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2019 Dual Fuel Air-Source Heat Pump Monitoring Report

slipstream

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EXECUTIVE SUMMARY

In 2019, the Michigan Electric Cooperative Association (MECA) Energy Optimization (EO) Program's Heat Pump Pilot decided to monitor eight residential centrally ducted, dual fuel air-source heat pumps. The pilot monitored systems from February to September to capture data from both the heating and cooling season.

The field monitoring study was designed to characterize energy consumption and associated operational costs and environmental impacts of different system configurations. The study targeted systems with both variable-speed and fixed-speed compressors for investigation. The main driver for the study was to fill the gap of field monitoring research on market-driven installations of dual fuel air-source heat pumps in cold climates.

Study objectives were to characterize the following:

- Reported satisfaction and comfort of Great Lakes Energy (GLE) members that installed a dual fuel air-source heat pump.
- Expected energy and operational cost savings from adopting a heat pump with a propane furnace backup compared to the same propane furnace and a standard central air conditioner (AC) in a typical year.
- Performance of dual fuel air-source heat pumps with a) variable-speed compressors, and b) fixed-speed compressors across a range of outdoor air temperatures.
- Economic, environmental, and grid impacts of opting for a dual fuel air-source heat pump instead of a propane furnace and standard central AC.

The study estimated annual operational cost savings to be approximately $300-$1,000 for each site and all payback periods were estimated to be less than nine years. Carbon dioxide savings averaged 10 percent over the seven-month monitoring period.

Key insights from the study include the following:

- Field study participants are satisfied with their dual fuel air-source heat pumps.
- All eight heat pumps in the study achieved significant energy and operational cost savings.
- Although heat pumps with variable-speed compressors tend to have higher efficiency, this will only result in substantial energy savings when other factors are optimized such as system selection, sizing, thermostat schedules, and lockout configuration.
- Dual fuel air-source heat pumps present an immediate opportunity to realize operational savings, and environmental and grid benefits.

The systems in this field monitoring study can serve as case studies for prospective adoptees of dual fuel air-source heat pumps and research findings can inform future EO program designs and product rebate qualification criteria to minimize heating costs for the homeowner, minimize utility costs, and reduce greenhouse gas emissions. Below are recommendations and potential next steps and future research to build off the findings of this study:

- Evaluate the impact of alternative rate designs and offer rates that yield the most benefits to members/customers and the grid.
- Develop a heat pump modeling tool that accounts for system selection, configuration, operational settings, and provides better savings estimates for HVAC contractors and members/customers.
- Create more comprehensive load profiles to help forecast the impacts of widespread heat pump adoption in different locations across EO-Collaborative utility territories.
- Increase granularity of emissions accounting to provide insights on how to minimize the emissions impact of heat pump technology and position EO-Collaborative utilities as decarbonization leaders.
- Conduct further research on heat pump sizing and its impact on dehumidification, heating energy consumption, and cooling energy consumption to help establish best practices for HVAC contractors in EO-Collaborative utility territories.
- Conduct field research on other heat pump technologies in other market segments to verify the technology's performance, better understand local barriers to adoption, and identify EO program market interventions to address the barriers.

Dual fuel air-source heat pumps present a significant opportunity as an energy efficient residential heating and cooling solution. Innovative rate design, market interventions, and resources for members/customers and trade allies can help ensure heat pumps provide economic, environmental, and grid benefits for years to come.

INTRODUCTION

To provide context for the remainder of the report, we explain some basic information about air-source heat pumps, why not all heat pumps are created equal, and why this study focuses specifically on dual fuel air-source heat pumps.

AIR-SOURCE HEAT PUMP BASICS

Like typical split system air conditioners, air-source heat pumps move heat from the ambient air and transfer it through refrigerant lines. Unlike air conditioners that are designed for cooling only, heat pumps can operate to either heat or cool indoor spaces. Air-source heat pumps can be centrally ducted or ductless. Depending on the home and the heating and cooling needs of the occupant(s), either may be a better fit.

During heating season, as outdoor air temperature decreases, an air-source heat pump's energy efficiency and heating capacity decrease and the home's heating needs increase. The rate of the heat pump's decline in performance (capacity and efficiency) at different outdoor air temperatures depends on the model installed.

Heat Pump Heating Capacity

Unlike a traditional furnace whose capacity to heat is indifferent to outdoor air temperature, an air-source heat pump's **capacity** to heat will decrease as outdoor air temperatures drop. This is because the air-source heat pump must work harder to absorb heat from the cold air. Conversely, a home's heating needs (or heating load) will increase as outdoor air temperature drops, and the rate of increase will depend on how well the home is weatherized. A better insulated and air-sealed home requires less heating to maintain a specific thermostat setting.

What is capacity?

Capacity refers to the amount of heating or cooling a system can provide and can be thought of as the system's "rate" of heat transfer. Capacity is typically communicated in British Thermal Units per hour (Btu/hr)

Figure 1 illustrates the relationship between outdoor air temperature, home heating load, and heat pump maximum capacity.[1] The ***capacity balance point*** (as distinguished from the commonly referenced balance point temperature) is the outdoor air temperature at which the home's heating needs and the heat pump's capacity intersect. This represents the outdoor air temperature when the rate of heat loss from the home equals the maximum rate of heat the heat pump can provide. Above the capacity balance point, the heat pump can fulfill the home's

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[1] Heat pump maximum capacities are displayed for two different Bryant heat pump models in their cold-climate line (AHRI 9893699) and legacy line (AHRI 204184545). Capacities for 47°F and 17°F are rated and contained in the AHRI database and capacity at 5°F for the cold climate system is voluntarily reported by the manufacturer on the NEEP Cold Climate Air Source Heat Pump (ccASHP) Product List. Both models have 45,500 btu/hr capacity at 47°F. However, the legacy line model's maximum capacity drops to 29,800 btu/hr at 17°F whereas the cold-climate model maintains a maximum capacity of 38,070 btu/hr down to 5°F.

heating demand with capacity to spare. Below the capacity balance point, the heat pump cannot fulfill the home’s heating demand and a supplemental heating source is required to maintain the temperature setpoint.

Figure 1. Impact of home thermal efficiency and heat pump compressor type on capacity balance points.

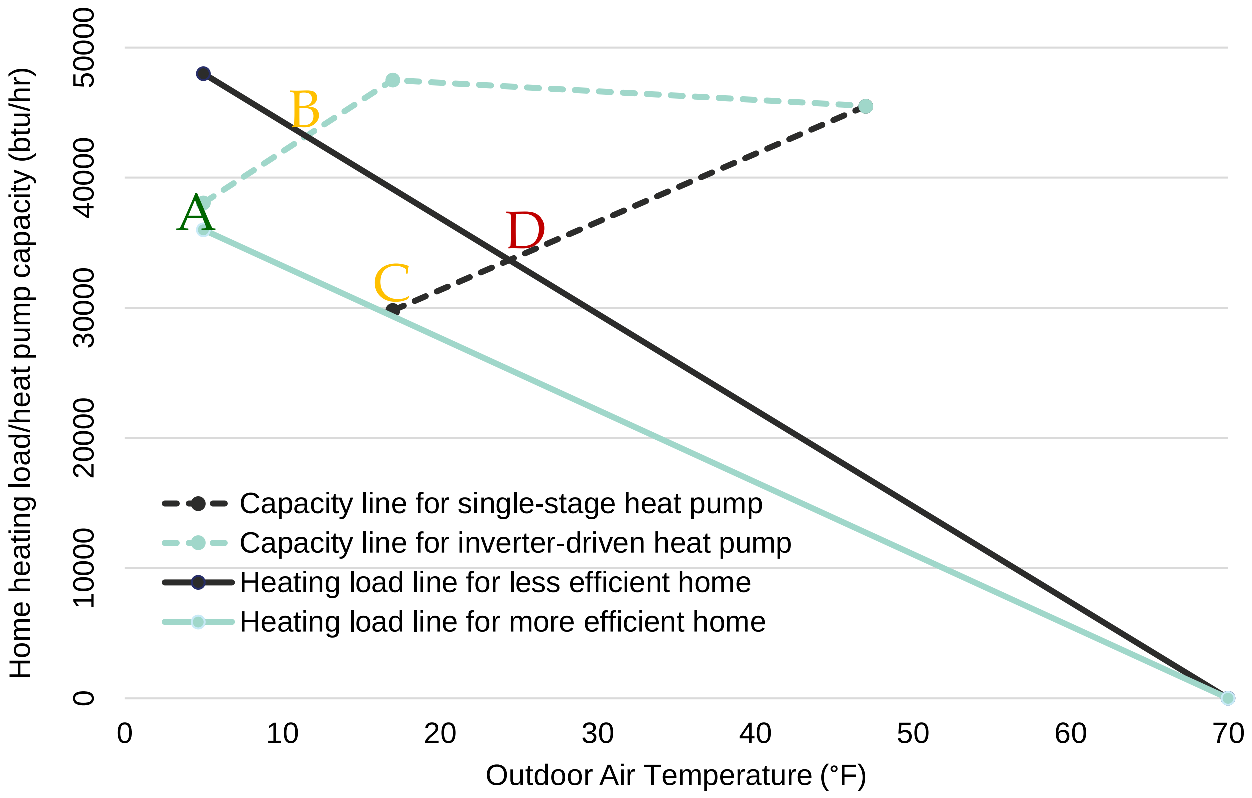


Figure 1 illustrates four capacity balance points to demonstrate the effect of a more thermally efficient home and the effect of a heat pump that can maintain higher heating output at lower temperatures. Point D represents the worst-case scenario for a given home since it is thermally inefficient, and the heat pump’s capacity drops off quickly as outdoor temperatures decrease. Point A represents best-case scenario since heating load for the given home is minimized from the home’s thermal efficiency and a heat pump that can maintain high levels of output at low temperatures is installed. Points B and C represent middle-ground scenarios.

Heat Pump Heating Efficiency

What is COP?

COP is a unitless ratio of heating or cooling output to energy consumed.

While the rate of heat pump capacity decay determines the ability for the heat pump to meet a home’s heating demand at lower temperatures, the heat pump’s **coefficient of performance (COP)** is a key driver of the ultimate cost to the consumer and the associated environmental and grid impacts of heating with a heat pump. Like heating capacity, the energy efficiency of a heat pump goes down as outdoor temperatures decrease. When there is a backup heating source that uses a different fuel, the ***economic balance point*** describes the outdoor air temperature at which operation of the heat pump's backup heating system would yield the same operating cost. Above the economic balance point, it is more cost effective to heat with the heat pump. Below the economic balance point, it is more economical to heat with the backup system.

NOT ALL HEAT PUMPS ARE CREATED EQUAL

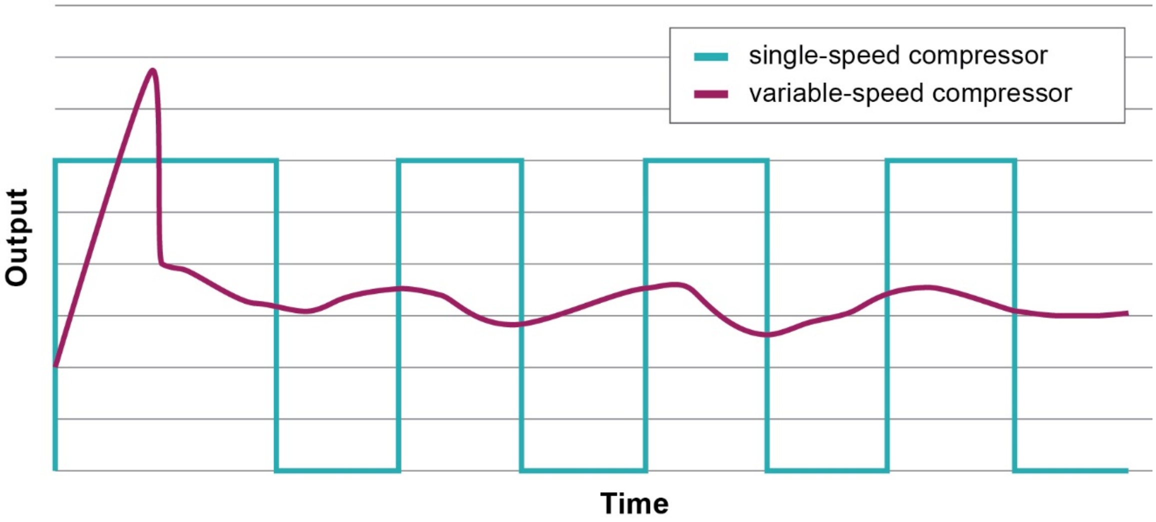
Air-source heat pumps are commonly categorized based on the compressor located in the outdoor unit. There are two primary types of compressors: fixed-speed, which may have one, two (or up to five) speeds of operation, and **variable-speed**. Air-source heat pumps with variable-speed compressors continually make minor adjustments to heating output and will generally outperform heat pumps with single or two-speed compressors due to increased COP at lower speeds.

When sized large enough, some variable-speed systems maintain a thermostat's setpoint when outdoor air temperatures drop as low as -4°F. Manufacturers will typically indicate which of their systems are engineered to perform better in cold weather. Figure 2 illustrates how a variable-speed compressor and single-speed compressor meet heating demand. To maintain the setpoint, the variable-speed compressor operates on one continuous, mostly low-power, cycle while the single-speed compressor cycles between off and full power.

What is a "variable-speed" compressor?

The compressor is the "engine" of a heat pump, with the function of increasing pressure and temperature of refrigerant vapor. A variable-speed compressor incorporates a variable frequency drive which can modulate its speed to provide more, or less, pressurization of the refrigerant thus, varying the refrigerant's flow and the rate of heat transfer to match the heating or cooling needs of the home.

Figure 2. The difference in operation of a single-speed and variable-speed compressor.



By avoiding steep and frequent power cycles, and because lower compressor power makes better use of system heat exchangers, compressors with a wider range of speeds achieve higher efficiency levels. The wider the range in capacity, and the more speeds available in between minimum and maximum capacity, the more likely the heat pump will be able to operate efficiently across a range of heating and cooling conditions.

In cold climates like Michigan's, single-speed heat pumps are typically sized for summer cooling needs rather than much larger winter heating loads. Single-speed heat pumps cannot modulate their cooling output to meet the home's cooling demand and oversizing these systems will result in poor cooling and dehumidification performance. Variable and multi-speed heat pumps can modulate their cooling output to meet the home's cooling demand, which allows them to be sized larger than the cooling load without compromising cooling and dehumidification performance.

