flex fuel systems. Above 30ºF, the ccASHPs typically operated in heat pump-only mode at capacities greater than the heating load. Below the change point of 10 ^{0}F, the back-up system (propane heating only) was used to meet the load. Between 30^{0}F and 10^{0}F, the heat pump-only events capacity started to drop so that the heating capacity meets the house load at 10^{0}F. In this temperature range there were also a large number of defrost events. Any heating cycle where the defrost system was active was categorized as a defrost cycle; this includes events where the heat pump ran for part of the cycle without defrost. Figure 5 shows that when OATs conditions were such that defrost was needed (10^{0}F to 30^{0}F), the heat pumps were running at higher capacity but were also likely to require defrost operation for part of the heating event. All six ccASHPs typically operated near the middle of the capacity range and rarely fired at maximum capacity.

For example, the system installed using the heat pump specs at Site 4 was sized based on a calculated design heating load of 35,500 Btu/hr. (at -15^{0}F), but the analysis showed the actual heating load was only 24,306[1] at that condition, a 31% reduction in the necessary load, which meant that the system never needed to operate at maximum capacity. During the instrumentation verification the maximum capacities of the ccASHPs were analyzed for each ccASHP. At each

[1] The Minnesota climate is very cold but heating loads in the 30kBtu/hr range are very common. Metro area homes tend to be smaller, 1200-1500 sq ft, and have a decent amount of insulation.

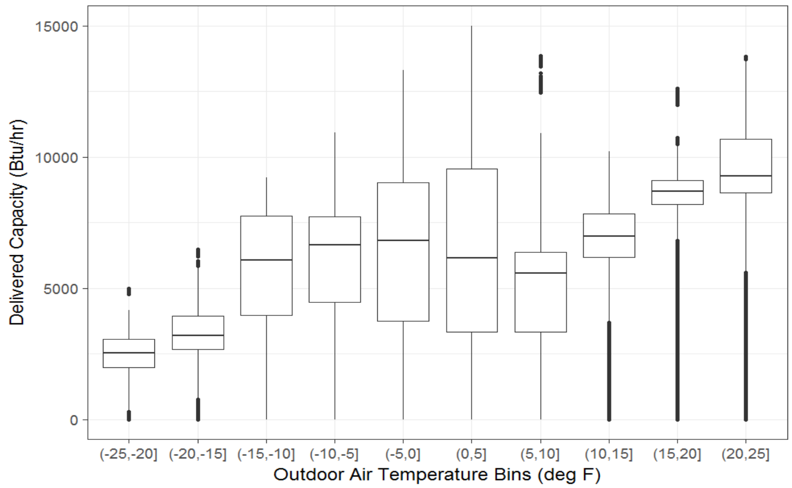
site, the maximum capacity (determined by forcing high speed compressor operation) was much greater than the highest capacities shown in typical heat pump-only operation. The 4 Ton systems at Sites 1 and 2 delivered maximum capacities of 55,000/hr at 47 ^{0}F. Btu and 49,000 Btu/hr. The 3 Ton systems at Site 3 and Site 4 delivered 38,000 Btu/hr. during testing. Improved controls to prioritize ccASHP high capacity operation over back-up heating would further increase the savings and reduction of delivered fuel usages. Additionally, lowering the switchover temperature for locking out the ccASHP could increase ccASHP usage.

Figure 5. Heating capacity for each heating event compared to the daily heating load of the home at site 4



The ductless mini-split manufacturers claim systems operate at outdoor temperatures as cold as -13 ^{0}F. Figure 6 shows the one minute average capacities of ductless systems installed in Northern Minnesota. This ductless heat pump delivered a consistent median capacity from 10 ^{0}F to -15 ^{0}F. The system continued to operate from -15 ^{0}F to -25 ^{0}F, but at a reduced capacity. Between -20 and -25^{0}F, this 1 Ton heat pump had a median delivered capacity of 2,600 Btu/hr., delivered to the space at approximately 20% of the rated capacity at 5^{0}F (13,600 Btu/hr). The maximum one-minute capacity below -20 ^{0}F was 5,000 Btu/hr. Operation at these extreme temperatures (beyond the rated performance) showed the capabilities of the system, but the reduction in capacity shows these units should not be used without backup at extreme temperatures (below -15^{0}F).