WHY STUDY DUAL FUEL?

Unlike fuel-fired furnaces and boilers, the capacity of air-source heat pumps to provide heat drops with outdoor temperature. This means that some type of backup heating system is usually needed in cold climates like Michigan's. A propane or natural gas forced-air furnace can readily serve as this backup for centrally-ducted air-source heat pumps, particularly for the 76 percent of Midwest homes that already heat their homes with a furnace.[2] However, most field studies of residential heat pumps have been conducted in the Northeast and West where the building stock contains more boiler or electric baseboard heating systems. These homes are better suited for ductless heat pumps. Even in the Upper Midwest, studies of air-source heat pumps have tended to focus on homes that already use electricity for space heating.[3]

Dual fuel heat pumps make it possible for homeowners to achieve cost savings by using a heat pump in moderate weather and only switch to a fuel-fired furnace in cold weather when the heat pump cannot satisfy the heating needs of the home. This switchover typically happens automatically based on an outdoor **lockout temperature**.[4]

What is a lockout temperature?

A lockout temperature is the outdoor air temperature where the heat pump ceases heating operation and allows the backup heating system to fulfill heating demand. The configured lockout temperature will vary across system installations. In some cases, a system may not have a configured lockout temperature.

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[2] Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) 2015.

[3] Nadel, S. (July, 2018). Energy Savings, Consumer Economics, and Greenhouse Gas Emission Reductions from Replacing Oil and Propane Furnaces, Boilers, and Water Heaters with Air-Source Heat Pumps. American Council for an Energy Efficient Economy (ACEEE).

Blanding, I. and Ehrendreich, G. (September, 2018). You're Getting Warmer: A Comparison of Gas Furnaces and Heat Pumps in Midwestern Homes. Midwest Energy Efficiency Alliance (MEEA).

[4] "Lockout" temperature is the term commonly used by residential HVAC contractors in the state of Michigan to describe this phenomenon. This same phenomenon is also commonly referred to as "switchover", "changeover", or "crossover" temperature.

This field monitoring study only included sites in the greater Grand Rapid area, which does not reflect the climate for all parts of EO-Collaborative utilities. Table 1 below shows the fraction of hours above four potential lockout temperatures in Grand Rapids and Sault Ste. Marie for a typical meteorological year.[5] This table demonstrates that although the climate is colder in Sault Ste. Marie than Grand Rapids, there is still a significant opportunity for dual fuel heat pumps to provide efficient electric heating benefits in both climates. Additional information on weather station data used in the study and a comparison of Grand Rapids and Sault Ste. Marie's typical outdoor air temperatures is in Appendix H.

Table 1. Fraction of hours above four potential lockout temperatures.

Lockout Temperature	Fraction of Hours Above the Lockout Temperature	
	Grand Rapids	Sault Ste. Marie
10°F	97%	91%
20°F	90%	80%
30°F	79%	70%
40°F	61%	51%

In the current literature on residential energy efficiency and beneficial electrification, the choice between electric heating and gas heating is often framed as an "either/or" decision. There is a lack of research assessing the viability of dual fuel heating to bring economic, grid and environmental benefits and a lack of research comparing performance of different dual fuel system configurations. One notable recent study that did examine dual fuel heat pumps was conducted in Minnesota by the Center for Energy and Environment. The study monitored four dual fuel systems over the course of two heating seasons. The systems were all high-efficiency, variable-speed units meant for cold climates and were selected, sized, and installed under the direction of the researchers who led the study.

The study described here builds on the Minnesota work by monitoring a wider variety of systems—and by studying systems installed without special oversight regarding system sizing and configuration. This affords an opportunity to examine performance of these systems as installed in the market without research controls.

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[5] Typical meteorological year (TMY) hourly average temperature data are used. It is important to note there will always be some marginal furnace energy consumption at temperatures above the lockout temperature during defrost mode, and depending on the controls, there may be some furnace energy consumption at temperatures above the lockout temperature during recovery from thermostat setbacks.

STUDY DESIGN

In this section we summarize the study participant sites as well as the methods for data collection and data analysis.

PARTICIPANT SITES

The study recruited eight Great Lakes Energy (GLE) members living in the greater Grand Rapids area. Each site's approximate location is shown in Figure 3. Ideally the study would have included homes in Northern Lower Michigan to analyze heat pump performance in a colder part of EO-collaborative utility territories. However, the sites monitored in this study are limited to the Grand Rapids area because there were no available sites in Northern Lower Michigan that met research qualifications.

All eight members worked with a participating trade ally who installed the dual fuel heat pump between 2016 and 2018. The study deliberately selected sites with a variety of heat pumps: four of the households had variable-speed systems, two had multi-speed systems, and two had single-speed systems. All eight heat pumps were backed up by propane furnaces with a variety of lockout temperatures. The heat pumps at two sites did not have a configured lockout temperature and instead operated until they were no longer capable of meeting the home's heating demand and maintaining the thermostat's setpoint.

Some households had auxiliary heating systems, such as wood stoves, but agreed not to use those during the study in order to avoid complicating the analysis. The homes range in size from 1,400 to 2,500 square feet and were constructed as early as 1860 and as recently as 2018.[6]

Study technicians made four visits to each site during the study, all in 2019:

1. an initial site visit in February to install monitoring equipment and implement a homeowner survey;

2. an interim heating-season visit in March for collecting data stored on battery-power loggers;

3. a season-changeover visit in June to remove heating-season-related monitoring equipment and install monitoring for the cooling season; and,

4. a final visit in September to remove all remaining monitoring equipment.

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[6] The house built in 1860 had a small addition, remodel, and weatherization work done in the early 2000s.

Figure 3. Locations of the field monitoring sites.

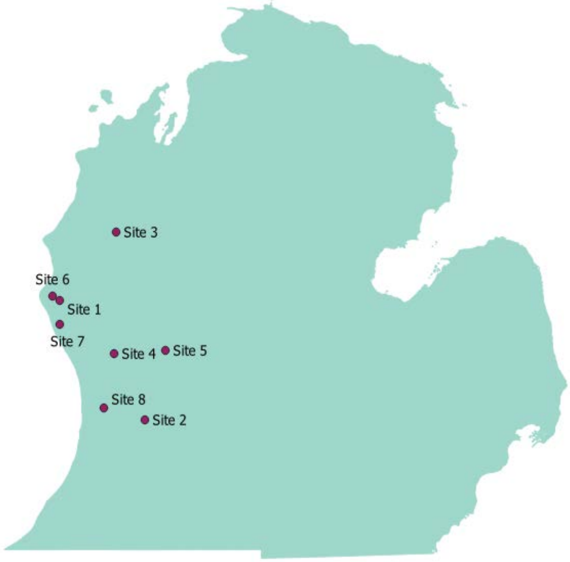

Table 2 provides a description of each heat pump and some key variables that could affect performance. Further information on the heat pumps, backup furnaces, and home characteristics can be found in Appendix G.

Table 2. Key heating system details.

Site	Lockout Temperature (°F)	Heat Pump Compressor Type	Heat Pump Cooling Capacity[7] (Btu/hr)	Heat Pump Heating Capacity[8] (Btu/hr)	Furnace Capacity (Btu/hr)
1	20	Variable-speed	34,600	32,200 26,400	80,000
2	25	Variable-speed	34,800	31,600 20,200	88,000
3*	30	Variable-speed	24,200	21,400 16,900	60,000
4	None	Variable-speed	45,000	46,500 48,500	80,000
5	None	Two-speed	37,200	33,600 21,400	60,000
6	28	Five-speed	23,200	24,000 16,100	60,000
7	20	One-speed	36,000	34,200 22,400	80,000
8	25	One-speed	28,000	28,200 16,800	80,000

*Included on Northeast Energy Efficiency Partnership's (NEEP) cold-climate product list.

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[7] AHRI rated Btu/h at 95ºF.

[8] AHRI rated Btu/h at 47ºF and 17ºF.

DATA COLLECTION

We installed monitoring equipment to collect data on propane consumption of the furnace and electric power consumption of the furnace (including the main blower), and the heat pump compressor. Refrigerant-line temperature, indoor air temperature, and outdoor air temperature were also monitored as described in more detail below.

To measure propane consumption, a temperature-compensated gas meter was installed with a pulse-output module on the propane line to the furnace. Pulse data was recorded with a data logger that recorded pulses over one-minute intervals. The pulse data were later converted to Btu with a standard conversion factor. [9]

Electric power consumption was measured by installing current transformers on the circuit for the furnace and both phases of heat pump power consumption. Current draw was combined with voltage measure for each phase and converted to true power and energy consumption via an eGauge meter, which also stored data at one-minute intervals.

A temperature sensor was installed on the refrigerant line entering the indoor coil for the heat pump; this temperature served as an indicator of the heat pump's operating mode (heating, cooling, or defrost).

In addition, two indoor temperature loggers measured the temperature at the thermostat and a secondary indoor location that was deemed the coldest conditioned room in the house. An outdoor temperature logger measured the outdoor air temperature near the heat pump outdoor unit.

Monitoring data was manually downloaded from all devices during site visits and transferred directly to Slipstream's secure network for analysis.

Table 3. Description of monitoring equipment installed at each residence.

Device	Location(s)	Purpose
AC-250 gas meter with pulse output module	Furnace gas line	Measure propane consumption
HOBO State Logger	Gas meter pulser	Record propane pulse data
eGauge (3000 Series) with current transformers	Electric circuit panel	Record electric power data for heat pump and furnace circuits
HOBO temperature logger with wired sensor	Refrigerant line at A coil	Refrigerant temperature

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[9] A conversion factor of 2,488 Btu/ft^3 was used from http://www.mulherngas.com/PDFs/NYPropaneGuide.pdf. One cubic foot of propane corresponded with 20 recorded pulses.

Device	Location(s)	Purpose
HOBO indoor temperature logger	1) Main living level near thermostat 2) Least-well heated area of house	Measure and record indoor air temperature, refrigerant temperature, and air temperature on ducts to detect cooling mode
HOBO outdoor temperature logger	Near heat pump outdoor unit	Measure and record outdoor air temperature

We encountered relatively minor data collection issues during the monitoring period. The process of addressing and resolving these issues is outlined in Appendix E.

Data were collected for the study for approximately seven months from February through September 2019. This monitoring period provided a wide range of temperatures over which energy consumption associated with the different modes of heat pump operation could be analyzed. Hourly outdoor air temperatures ranged from -3°F to 91°F, which represents the full range of temperatures typically experienced in the area.

DATA ANALYSIS

The study collected monitoring data, as described above, and survey data from each study participant. The following topics were analyzed according to the methods described below:

1. **Characterizing heat pump energy consumption**
   Dual fuel heat pump energy consumption is characterized by defining the systems' modes of operation and comparing the measured input energy consumption in each mode across outdoor temperatures. Conditions defining modes of operation are described in detail in Appendix C.

2. **Participant satisfaction**
   During the initial site visit, homeowners completed a survey regarding their comfort preferences, thermostat behavior, satisfaction with their dual fuel air-source heat pump, and propane consumption before and after installing their heat pump. Survey insights are reported in the Participant Satisfaction section and a copy of the full survey delivered to participants is in Appendix F.

3. **Estimating cost, emission, and grid impacts**
   To calculate the cost, emissions, and grid impacts, we needed to estimate baseline energy consumption to compare to each site's measured energy consumption. Each site's baseline heating consumption is estimated from a linear model using field data and assuming the same furnace is installed in the baseline. The model included days with only furnace heating operation. Each site's baseline cooling consumption is estimated assuming a SEER 14 air conditioner was installed instead of the more efficient heat pump. Details on our approach for estimating daily heating output is available in Appendix A.

4. **Estimating energy efficiency at different outdoor temperatures**
   Energy efficiency of the heat pumps is estimated at different outdoor temperatures with two different approaches. The first approach estimates daily COPs for the monitoring period based on the heat pump input energy and estimated daily heat pump output energy. The second approach models what the COP “would have been” below the configured lockout temperature. Details about this estimation strategy and its limitations can be found in Appendix B.

FINDINGS

This section summarizes findings from the study which are ordered as follows:

- Characterizing Energy Consumption
- Participant Satisfaction
- Cost Savings
- Emissions Savings
- Grid Impact
- Optimizing Heat Pump Performance

CHARACTERIZING ENERGY CONSUMPTION

To characterize the energy consumption of the dual fuel heat pumps, six different modes of operation were defined:

1. **Standby**: Neither the furnace nor the heat pump was operating.

2. **Furnace Heating**: The furnace was operating to heat the home.

3. **Heat Pump Heating**: The heat pump was operating to heat the home.

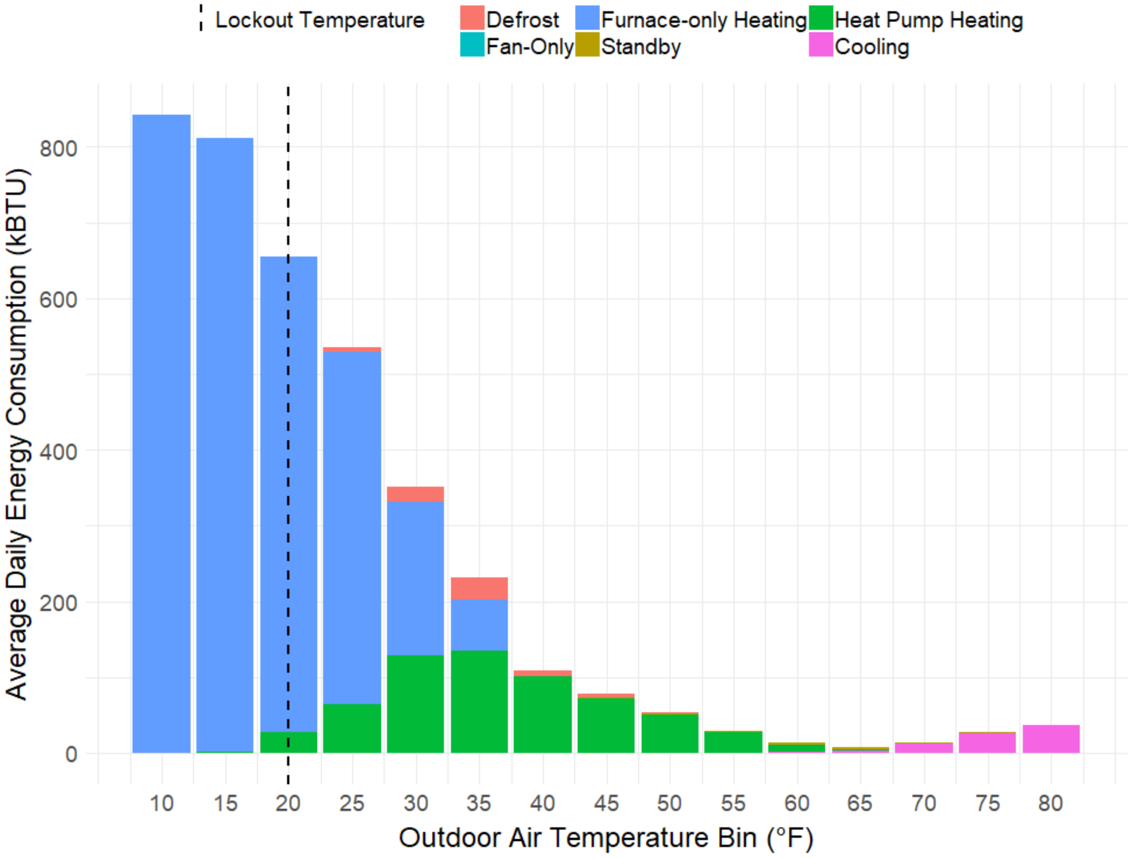
4. **Defrost**: Both the heat pump and furnace were operating to heat the outdoor compressor and heat the home respectively.

5. **Fan-only**: Only the furnace fan was operating, with no propane or heat pump energy consumption.

6. **Cooling**: Only the heat pump was operating to cool the home.

Figure 4 shows the relationship between average daily temperature and average daily energy consumption for each of the six heat pump modes of operation during the 219-day monitoring period for Site 1. For purposes of analyzing overall home heating energy consumption, propane input energy is simply added to electrical input energy of the heat pump and furnace, using units of thousand Btu for both.

Figure 4. Site 1 average daily energy consumption by mode.



Overall heating energy consumption increases as outdoor temperature decreases for a couple reasons. First, more heating is demanded by the home as the difference between outdoor and indoor temperature widens, causing the most energy-intensive heating to occur during the coldest days of the year. Second, as temperatures go down, energy efficiency of the overall system decreases, and more energy is consumed per unit of heat provided to the home. Heat pump efficiency decreases as outdoor temperature drops. And while furnace efficiency is not as sensitive to outdoor temperature, the lower basic efficiency of the furnace compared to the heat pump means reduced overall efficiency as the contribution of the furnace increases.

Energy consumption in heat pump heating mode drops off when the average daily temperature equals the lockout temperature, which is 20°F for Site 1.[10] Why is there so much furnace consumption at average daily temperature ranges above the heat pump lockout of 20°F? This

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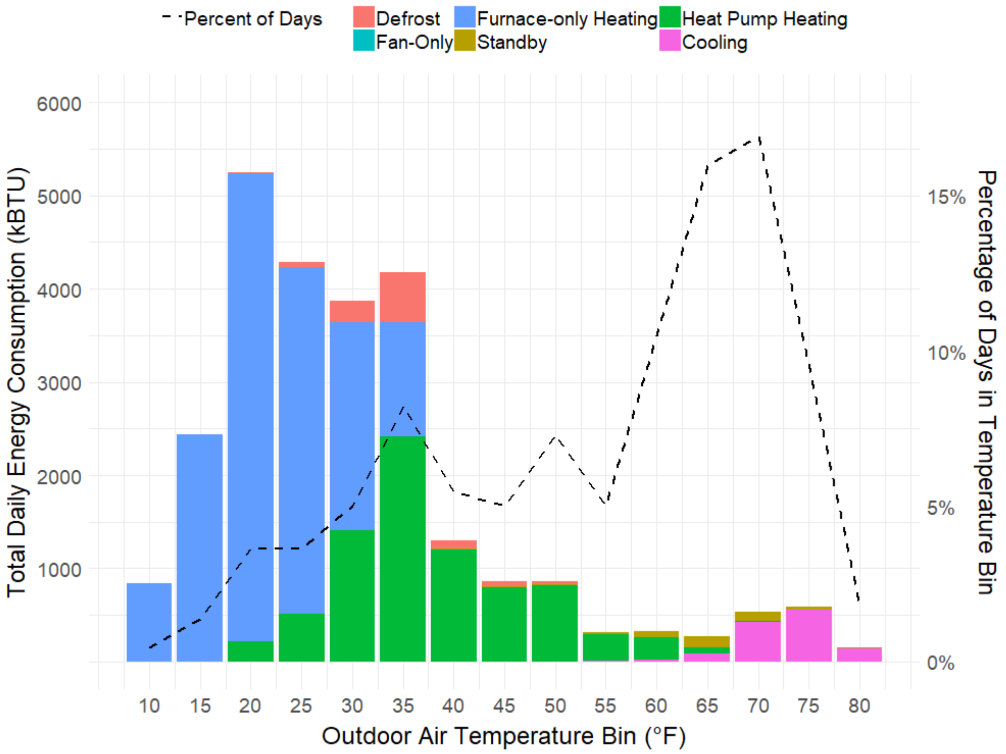
[10] In some systems, heat pump consumption was detected at an average temperature that was below the lockout temperature. This can be explained by intraday hourly temperature variation. During hours when the outdoor temperature is below the lockout temperature, the thermostat prevents the heat pump from operating and calls on the furnace for heating. During hours when the outdoor temperature is above the lockout temperature, the thermostat calls on the heat pump for heating.

can be partially explained by intraday outdoor temperature variations.[11] Furnace consumption above the heat pump lockout can be further explained by indoor air temperature variations. While there was no strong evidence of deep thermostat setbacks at Site 1, it is possible that occupants adjust the thermostat frequently but on an irregular schedule.

Figure 5 below illustrates total energy consumed at Site 1 in each five-degree average daily temperature bin during the 219-day monitoring period. Although the coldest temperature bins are the most energy-intensive, they occur less frequently as indicated by the dotted line showing the proportion of days in each average daily temperature bin throughout the monitoring period.

Figure 5. Site 1 total daily energy consumption by mode.



The energy consumption characterization graphs for the remaining 7 sites are in Appendix C.

PARTICIPANT SATISFACTION

Field study participants report high satisfaction with their dual fuel heat pumps. The survey results provide both general feedback on satisfaction and details on field study participants' experience owning a dual fuel heat pump.[12]

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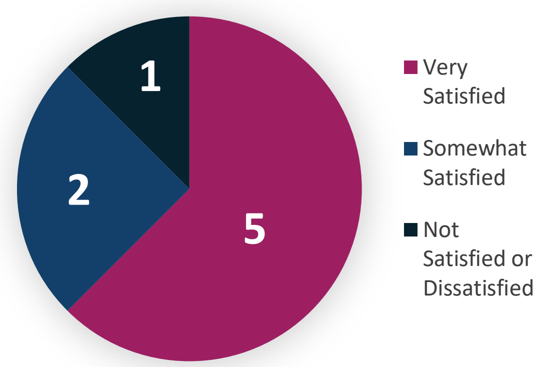
[11] For Site 1, the hourly outdoor average temperature varied as much as 35°F in any given day. This means that if the daily average outdoor temperature was 40°F, there may have been a period during that day when the outdoor temperature was as low as 5°F and the home needed heat.

[12] The survey questions are available in Appendix F.

Figure 6 shows that the eight field study participants expressed high satisfaction with their decision to purchase a dual fuel heat pump. The reasons driving this satisfaction vary with the most common reported benefits being improved comfort, fuel savings, and additional capabilities of heat pumps compared to the replaced system. The major drawbacks reported are disruptive noises and increased electricity bills.

Figure 6. Field study participant satisfaction.



Reported Benefits

Field study participants express strong satisfaction with the dual fuel heat pump's ability to heat, with seven respondents stating they are "very satisfied" and one participant indicating being "somewhat satisfied." General homeowner satisfaction with an air-source heat pump's ability to heat is supported by the Heat Pump Adoptee Survey conducted by the EO program in 2018. Eighty percent of the 60 respondents in that survey reported improved comfort after installing their heat pumps, while the other 20 percent reported "no significant change" in comfort.

Five of the eight field study participants claimed their favorite aspect of owning a dual fuel heat pump is energy savings, which translates to fuel cost savings and reduced dependence on propane. The cost and inconvenience of propane fill-ups are serious concerns for some field study participants. The EO Heat Pump Adoptee Survey supports this finding with 78 percent of respondents citing fuel savings and/or inconvenience of purchasing heating fuel as a motivation for purchasing an air-source heat pump. After being asked about fuel savings from replacing a propane furnace with a dual fuel heat pump, one satisfied field study participant said, "Before the heat pump, I was seeing the propane truck every six weeks, now I'm barely seeing it at all!".

Field study participants also cited more capabilities of dual fuel heat pumps compared to their replaced system as a beneficial aspect of ownership. The following three examples describe beneficial features of dual fuel heat pumps that did not exist in the field study participants' replaced system.

One field study participant listed cleanliness as a major benefit from replacing their wood stove with a dual fuel heat pump. For this participant, heating with the wood stove created a lot of dust. After installing the dual fuel heat pump system, this satisfied member remarked that the dual fuel heat pump heats the house effectively without making the house dirty.

A second participant listed "multi-functionality" as their favorite aspect of owning a dual fuel heat pump. For member/customers living in rural parts of Michigan, resiliency and access to fuel can be an important consideration for their home's energy security. The "multi-functional" dual fuel heat pump system can operate both as an electric and propane system, which adds resiliency in the case of a power outage, propane shortage, or exorbitant fuel prices. The "multi-functionality" of dual fuel heat pumps can provide additional energy security for member/customers that prioritize resiliency.

A third field study participant replaced a 17-year-old, open-loop ground-source heat pump (GSHP) with a dual fuel air-source heat pump. This participant chose a dual fuel air-source heat pump instead of another GSHP because the air-source heat pump does not “pump well water all the time like we did for the geothermal system.” For member/customers that value conserving water, the lack of water consumption is another benefit of a dual fuel air-source heat pump compared to an open-loop geothermal system. This participant also cited how their house seemed warmer at the same set indoor temperature after installing the new heat pump. The difference in comfort is likely more indicative of the evolution in heat pump technology, rather than signaling comfort advantages of air-source over ground-source heat pumps in today’s market.

Reported Drawbacks

While field study participants generally provided positive feedback on their experience with dual fuel heat pumps, they also provided feedback on some drawbacks. The two primary drawbacks reported by field study participants are disruptive noises that come from the outdoor unit and high electric bills.

Three of the eight field study participants reported occasional disruptive noises from the heat pump, which likely arise from defrost operation. For this reason, it is generally recommended to install the heat pump’s outdoor unit outside low-usage rooms. Indeed, the three field study participants who reported disruptive noises had outdoor units that had been installed outside a master bedroom, an office room and a living room, while those who did not report noise issues had their outdoor units outside less-used rooms (bathroom, garage, mud room, or guest bedroom).

One study participant reported higher-than-expected electricity costs. Installers can mitigate this problem by clearly communicating the operating cost implications of dual fuel heat pumps prior to installation. These systems offset propane heating with efficient electric heating, so members should expect decreased propane bills and increased electric bills during the heating season. It is also noteworthy that this participant runs their furnace fan continuously, and likely under high power settings, throughout the year to improve indoor air quality. Field monitoring data showed that their fan configuration settings cost them approximately $295 more than “auto” fan settings, which is certainly contributing to their high electricity bills.

COST SAVINGS

Annualized cost savings are estimated by comparing the dual fuel heat pump with a baseline system of the same high-efficiency furnace but paired with a 14 SEER air conditioner. Member payback periods are reported including and excluding the cost of a baseline air conditioner and annual cooling savings.

Annual Costs

The cost savings from installing a dual fuel heat pump can largely be attributed to the propane cost offset by efficient electric heating. During heat pump heating, the heat pump can deliver heating output with much lower required input energy than the propane furnace, which results in energy savings. However, electric heating must overcome moderately higher fuel prices to generate cost savings. The ***cost-equivalent COP*** is the minimum efficiency where heat pump heating is more cost-effective than propane heating. Under this study's fuel price assumptions, propane costs approximately $2.03/gallon and the electricity rate is $0.12/kWh, which results in a cost-equivalent COP of 1.56.[13] The dual fuel heat pumps in this study had significant operation above the cost-equivalent COP and, thereby, generated substantial cost savings.

Table 4 reports estimated annualized energy and cost impacts from installing a dual fuel heat pump as compared to the baseline of a high efficiency furnace with a SEER 14 air conditioner.[14] The dual fuel heat pumps showed significant annual overall cost savings with an average of $579 and a range of $273-$1,085 for all sites.

On average, heat pump heating offset 468 gallons of propane per year across all sites, or 52 percent of the expected propane consumption without the heat pump. Most sites kept propane consumption below 500 gallons, the size of a typical residential propane tank, which may have helped avoid inconvenience and costly wintertime propane fill-ups depending on propane consumption from other end uses in the house. These results support the claim that adding a heat pump for heating can help avoid the inconvenience and potentially high cost of wintertime propane refills.

Annual cooling consumption averaged 1,263 kWh which results in a seasonal total cost of cooling of approximately $155. Lower demand for cooling compared to heating is the primary explanation for the small cooling cost savings. Also, the gap in efficiency between the baseline and efficient technology tends to be smaller for cooling than heating in dual fuel heat pumps, which lowers the savings potential for cooling. A heat pump can heat two to three times more efficiently than a propane furnace, which provides much more energy savings potential than the difference between a SEER 14 cooling system and the installed system's cooling efficiency.

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[13] The propane price assumption of $2.03 is an average of Michigan propane prices from January 2019 to March 2019 from the EIA. Source: https://www.eia.gov/petroleum/heatingoilpropane/#itn-tabs-1. The electricity rates assumptions are based on the average electricity rate across MECA utilities

[14] The TMY data from the site's nearest weather station used the following source: https://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Table 4. Annual cost savings and energy reduction.