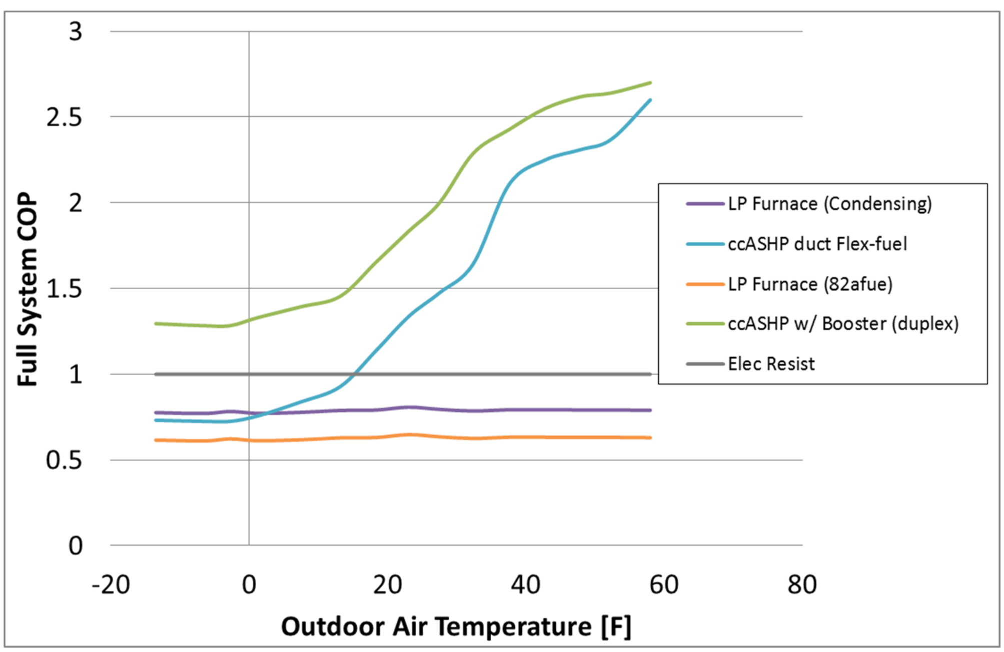
Figure 6. One ton Ductless mini-split capacity at colder temperatures



Conclusions

ccASHPs proved to be beneficial for typical Minnesota homes when replacing propane furnaces or electric heating. When operating in heat pump-only mode, the system manufacturer specifications for COP and capacity adequate for sizing the systems. Cold weather increased the need for back-up systems, defrost operation, and reduced the performance of the heat pump, but overall system efficiencies remained high. Figure 7 shows the COP of each heat pump system and the baseline/back-up systems over the range of expected outdoor temperatures.

Figure 7. System COP curves for the field tested ccASHP and their backups



Performance maps, the heating loads of a home, and the normalized Minnesota weather conditions were used to estimate average annual energy savings and CO_2 reductions. Table 3 shows the results of that analysis. For the flex fuel systems, the increased COP reduced the total propane consumption by about 60%, for the majority of MN homes, which is less than 500 gallons of annual consumption. This limits the need for costly winter refueling, as 500 gallons is the typical residential storage volume. In addition, all of the heat pumps showed considerable cost savings for the homeowner, from 30% to 56%. For retrofits, paybacks will typically be longer than 10 years, unless equipment replacement is necessary. At either heating or cooling system failure, heat pumps paybacks drop to 5- 6 years. Finally, assuming current MISO grid seasonal emissions factors, the substantially higher COPs of the ccASHP systems resulted in reduced CO_2 emissions when compared to baseline systems (Edwards et al. 2018).

Table 3 . System Summary by Minnesota Climate zone for a typical MN home

System Type	Baseline	Location	Annual System COP	Site Energy Saving	Cost Savings	Propane Saving	Savings [$/yr.]	Emissions Reduction
Ducted	Condensing LP Furnace	Metro	1.3	41%	30%	63%	$450	6%
Ducted	82% LP Furnace	Metro	1.1	49%	40%	67%	$760	
All elect.	Elect. Resistance	Metro	1.9	47%	47%	N/A	$780	
Ductless	Elect. Resistance	Metro	2.3	56%	56%	N/A	$425 ~50% of load	
Ducted	Condensing LP Furnace	Northern MN	1.2	36%	26%	55%	$485	4%
Ducted	82% LP Furnace	Northern MN	1.0	44%	36%	61%	$855	
All elect.	Elect. Resistance	Northern MN	1.8	44%	44%	N/A	$900	
Ductless	Elect. Resistance	Northern MN	2.2	53%	53%	N/A	$480 ~50% of load	

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