Site	Annual Cost of Operation		Annual Cost Savings			Propane Reduction
	Baseline	Actual	Heating	Cooling	Total	
1	$2,406	$1,595	$792	$19	$811	64%
2	$2,380	$1,702	$675	$3	$678	50%
3	$1,293	$1,020	$243	$30	$273	41%
4[15]	$3,243	$2,158	$1,008	$77	$1085	67%
5	$1,953	$1,377	$543	$33	$576	59%
6	$1,375	$1,067	$285	$23	$308	43%
7	$1,748	$1,449	$288	$11	$299	34%
8	$1,862	$1,259	$599	$4	$603	63%
Average	$2,033	$1,453	$554	$25	$579	53%

Payback Period

Payback period is dependent on incremental costs, and an individual homeowner's situation dictates the incremental costs that should be used. The scenario where a homeowner seeks to add air conditioning or replace an old air conditioner at the time of their heating system replacement has lower incremental costs and a shorter payback than the scenario where a homeowner purchases the heat pump solely for heating. All field study participants represented this first scenario but for illustration we present payback results for both scenarios in Table 5 and Table 6 below.

The National Renewable Energy Laboratory (NREL) publishes a database of costs for energy efficiency measures and is the primary data source used for total installed costs. It is important to acknowledge that the NREL database provides estimates of incremental costs based on average equipment and installation costs, which does not reflect the actual payback period of any field study participant. Actual heat pump system costs vary substantially depending on the product, installer, and other local market conditions. Based on HVAC contractor feedback, the EO program trade ally representative estimates that a dual fuel heat pump's incremental cost typically ranges from $1,000-$4,000 in EO-Collaborative territories, with the highest-end heat pumps costing $4,000 more than a SEER 14 air conditioner. In this analysis we applied a 30 percent cost premium to the 5-stage and variable-speed heat pumps to account for more expensive components and contractor intuition.[16] The simple payback period is calculated and compared with the expected useful life of 15 years for a dual fuel heat pump to assess cost-effectiveness.[17]

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[15] Cooling energy consumption, and thereby cooling savings, are much higher for this site because an occupant's medical condition required low indoor temperatures overnight, which required cooling operation during all seasons.

[16] A 2018 ACEEE paper on heat pumps also used a 30% cost premium for cold-climate models.

[17] Michigan Energy Measures Database (MEMD) uses 15 years as expected useful life (EUL) for a dfASHP.

In Table 5, dual fuel heat pump incremental costs are estimated by subtracting NREL's cost estimates for a 96 percent propane furnace and a heat pump from their cost estimates for a 96 percent propane furnace and a SEER 14 air conditioner.[18] Table 5 shows that the dual fuel heat pumps in this field study all have an estimated simple payback period that is below the 15-year expected useful life of the equipment. This suggests they are all likely to be cost-effective purchases for the field study participants replacing a propane furnace and air conditioning unit. The simple payback period ranges from one to nine years and has an average payback of four years across sites.

Table 5. Incremental cost and simple payback with a 96 percent furnace and SEER 14 air conditioner baseline.

Site	Incremental Cost	Annual Cost Savings	Simple Payback Period
1	$2,564	$811	4 years
2	$3,214	$678	5 years
3	$2,412	$273	9 years
4	$2,585	$1,085	3 years
5	$900	$576	2 years
6	$2,022	$308	7 years
7	$700	$299	3 years
8	$600	$603	1 year
Average	$1,875	$579	4 years

For whatever reason, if a homeowner does not intend to use the heat pump's air conditioning capabilities, the payback analysis changes. In Table 6, incremental cost increases to the full cost of the heat pump because the cost of an air conditioner is not included in the baseline. Table 6 shows that the subsequent simple payback period increases significantly for homeowners that purchase a dual fuel heat pump without the intention of cooling. Despite increased incremental costs under this scenario, five of the eight sites would still succeed in paying off costs within the system's 15 year expected useful life.

Table 6. Incremental cost and simple payback with a 96 percent furnace and no cooling system baseline.

Site	Incremental Cost	Annual Cost Savings[19]	Simple Payback Period
1	$6,776	$792	9 years
2	$7,426	$675	12 years
3	$6,120	$243	26 years

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[18] The installed heat pumps unit and labor cost is calculated based on its size and SEER rating.

[19] This scenario assumes no cooling energy consumption. Only cost savings from heating are included.

4	$7,301	$1,008	8 years
5	$5,112	$543	10 years
6	$5,730	$285	21 years
7	$4,912	$288	18 years
8	$4,560	$599	8 years
Average	$5,992	$554	14 years

The challenges of coordinating heating and cooling system replacements should not be underappreciated. Although incremental costs are reasonable to overcome, the average estimated total system cost was $10,381 and could be a large upfront investment for some homeowners. Additionally, those that have existing air conditioning, or do not demand air conditioning, may be reluctant to add a heat pump to their furnace replacement and bump up their purchase price by about $5,992 on average.

Impact of Fuel Prices on Cost-Effectiveness

Fuel prices are a driving factor impacting annual savings and payback periods. Any change in the price of propane or electricity would alter the achievable heating savings and the cost-equivalent COP. Propane prices are generally more variable than electricity prices. Seasonal fluctuations in the market price tend to result in the highest prices occurring in the middle of the winter and the lowest prices occurring in the Fall. As one example of an extreme swing in price, from January-February 2014 prices spiked from $2.50/gallon to $3.75/gallon. The latest average price of propane in Michigan reported by the EIA for October 2019 is $1.57. This compares to a price of $2.03 in March 2019 and illustrates how avoiding a mid-winter propane fill-up can provide significant savings for a homeowner. Many propane providers offer customers “guaranteed” or “prepay” pricing to avoid the risk of seasonal fluctuations. In these pricing structures, a household can guarantee their propane price for the entire year if their consumption meets the provider’s threshold. Locking in a price may protect customers against seasonal fluctuations within a year, but vulnerability to price fluctuations persists over the lifetime of their furnace.

While electricity prices do not tend to vary as much as propane, enrollment in a heat pump rate can also positively impact the cost-effectiveness of a dual fuel air-source heat pump. The field study participants are all members of Great Lakes Energy, which offers a heat pump rate of $.078 per kWh for heating (a $.03 per kWh reduction from the standard rate). Sites 1, 4, and 8 are enrolled in the pump rate. The primary barrier to enrollment is the upfront installation costs of a submeter. In the long run, enrollment in these special rates make heat pump heating even more cost-effective and incentivizes replacing combustion heating with as much efficient electric heat as possible.

EMISSIONS SAVINGS

Environmental impact of the installed systems was assessed according to each system’s estimated carbon emissions impact. Functionally, emissions savings are estimated with similar methods and the same baseline as cost savings calculations. However, instead of applying fuel-specific prices, we apply fuel-specific emissions factors. While both electric costs and propane costs vary over time and by location, most EO-Collaborative utilities' member/customers are enrolled in time-invariant rates which is why the average volumetric charge of $.12/kWh is used in the analysis of cost impacts. The emissions analysis accounts for the time-varying nature of electricity's emissions intensity at the regional level by merging field study participants' energy consumption data with hourly marginal fuel level data published by the Midcontinent Independent System Operator (MISO).[20] The EPA's 2016 Emissions and Generation Integrated Resource database (eGRID) is used to identify the emissions rate for each electric fuel source in the MISO region.[21]

While the study would have liked to assess annual emissions impacts, due to anticipated inconsistency in dual fuel heat pump's hourly load profile over the course of the year, we decided to simply evaluate emissions impacts during the monitoring period from February-September 2019. The primary advantage of this accounting approach is that the true emissions impacts of the dual fuel heat pump systems installed are characterized as best as possible (with publicly available emissions data). The primary drawback of this approach is that sub-annual estimates are difficult to apply outside this field study. Reported results likely underestimate the emissions savings potential over the full life of the equipment since the industry expects emissions intensity of the electric grid to decrease over the next 15 years.

Like the cost-equivalent COP discussed above, there is also an ***emissions-equivalent COP*** that defines the COP where heat pump heating and propane furnace heating produce equal emissions. The emissions factor of propane is 0.489 lbs CO_2/kWh whereas the average emissions factor of electricity over the course of the monitoring period was 1.558 lbs CO_2/kWh.[22] According to these emissions factors, the estimated emissions-equivalent COP for dual fuel heat pumps in our study is 2.97.[23] Table 7 below illustrates the COP for each site along with each site's emissions savings over the course of the monitoring period. Emissions savings averaged 10 percent across all sites.

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[20] Field study energy consumption data was initially merged with 5-minute marginal electric fuel source data but the difference in accounting at the 5-minute level was very small. A marginal emissions factor reflects the fuel that is next in line to be dispatched. This contrasts with an average emissions factor which reflects the overall fuel mix. Since the dual-fuel air-source heat pump adds incremental load, it is more defensible to use marginal emissions factors over average emissions factors.

[21] Emissions factors can vary for the same fuel depending on a variety of factors including the efficiency of an individual power plant. The eGRID database calculates fuel-specific emissions factors for different regions including MISO. https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

[22] The propane emissions factor uses EIA reported emissions factor of propane of 139.05 lbs CO_2/mmbtu and assumes the furnace is 97 percent AFUE.

[23] This value is lower than 3.18 (1.557/.489) because on average for all 8 sites approximately 10 percent of heat pump consumption constituted as propane consumption during defrost mode and this energy usage is counted in our estimation of heat pump COPs.

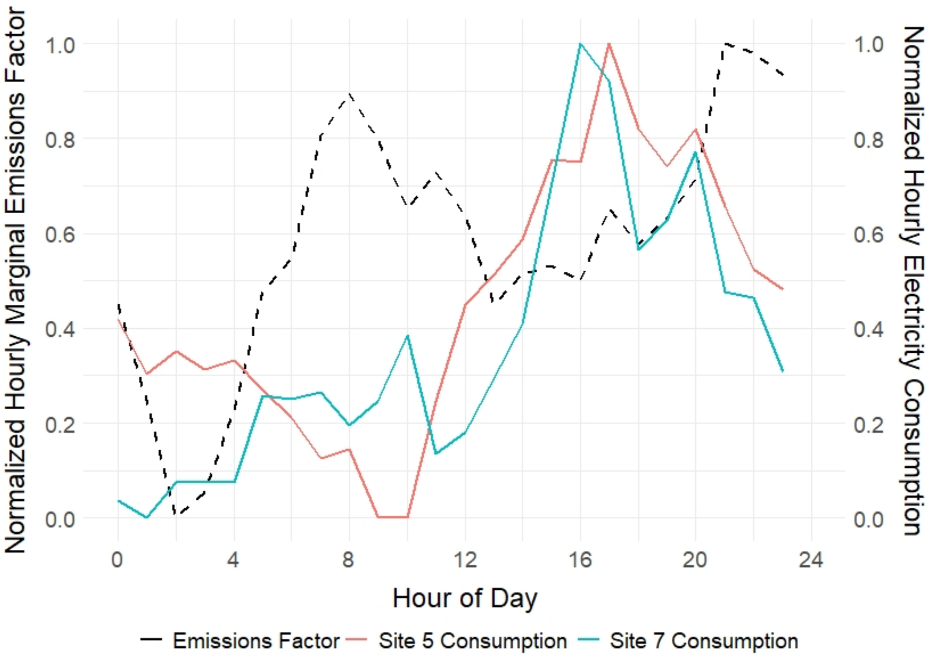
Table 7. Emissions savings by site.

Site	Monitoring Period COP	Monitoring Period Emissions (CO_2)		
		Baseline (lbs)	Actual (lbs)	Savings (%)
1	3.09	7,527	6,832	9%
2	3.22	6,329	5,652	11%
3	2.95	4,723	4,338	8%
4	3.33	12,241	10,710	13%
5	2.75	6,540	5,979	9%
6	2.92	5,539	4,854	12%
7	3.02	6,312	5979	5%
8	3.34	7,983	6,708	16%

All sites experience emissions savings even though the monitoring period COP for a few sites is less than the emissions-equivalent COP of 2.97. There are a couple possible explanations for why this is occurring. First, while most sites do not have significant cooling consumption, the heat pumps achieve emissions savings during cooling mode because all heat pumps installed had cooling efficiency above the baseline system. Second, each of the eight sites has a unique time-of-use pattern (commonly referred to as the “load shape”) which may mean each heat pump may be operating during cleaner or dirtier hours over the course of a given day and across different seasons. While the marginal emissions factor averaged 1.558 lbs CO_2/kWh over the course of the monitoring period, it ranged from as low as 0 lbs CO_2/kWh when zero-carbon sources were on the margin to 2.203 lbs CO_2/kWh when coal was on the margin.

Figure 7 below displays the minimum-maximum normalized hourly consumption profile for Site 5 and Site 7 and the minimum-maximum normalized emissions intensity of the grid in the MISO region over the course of the monitoring period from February-September. During the relatively cleaner hours, 1-4, Site 5 consumed more of its relative proportion of total energy consumption than Site 7. During the relatively dirtier hours, 5-10, Site 5 consumed less of its relative proportion of total energy consumption than Site 7. Alignment of consumption during dirtier or cleaner hours helps explain why Site 5 has close to double the emissions savings as Site 7 even though the average daily COP is lower.

Figure 7. Coincidence of hourly electricity consumption and hourly emissions factor.



If analysis of emissions impacts was extended to a full year, other time-varying trends in emissions would likely reveal opportunities to decrease consumption during high-emissions periods and increase consumption during low-emissions periods. For example, due to clean generation's competitive price on the electricity wholesale market, time-of-use rates designed to lower system costs also likely reduce emissions.

GRID IMPACTS

The study roughly examined two specific grid impacts that would be impacted by increased adoption of dual fuel heat pump technology:

1. Increase in load
2. The opportunity for load flexibility to enable better grid management

Increase in Load

When a dual fuel heat pump is adopted instead of a furnace and central air conditioning, overall energy use goes down, but electric use goes up. Generally, added load increases utility sales revenue and allows utilities to spread fixed costs over more sales, which can put downward pressure on rates. Compared to the modeled baseline of heating only with a propane furnace and a SEER 14 air conditioner, field study participants would add an average of about 3,000 kWh each, with participants with variable-speed systems adding about 4,000 kWh on average and participants with fixed-speed systems adding 2,000 kWh on average. Installation of dual fuel heat pumps resulted in a modeled estimated electrification of 54 percent of the annual heating load for participants in the study.

Table 8. Estimated annual load impact from participant dual fuel heat pump adoption.

Site	Electricity Added from heating (kWh)	Electricity Saved from efficient cooling (kWh)	Net Impact (kWh)
1	5,204	154	5,050
2	3,854	22	3,832
3	1,703	245	1,457
4	6,298	625	5,673
5	3,333	270	3,063
6	1,542	186	1,355
7	1,782	89	1,693
8	2,009	30	1,980
Average	3,216	203	3,013

Load Flexibility

In a future scenario where many homes use heat pumps for space heating, winter peak demand could increasingly become a challenge during polar vortex events like the one experienced on January 30, 2019. Electric resistance air handler boosters that draw power at the same time during low temperature periods could result in high energy costs and expose vulnerabilities in the distribution network where there is limited capacity. Demand response is one viable solution for homeowners with all-electric air-source heat pumps willing to allow indoor temperatures to dip below their setpoint.

Dual fuel heat pump systems lend themselves to winter demand response programs because they are typically set by the installer or homeowner to stop electric and start backup heat at cold temperatures, which tend to coincide with grid constrained and peak events. Smart, integrated controls can further help an electric provider leverage these consumer sited, dual fuel grid assets for peak or other load shedding events.

This study characterizes the variety of load shapes when there is no program intervention that incentivizes changes in the time-of-use. Figure 8 below highlights the diversity of load curves of three of the field study participants. The entire monitoring period (which contains both heating and cooling periods) for all sites is included. Site 1 has a fixed thermostat setpoint over time which results in a relatively flat load curve over the course of a 24-hour period. In contrast, Sites 2 and 4 have peaky load curves with Site 2 exhibiting both a morning and evening peak and Site 4 exhibiting a steep evening peak.[24]

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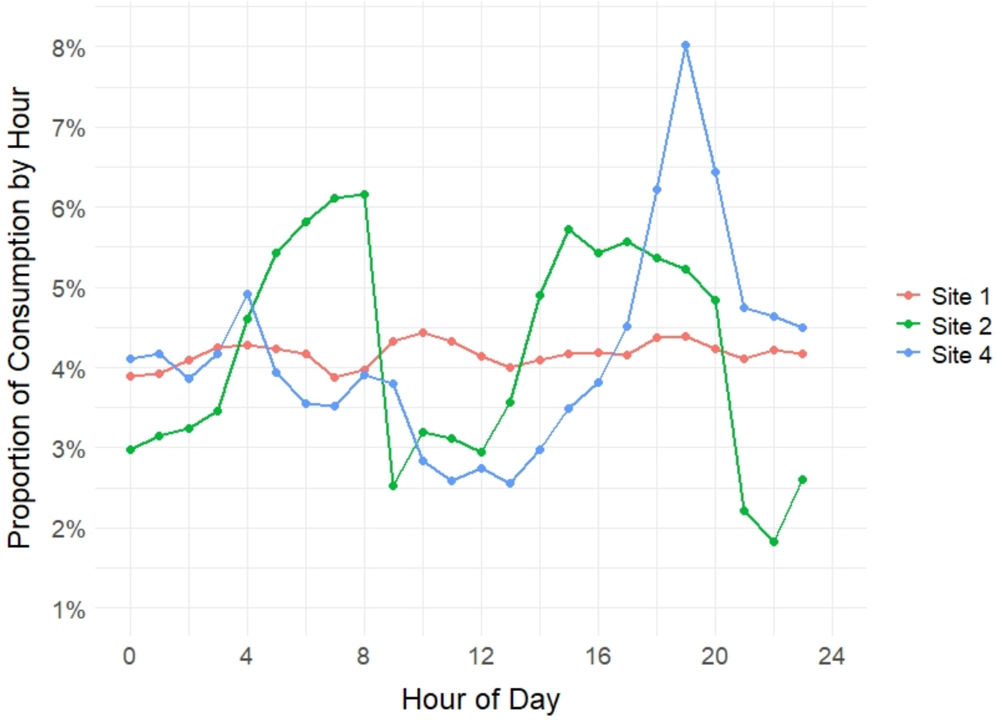
[24] Site 4 evening peak is less steep when only looking at heating-dominated months of February-April since the thermostat setback was most prominent over the summer months.

Figure 8. Monitoring period hourly electric load shape for three sites.



The ability of dual fuel heat pumps to meet occupant comfort with a flexible load profile over time and to immediately switch over to non-electric backup heat make them a valuable grid asset. Encouraging the adoption of time-of-use rates is one solution that can align member interests and system interests. These rates incentivize increased energy consumption during periods of low electricity cost and incentivize decreased energy consumption during periods of high electricity cost.

OPTIMIZING HEAT PUMP PERFORMANCE

Performance of dual fuel heat pumps in this study vary based on many factors, such as configured lockout temperature, system sizing, and model specifications. These factors should all be considered during system selection and configuration to ensure that the dual fuel heat pump installed matches the homeowner's needs and is operating to its fullest potential. The sections below present estimates for the energy efficiency of each site's heat pump, discuss factors that impact heat pump performance, and question the adequacy of common heat pump efficiency metrics.

Heat Pump Energy Efficiency

The energy efficiency of the heat pumps in our study is evaluated with the COP metric, which is the ratio of output energy provided per unit of input energy.[25] Because the heat pump COP changes with outdoor air temperature, the COP is characterized across outdoor temperatures ranges and estimated based on a weather-normalized heating season COP.

We estimated heat pump COP by modeling the total heating energy use of each home and calculating the ratio between the estimated heat pump heating output and the measured heat pump energy input.[26] More details of these methods is available in Appendix A and Appendix B.

The boxplots in Figure 9 show the distribution of daily COP estimates in ten-degree temperature bins.[27] Sites are grouped by compressor type.[28] Each "box" represents the 25th to 75th percentile of the estimated daily COPs. The solid line in the middle of the box is the median COP, and the "whiskers" that extend beyond the box represent COP values below the 25th percentile or above the 75th percentile, excluding outliers.[29] Figure 9 shows slightly higher median daily COPs for the variable-speed heat pumps than the fixed-speed heat pumps across all outdoor air temperature bins. Although these results support the theory that heat pumps with variable-speed compressors perform better than fixed-speed heat pumps, the boxplots show a wide distribution of daily COP estimates regardless of compressor type. This suggests that factors besides compressor type have a significant impact on system performance.[30]

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[25] Heat pump COP cannot be calculated directly from the collected data in this field study. Instead, we indirectly estimated heat pump COP based on an estimated heating load line for each home. These methods are described in Appendix A and Appendix B.

[26] The heat pump heating output is estimated by subtracting the furnace heating output energy from the modeled total heating energy. This analysis is conducted on daily data.

[27] The input energy used for the heat pump's COP calculation include heat pump compressor energy, fan energy during heat pump heating mode, compressor energy in defrost mode, fan energy in defrost mode, and propane energy in defrost mode with all energy unit converted to Btu.

[28] Any heat pump with discrete stages is defined as "fixed-speed" in this study, even if it has an inverter-driven compressor. Notably, site 6 in this study operates at 5 stages, but has an inverter-driven compressor. Site 6 was classified as "fixed-speed" because it has discrete stages.

[29] Outliers are defined as above the upper hinge by 1.5*IQR (inter-quartile range) or below the lower hinge by 1.5*IQR.

[30] Observed daily COPs for each site in the study are reported in Appendix D.

Figure 9. Estimated daily COP across temperature bins by compressor type.

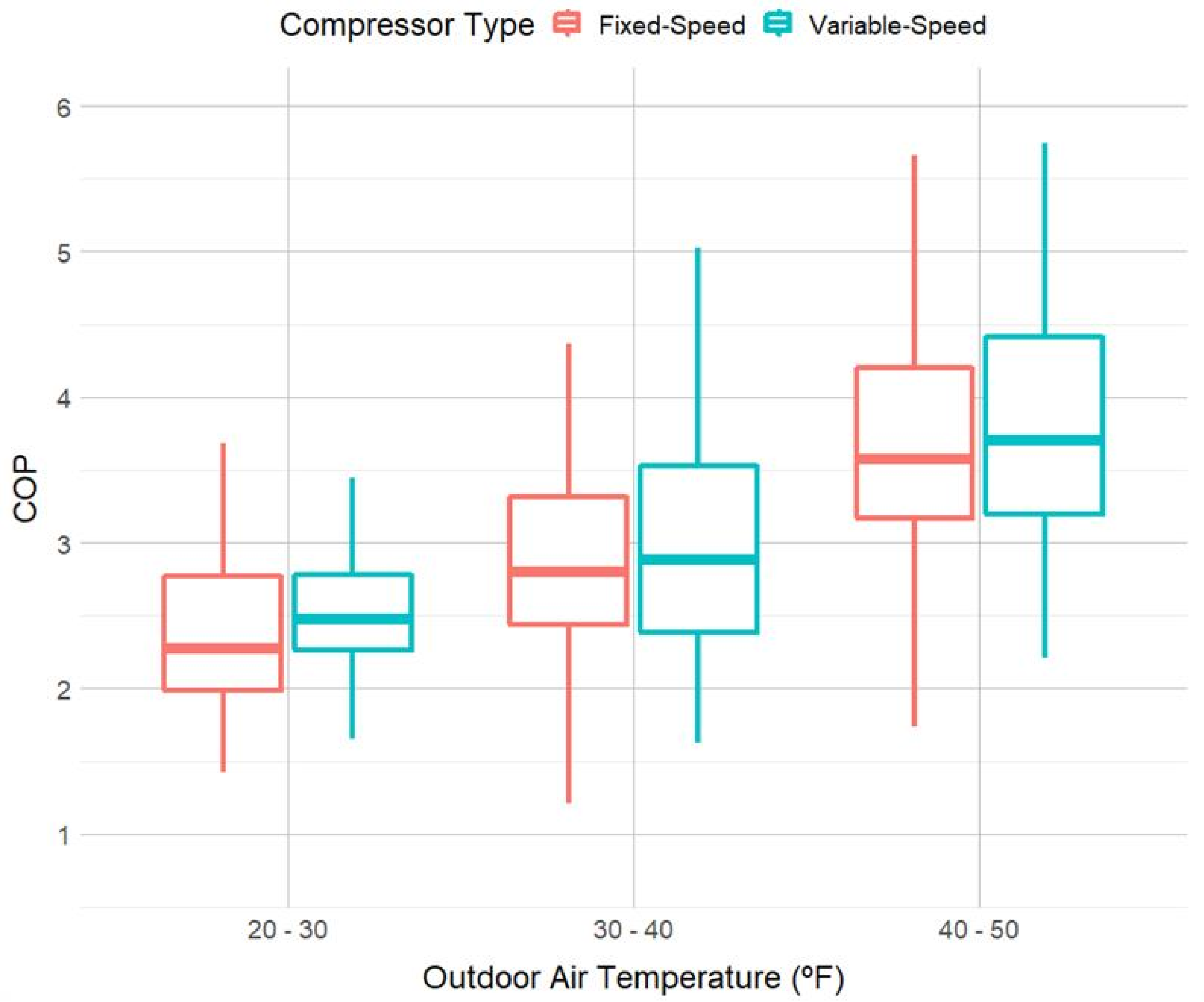

Table 9 reports each site's heating season COP and lockout temperature.[31] The heating season COP tends to increase for sites with higher lockout temperatures because these sites operate during warmer outdoor temperatures where heat pumps tend to heat more efficiently.

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[31] The heating season COP is a site-specific COP estimate based on the observed outdoor temperatures with heat pump heating operation. The COP averages in each five-degree temperature bin are weighted based on TMY data from the site's nearest weather station.

Table 9. Heating season COPs.

Site	Heating Season COP	Lockout Temperature (°F)
1	3.26	20
2	3.65	25
3	3.32	30
4	3.28	None[32]
5	2.70	None
6	3.74	28
7	3.42	20
8	3.89	25

Generally, the results presented in Table 9 align with the limited research on dual fuel heat pumps in the Upper Midwest. From 2015-2017, the Center for Energy and the Environment (CEE) monitored four residential cold-climate dual fuel air-source heat pump systems in the state of Minnesota.[33] Using similar methods to those employed in this study, CEE researchers reported weather-normalized annual COPs in the range of 2.51-2.78 for three of their studied sites, which compares to a slightly higher range of estimates from 2.70-3.89 in this study.

The difference in reported COPs between the two studies may be explained by the temperature differences during heat pump operation. Researchers directed installation of the systems in the Minnesota study and ensured heat pump lockout temperatures were configured between 5-10°F. This study monitored market-installed systems where contractors determined the heat pump lockout temperatures. These lockout temperatures tended to be higher than the lockout temperatures in CEE's study (as shown in Table 9). In addition, the climate in Minnesota is generally colder than the greater Grand Rapids area, which likely caused heat pumps in the Minnesota study to operate during more low-temperature periods.

Lockout Temperature

The lockout temperature is an important configuration setting that should be optimized for dual fuel heat pumps to achieve their full savings potential. As stated earlier, cost-equivalent COP is the minimum efficiency where heat pump heating operation is less expensive than propane furnace heating. Correspondingly, a **cost-equivalent lockout temperature** is the lowest outdoor temperature where the heat pump's COP is larger than the cost-equivalent COP, which is 1.56 under this study's fuel price assumptions.

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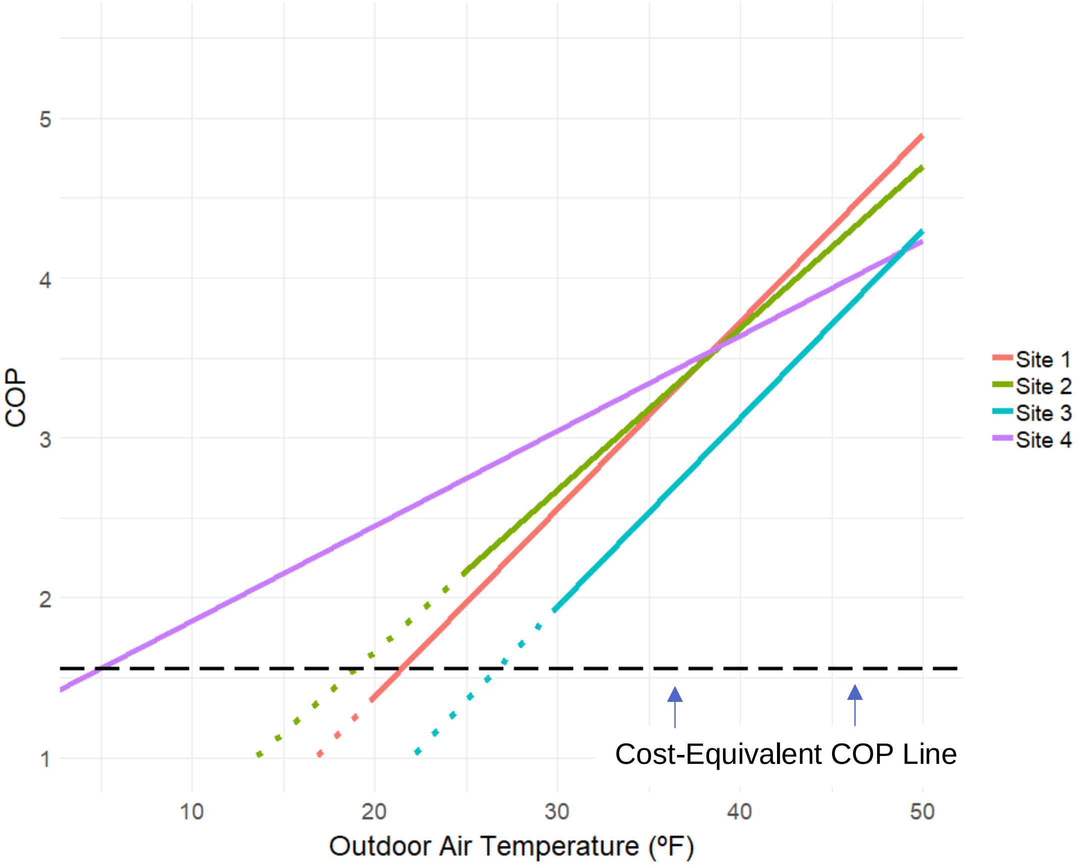
[32] Sites with "None" for their lockout temperature did not have their lockout temperature "configured" by HVAC contractors. Instead, the decision to heat with the furnace or heat pump is based on a manufacturer's algorithm.

[33] Schoenbauer, Ben, Nicole Kessler, and Marty Kushler. 2017. "Field Assessment of Cold-Climate Air Source Heat Pumps." Conservation Applied Research and Development (CARDFINAL Report. Minneapolis, MN: Center for Energy and Environment.

For many sites in this study, the cost-equivalent lockout temperature is not observed because their heat pump's lockout temperature prevented the heat pump from operating at low temperatures. Models were developed to characterize how the heat pumps "would have" operated below their configured lockout temperatures and estimated each site's cost-equivalent lockout temperature.[34]

Figure 10 and Figure 11 show estimates of COP across outdoor air temperatures for sites with variable-speed compressors and fixed-speed compressors respectively. The intersection of each site's COP estimation line and the horizontal cost-equivalent COP line represents the cost-equivalent lockout temperature for each site. The dotted portion of each site's COP estimation line represent temperatures below the site's lockout and the solid portion signifies temperatures above the site's lockout. Sites with dotted lines intersecting the horizontal cost-equivalent COP line could economically benefit from lowering their lockout temperature, while sites with solid lines intersecting with the horizontal cost-equivalent COP line could economically benefit from increasing their lockout temperature.

Figure 10. Modeled COPs for sites with variable-speed compressors.



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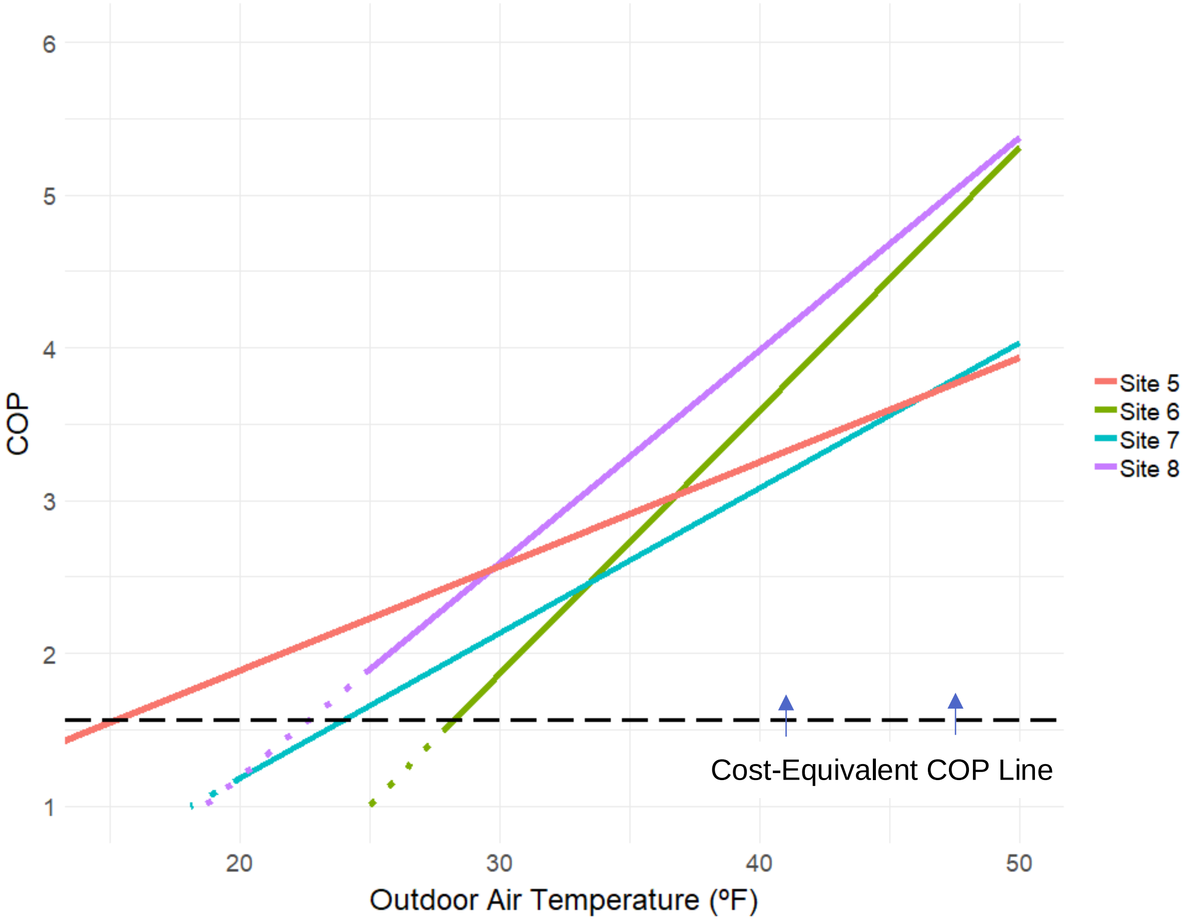
[34] A weighted regression model was used to estimate COP below the configured lockout temperature. More information on this approach and skepticism about the linear relationship between COP and outdoor temperature can be found in Appendix B.

Figure 11. Modeled COPs for sites with fixed-speed compressors.



It is important to acknowledge that it is possible that the heat pumps may not have enough capacity to meet heating demand at the cost-equivalent lockout temperature. Homeowners should ensure that their heat pump can meet their heating demand at the cost-equivalent lockout temperature before adjusting their lockout temperature.

Table 10 reports each site's lockout temperature, COP at lockout temperature, and estimated cost-equivalent lockout temperature. Although the results show that some sites could economically benefit from lowering their lockout temperature, the heat pump may not have enough capacity below the configured lockout temperature. Capacity limitations likely factored into the HVAC contractor's lockout temperature configuration during installation. To achieve their fullest savings potential, dual fuel heat pump's lockout temperature should be configured as close to the cost-equivalent lockout temperature as possible.

Table 10. Cost equivalent lockout temperature.

Site	Lockout Temperature		COP at Lockout Temperature
	Configured	Cost-Equivalent	
1	20	23	1.38
2	25	20	2.17
3	30	28	1.94
4	None	7	None
5	None	17	None
6	28	29	1.52
7	20	25	2.18
8	25	24	1.89

Sizing Considerations

Heat pump sizing is an important factor for HVAC contractors and homeowners to consider before installing a dual fuel heat pump. Larger heat pump systems can meet homes' heating needs at colder temperatures and, thereby, offset a larger portion of propane heating. Although larger heat pump systems can provide a higher portion of the total heating load, their lockout temperatures must be set low enough to allow them to heat during cold temperatures.

Because Sites 4 and 5 do not have configured lockout temperatures, this study is able to compare the impact of system sizing on heat pump heating operation. For these sites, the heat pump will operate if it has capacity to keep the home warm, and when it cannot, the furnace will turn on to make up the difference.[35] Presumably Site 4 has a larger heating load because it has a larger furnace and higher average daily energy consumption than Site 5.

Table 11 shows the difference in the two systems' capacity only widens as temperatures go down. Site 4 has a rated heating capacity at 17°F that is over double the heating capacity of Site 5, showing that Site 4's heat pump is designed to operate at colder temperatures.

Table 11. Heat pump and furnace capacities for sites 4 and 5.

Site	Nominal Furnace Capacity (Btu/hr)	Rated Heat Pump Capacity (Btu/hr)	
		47°F	17°F
4	80,000	46,500	48,500
5	60,000	33,600	21,400

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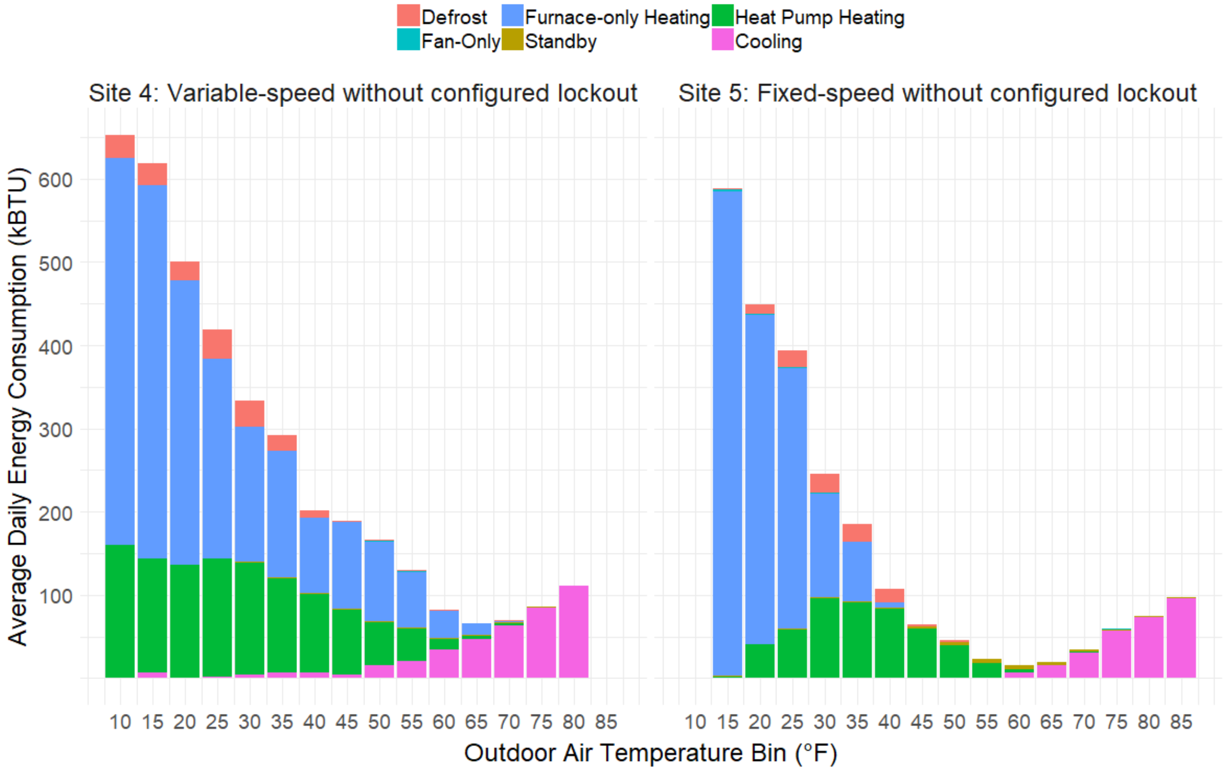
[35] The switchover logic when there is no heat pump lockout temperature could potentially be driven by an inability of the heat pump to meet the thermostat's setpoint or could be driven by the steepness of a drop below the setpoint temperature.

Figure 12 below compares the energy input profiles for these two sites. Site 4 has substantial heat pump heating energy consumption at the lower temperatures because the system is capable of providing sufficient heat to the home at lower temperatures.[36] Site 5's heat pump heating energy consumption trails off in the colder outdoor temperatures because the system is not capable of keeping up with the home's heating demand.

Figure 12. Average daily energy consumption for sites without a configured lockout temperature.



These results show that sizing heat pump systems larger can result in increased heat pump heating operation. The size of the heat pump is an important discussion point between the HVAC contractor and homeowner before installing a dual fuel heat pump because it will impact the configured lockout temperatures, upfront costs, and expected energy savings.

Defrost Considerations

Although defrost cycling is a core function for heat pumps operating in cold climates, its impact on system costs is relatively small for the field study's systems. Defrost cycles are needed to reduce frost accumulation on the outdoor coil that limits capacity and reduces efficiency. All studied systems defrost with a process called reverse cycling. During this process, the refrigerant flow is reversed causing hot refrigerant vapor to be pumped through the outdoor coil

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[36] Site 4 has cooling mode during low temperatures due to the occupant's low overnight setpoint in the heating and cooling season. There is significant furnace heating consumption in high temperature ranges for this site because the sharp difference between their low nighttime setpoint and high morning setpoint often requires "furnace recovery" to satisfy their indoor air temperature requirements.

and melt frost on the exterior. During reverse cycling, the home is heated exclusively by the furnace.

Defrost cycles are most commonly initiated according to time and temperature measurements, which are reasonable indicators of frost accumulation on the outdoor coil. Sites 1-7 initiate defrost cycles based on time and temperature measurements. Site 8 relies on a simple timer configured to a 90-minute interval to initiate defrost cycles, which may waste energy by calling defrost cycles when the conditions do not require it.

The average defrost cycle length of heat pumps in this study ranged from three to eight minutes, with an average of four minutes. Energy consumption in defrost mode is made up of three components: furnace and blower fan electric energy, furnace propane energy, and heat pump electric energy. On average, heat pump electric energy accounts for 9 percent of total energy consumption in defrost mode, furnace and fan blower electric energy are 2 percent, and the furnace propane energy accounts for 89 percent.[37]

Table 12 shows site time and costs accrued during defrost mode. Results show sites with low or no configured lockout temperatures accrue more time in defrost and consequentially higher defrost costs. This is because defrost cycles are more prevalent during colder temperatures and heat pumps with no lockout temperature run more frequently during low-temperature periods. Additionally, results suggest inefficiencies associated with Site 8's simple timer defrost initiation may increase heating costs. Site 8 has a relatively high lockout temperature of 25°F, which is typically associated with lower defrost costs, yet the site has the second highest defrost costs in the study. This suggests the basic timer based defrost algorithm may be wasting energy.

Table 12. Defrost characterization.

Site	Lockout Temperature	Defrost Mode's Proportion of:	
		Heat Pump Heating Runtime	Annual Heating Cost
1	20	1.0%	3.7% ($56)
2	25	0.6%	0.8% ($14)
3	30	1.0%	1.7% ($16)
4	N/A	2.5%	4.4% ($77)
5	N/A	3.0%	4.6% ($55)
6	28	1.2%	2.2% ($20)

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[37] While the heat pump does not directly consume propane to execute reverse cycle defrosting, indirectly a portion of the heat energy provided by the furnace is exchanged through the indoor coil. The remainder of the heat energy provided by the furnace is supplied to the home. There is no reliable method to measure and disaggregate the two uses of heat energy provided by the propane combusted by the furnace.

7	20	0.6%	0.5% ($7) [38]
8	25	2.7%	4.6% ($55)

Although defrost operations vary between sites, defrost optimization is not seen as a priority for generating additional energy savings. The results in Table 12 show that energy consumed in defrost mode is between 0.5 to 4.6 percent of the total heating energy costs across the eight sites. A significant technological advancement that reduces defrost energy consumption by 50 percent would only decrease cost savings by, at most, a relatively insignificant 2.3 percent for the field study participants.

Limitations of Heat Pump Energy Efficiency Metrics

The metrics commonly used to measure heat pump efficiency have limitations when applied to heat pumps in cold climates. Heat pump heating efficiency is typically measured with the heating seasonal performance factor (HSPF), a ratio of heating output to power input based on an expected season of heating hours. Seasonal energy efficiency ratio (SEER) is constructed like HSPF, but according to expected cooling hours in the season.

What is HSPF?

HSPF is specifically used to measure the heating efficiency of air-source heat pumps. It is calculated as the ratio of output capacity (in Btu/hr) to power input (in watts).

One limitation of the HSPF metric is that the values publicly available from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) are constructed based on Climate Zone IV. All the sites in the field study and much of the Northern United States are in Climate Zone V. The HSPF metric would be better suited to measure heating efficiency in cold climates if it differentiated estimated efficiency by climate zone.

Another limitation of HSPF is that it only provides information on heat pump efficiency at 47°F, which may not be indicative of its efficiency at colder temperatures. Heat pump manufacturers often publish estimated COPs at lower temperatures, such as 5°F and 17°F. These provide a much better representation of a heat pump's ability to heat efficiently at cold temperatures than HSPF.

Finally, the HSPF and SEER efficiency metrics are calculated from a lab testing procedure that operates the heat pump at different fixed speeds and levels of indoor air flow. This test procedure works well for single-speed and multi-speed heat pumps but may understate the efficiency for heat pumps with variable-speed (inverter-driven) compressors. Heat pumps with inverter-driven compressors gain energy efficiency through their compressor's ability to reduce excessive cycling by modulating its speed. Since heat pumps are only tested at fixed speeds and air flows in the lab, these results do account for all the efficiency gains from inverter-driven compressor technology.

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[38] Site 7 had a vacation from February 7th, 2019- March 27th, 2019 and their heat pump heating was disabled during this period. The absence of heat pump heating during this period likely decreased the total amount of time the system spent in defrost mode and its contribution to heating costs.

Although significant work is needed, there are two promising developments that are beginning to address the problems with efficiency metrics for air-source heat pumps. First, the Northeast Energy Efficiency Partnership (NEEP) created a product list for “Cold Climate Air Source Heat Pumps” that identifies heat pumps that are designed for cold climate performance. NEEP’s product list includes information on COP down to 5°F, which addresses HSPF’s issue of only representing efficiency at high temperatures.[39] Unfortunately, NEEP’s product list only contains manufacturer-provided information on heat pumps that meet their cold climate specifications, so their improved metrics are not available for many heat pumps on the market.

Second, the Canadian Standards Association (CSA) has developed a dynamic, load-based testing procedure that accounts for inverter-driven compressor’s efficiency gains from reduced cycling behavior, which is unaccounted for in AHRI current testing protocol.[40] Additionally, the CSA testing protocol includes ratings for heating and cooling efficiency across 8 climate zones. Although the CSA standards could solve some of the current problems with heat pump efficiency metrics, review of this time-intensive testing procedure is currently underway and will require more time before robust results are available.

In closing, current simple heat pump energy efficiency metrics are inadequate for estimating energy efficiency in real-world conditions. There is significant variation in outdoor temperatures across different locations and significant variation in outdoor temperatures within a given location throughout the year. The most immediate way to improve predicted efficiency and energy savings estimates for members/customers and HVAC contractors would be to create a modeling tool that better accounts for differences in factors impacting system performance such as cold-temperature efficiency, sizing, and configured lockout temperature. To the extent possible, the EO program could find it valuable to better align rebates with drivers of system energy efficiency other than just HSPF and SEER.

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[39] NEEP Cold Climate Air-Source Heat Pump Specification (Version 3.0).
[40] CSA EXP 07.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Dual fuel air-source heat pumps are a rapidly evolving energy efficient technology that can meet member/customer space heating needs for homes with ductwork and can provide higher efficient cooling. A field study was conducted to characterize the potential for dual fuel heat pumps to provide cost, environmental, and grid benefits to MECA EO-Collaborative utilities and their members/customers. The primary conclusions from this research project are listed below:

1. **Field study participants are satisfied with their dual fuel air-source heat pumps.** Field study participants revealed they are satisfied with their decision to purchase a dual fuel heat pump. Participants expressed strong satisfaction in the technology's ability to heat their home and reduce costs and inconvenience associated with propane-only heating systems. Participants frequently cited their "favorite aspect" of owning a dual fuel air-source heat pump as a feature that did not exist in their replaced heating system, such as its cleanliness, resiliency to fluctuations in fuel prices, or reduced water consumption compared to an open-loop GSHP.

2. **All eight heat pumps in the study achieved significant energy and cost savings**. Estimated reductions in propane use ranged from 34 percent to 67 percent and estimated annual savings ranged from $273 to $1,085 for field monitoring study participants. Payback periods ranged from one to nine years and averaged 4 years across all sites.

3. **Although heat pumps with variable-speed compressors tend to have higher efficiency, this will only result in substantial energy savings when other factors are optimized such as system selection, sizing, thermostat schedules, and lockout configuration.**
   Energy savings are maximized when the systems operate cost-effectively over an extensive range of operating hours. The heat pump model and its compressor type will impact the heat pump's efficiency at different outdoor temperatures. However, heat pump energy savings are still dependent on how often they are used, which is in turn dependent on the size of the system and the temperature range of operation. Larger systems can meet demand of larger home heating loads, resulting in more operating hours than smaller systems. Even if the heat pump is sized to meet a high portion of a home's heating demand, the operating hours can still be limited by a configured lockout temperature above the site's cost-equivalent lockout temperature. Overall, dual fuel air-source heat pumps savings will be maximized with a high-efficiency, variable-speed heat pump that is sized and configured to operate at low temperatures.

4. **Dual fuel air-source heat pumps present an immediate opportunity to realize operational savings and environmental and grid benefits.**
   Each dual fuel heat pump in this field study brought economic, environmental and grid benefits. On average, studied systems saved $579 in annual operating costs and

reduced carbon emissions by 10 percent during the monitoring period. Dual fuel air-source heat pump's ability to switch between propane and electric heating also presents grid managers with an opportunity to better address system peaks and grid emergencies during the heating season and encourage or discourage electric load at different times throughout the year.

RECOMMENDATIONS

To build off the findings of this study, the following next steps and recommendations may be considered:

1. **Evaluate the impact of alternative rate designs and offer rates that yield the most benefits to members/customers and the grid.**
   Cost results presented in this study are sensitive to changes in electricity and propane prices. Efforts to lower the volumetric rate for heat pump consumption could lead to an increase in the dual fuel air-source heat pump's cost-effective hours of operation for members/customers. Some field study participants cited high installation costs of the GLE subtractive meter as a deterrent to participating in the $.03/kWh rate credit. Further investigation to identify the impact of subtractive meter installation costs on rate credit participation could help increase enrollment. In addition, investigation of alternative rates that align time-of-consumption with electricity generation costs could bring even further benefits to EO-Collaborative utilities and their members/customers. Any new opt-in or opt-out rate offer should ensure that it is easy to understand and has buy-in from member/customers.

2. **Develop a heat pump modeling tool that accounts for system selection, configuration, operational settings, and provides better savings estimates for HVAC contractors and members/customers.**
   As discussed in this report, traditional energy efficiency metrics for heat pumps have serious limitations. This field study confirms that many factors, such as system configuration, sizing, compressor type, thermostat behavior, and heat pump model, significantly impact estimated savings. A heat pump modeling tool that can adjust estimated savings according to these factors could help HVAC contractors and members/customers better estimate the cost-effectiveness of potential heat pump configurations. A better modeling tool could also potentially serve as a resource to better align heat pump rebates with heat pump savings.

3. **Create more comprehensive load profiles to help forecast the impacts of widespread heat pump adoption in different locations across EO-Collaborative utility territories.**
   In this analysis, heat pump load profiles are characterized at the hour-of-day over the monitoring period. Further analysis of dual fuel air-source heat pump's load shapes across months and days of the week could help build more accurate forecasts of dual fuel heat pump load impacts, which can inform load forecasting under different dual fuel

heat pump adoption scenarios. These forecasts could inform future planning for infrastructure development and demand-side management programs.

4. **Increase granularity of emissions accounting to provide insights on how to minimize the emissions impact of heat pump technology and position EO-Collaborative utilities as decarbonization leaders.**
   The emission factors in this field study utilized electric generator data from the MISO Central Region. In future research, the analysis could use more granular geographic data on emissions factors for more precise emissions accounting. Additionally, detailed characterizations of emissions profiles across months, days of the week, and under different grid scenarios can help EO-Collaborative utilities identify high emissions periods and mitigate their carbon impact. This proactive approach towards carbon accounting positions EO-Collaborative utilities and their members as leaders in environmental stewardship and mitigates risk against future carbon reduction policy.

5. **Conduct further research on heat pump sizing and its impact on dehumidification, heating energy consumption, and cooling energy consumption to help establish best practices for HVAC contractors in EO-Collaborative utility territories.**
   In Michigan’s climate, heat pumps with variable-speed compressors that are sized larger than the home’s cooling load can offset more propane without compromising cooling performance. However, contractors tend not to take full advantage of this capability due to concerns about dehumidification performance in the summer. Further research on the implications of sizing variable-speed heat pumps above their cooling capacity can help establish best practices for sizing variable-speed heat pumps.

6. **Conduct field research on other heat pump technologies in other market segments to verify the technology’s performance, better understand local barriers to adoption, and identify EO program market interventions to address the barriers.**
   This field study addressed dual fuel air-source heat pumps, which is a good option for members replacing a residential furnace and central AC system. Other heat pump technologies like VRF systems, ground-source heat pumps, and ductless heat pumps may be best to provide high-efficient electric space heating for other specific commercial and residential market segments. Further characterization of these market segments and each technology’s ability to serve them will help EO-Collaborative utilities inform, educate, and incentivize more members/customers to adopt efficient electric heating technologies.

APPENDIX

The appendix further details analytic methods used in this field study. The appendix items are organized as follows:

- Appendix A: Site Heating Load Estimation
- Appendix B: COP estimation
- Appendix C: Mode Characterization by Site
- Appendix D: Daily COP estimates for each Site
- Appendix E: Data Collection
- Appendix F: Participant Experience
- Appendix G: Participant System and Home Details
- Appendix H: Climate Zones

APPENDIX A: SITE HEATING LOAD ESTIMATION

The heating load lines for sites in this study are estimated with two different strategies. They are described below.

Approach 1: Regression analysis on days with only furnace operation

The heating load was estimated for seven of the eight sites in this field study through a linear regression approach. The approach is outlined as follows:

1. Limit the data for each site to days of “furnace-heating only”. More specifically, these are days when the dual fuel air-source heat pump provides heat to the home, but only with the propane furnace heating and not with the heat pump heating.

2. Estimate a site-specific balance point temperature based on the degradation of heating input energy and the difference between daily indoor and daily outdoor temperature (ΔT). The estimated balance point for each site is added to their “furnace-heating only” data.

3. Estimate the following regression on each site’s “furnace-heating only” data with the balance point temperature included. The “furnace input” variable is the daily total measured propane consumption minus the propane consumption in defrost plus the fan power input in furnace heating mode.

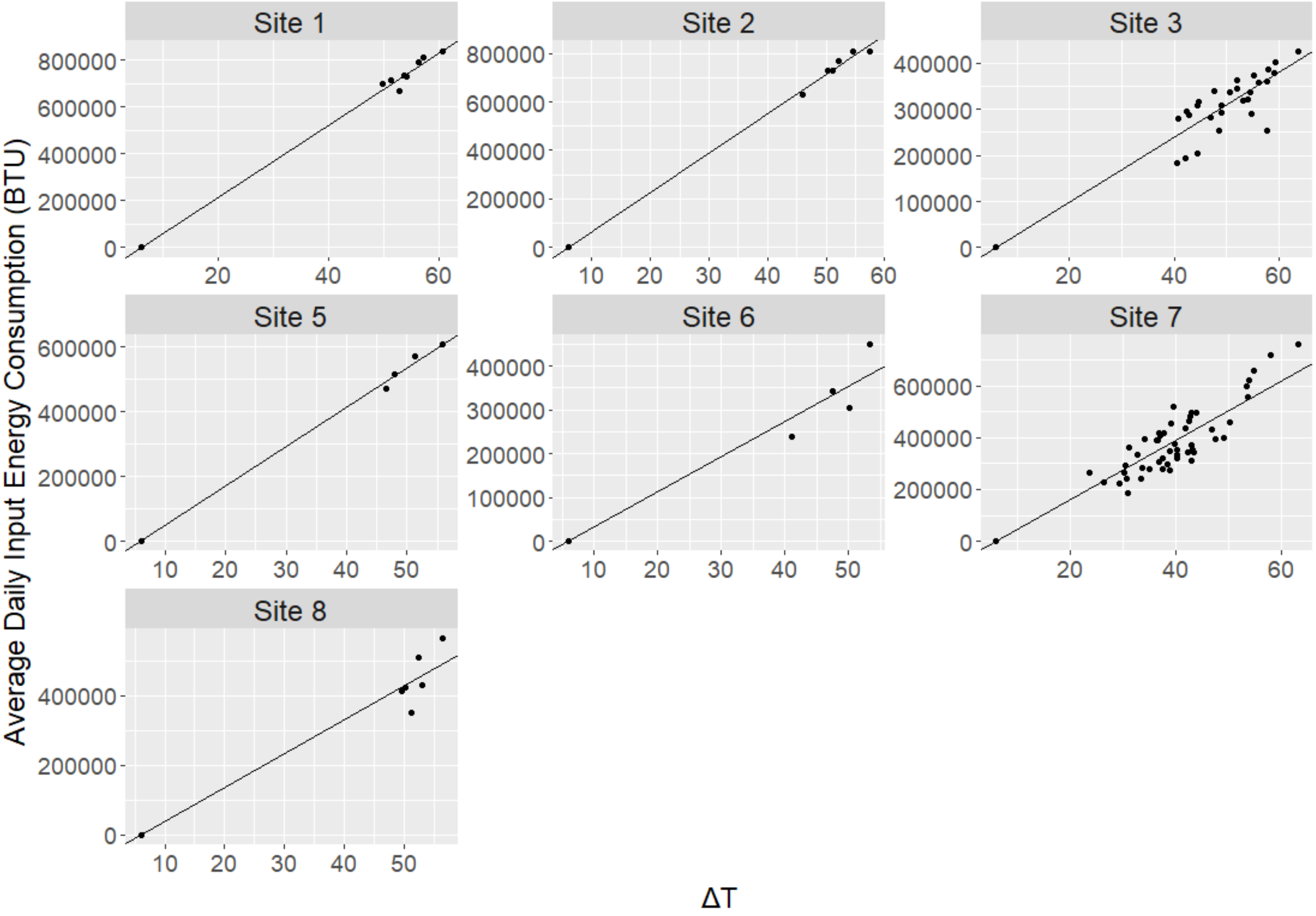
$$furnace\ input_t = \alpha + \beta_1 \Delta \mathrm{T}_t + \varepsilon_t$$

4. Utilizing the site’s regression results, estimate the daily heating output as follows:

$$Daily\ Heating\ Output\ Estimate_t = (\alpha + \beta_1 * \Delta \mathrm{T}_t) * furnace\ efficiency$$

The following graphs show each site’s heating load estimation based on the methods outlined above:

Figure 13. Heating load regression by site.



Approach 2: Regression analysis utilizing Manufacturer COP data

Site 4 did not have days without heat pump heating operation, which made the first approach inappropriate for this site's heating load estimation. A secondary approach was used to estimate this site's heating load line, which is outlined below:

1. Estimate the heat pump COP for available outdoor air temperature according to manufacturer's published product data. Calculate the COP for each available temperature according to "total capacity", "an average of min/max output", and an average of the COP results for each available Entering Dry Bulb (EDB).[41]

2. Run a regression of estimated COP on lab-tested temperature. This heat pump's product data has lab testing results at -3, 7, 17, 27, 37, 47, 57, and 67ºF. The regression results provide an estimate of COP as a function of outdoor air temperature.

3. Apply the "COP Estimation Function" to the hourly outdoor temperatures in Site 4's data. This results in a COP estimation for each hour of Site 4's data.

4. Calculate "Total Hourly Energy Output" as follows:

5. $Total\ Hourly\ Energy\ Output_t = \ hp\ heating\ input_t * estimated\ cop_t + (furnace\ input_t - \ furnace\ defrost\ input_t) * furnace\ efficiency + furnace\ fan\ input_t + hp\ fan\ input_t$

6. Sum the "Total Hourly Energy Output" to "Total Daily Energy Output" values.

7. Estimate a regression of "Total Daily Energy Output" on average daily outdoor temperature.

8. Utilize the regression coefficients to estimate the daily heating load as follows:

    a. $Daily\ Heating\ Output\ Estimate_t = \alpha + \ \beta_1 * \mathrm{Tout}_t$

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[41] Product Data Link: https://dms.hvacpartners.com/docs/1009/Public/02/PDS280A-01.pdf
AHRI: 8203840.

APPENDIX B: COP ESTIMATION

Typically, COP for heat pumps is calculated directly by measuring airflow and enthalpy difference across the indoor coil, calculating heat pump output from these values, and taking the ratio of output to electric power input. Measurement of airflow and enthalpy difference was beyond the scope of this project.

Instead, this study employed an indirect method to estimate heat pump COP based on an estimated heating load line for each home, which is described below:

Monitoring Data COP Estimation

Estimated heat pump heating output is calculated by transforming the estimated daily heating output calculated in Appendix A as follows:

$$Heat\ Pump\ Heating\ Output_t = Daily\ Heating\ Output\ Estimate_t - (furnace\ input_t * furnace\ efficiency)$$

After calculating the daily heat pump heating output, the COP is calculated according to this equation:

$$COP_t = \ Heat\ Pump\ Heating\ Output_t - Heat\ Pump\ Heating\ Input_t$$

Where:

$$\begin{aligned} Heat\ Pump\ Heating\ Input_t \\ &= heat\ pump\ heating\ compressor\ input_t + heat\ pump\ heating\ fan\ input_t \\ &+ defrost\ compressor\ input_t + defrost\ fan\ input_t \\ &+ defrost\ propane\ input_t \end{aligned}$$

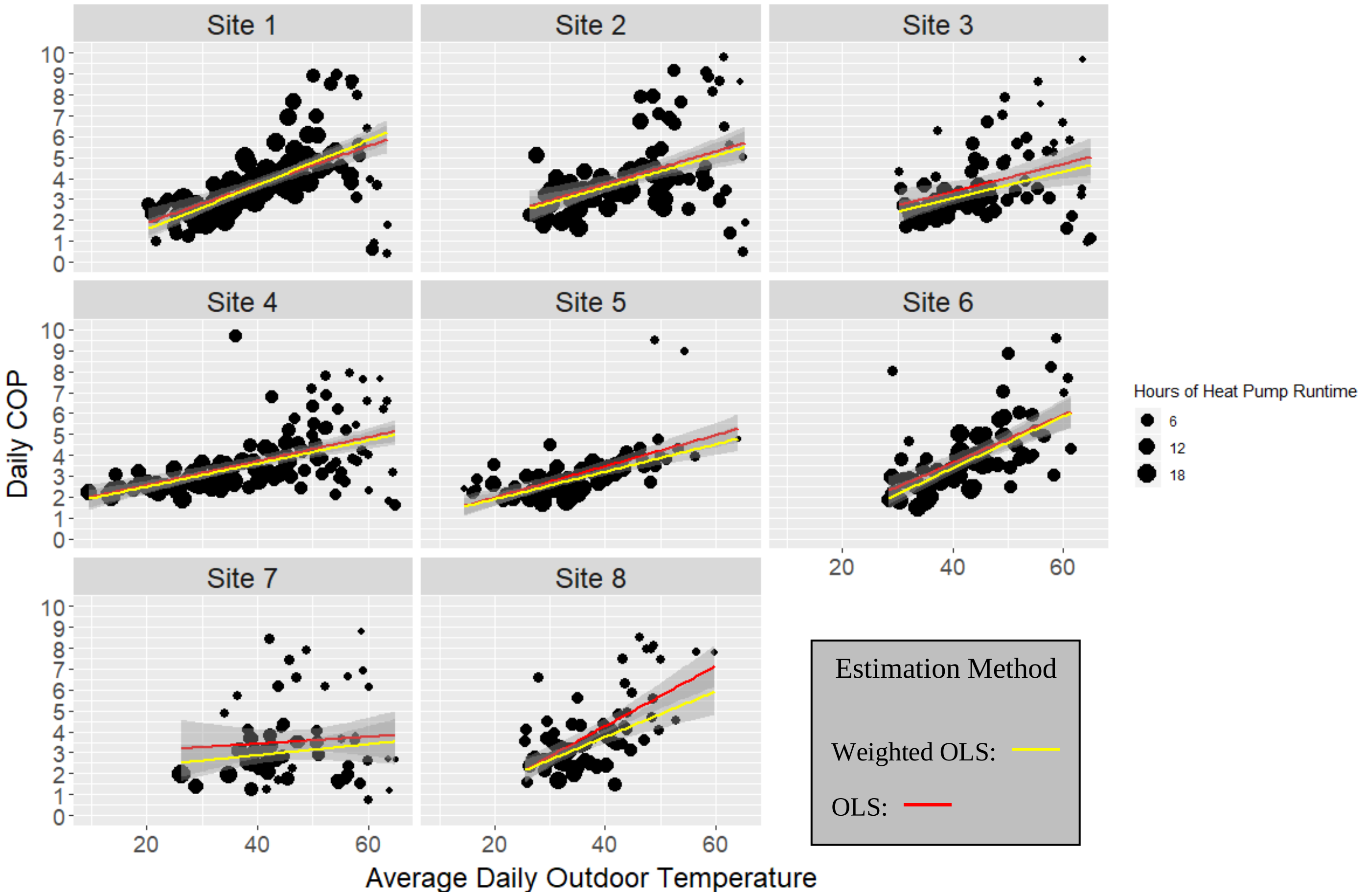
Weighted Regression COP Extrapolation

A weighted linear regression approach was taken to extrapolate COP estimations below each site’s configured lockout temperature from the estimated daily COP results generated over the monitoring period. The section below explains our model selection and the limitations of our assumption that COP declines linearly with decreasing outdoor air temperature.

We determined that a weighted ordinary least squares (OLS) regression method, weighted on heat pump heating runtime, is preferable to a typical OLS approach. It was hypothesized that weighted OLS is a better estimation strategy because days with high heat pump heating runtime are likely better predictors of the COP than days with low heat pump heating runtime.

Figure 14 shows the sensitivity of our COP estimates to the two estimation strategies, with the yellow line representing the model fit from weighted OLS, the red line showing the model fit from OLS without weighting, and the size of each point correlating with daily heat pump runtime. The results show that the two estimation strategies generate similar model fits, but weighted OLS tends to be less sensitive toward outlier days with high outdoor temperatures and low heat pump runtime. For this reason, the weighted regression approach was selected.

Figure 14. Estimation Method Comparison: OLS vs. Weighted OLS.



Skepticism that COP Declines Linearly with Decreasing Outdoor Air Temperature

Although it was determined that estimating the relationship between COP and outdoor air temperature based on a linear model is the best approach considering the data available, results from this field study and theoretical limits on COP degradation suggest that this relationship may not always be linear.

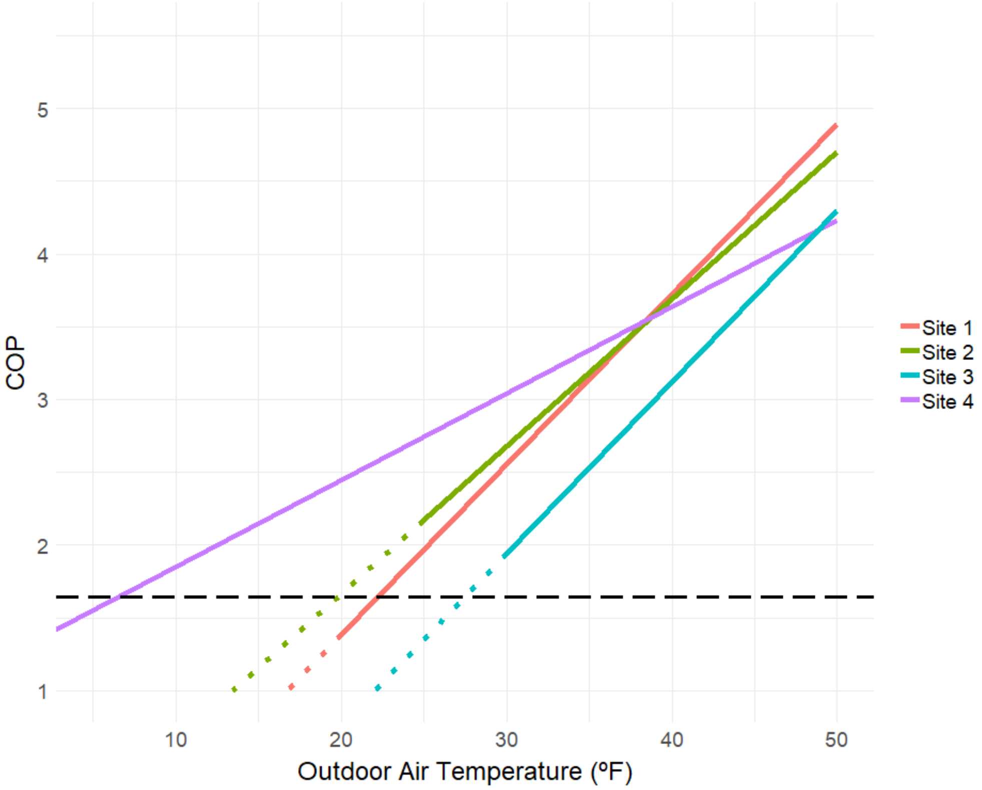
From Figure 15 and Figure 16, the model fits for each site will eventually cross zero, with sites with steep model fits predicting sub-zero COPs at higher temperatures than flatter model fits. Theoretically, heat pump COPs should not be negative, so a linear model will eventually violate theoretical limits. Instead, it seems more likely that the models break the linear trend and “flatten” as the COP approaches its theoretical limit of zero (0).

Sites with high lockout temperatures have COP regression lines with only high temperature data, which can become problematic if COP is not linear and degrades faster in high temperatures than low temperatures. If this is the case, sites with high configured lockouts will estimate a linear relationship based on only high temperature days that may decline in COP faster than lower temperature days, which is problematic for extrapolation.

An example of this phenomenon is Site 6 in Figure 16. Site 6 has a lockout temperature of 28ºF, which excludes heat pump COP estimation for a large portion of cold temperatures. According to Site 6's manufacturer-reported product data, the COP increases 32 percent more for a marginal increase in outdoor temperature during high temperatures (27ºF to 47ºF) compared to lower temperatures (7ºF to 27ºF). In Site 6, the heat pump only operates in the warmer portion of the temperature ranges due to its lockout temperature of 28ºF.[42] This site's model is estimated based on only higher air temperatures and, thereby, without the lower temperature data where COP changes less with a marginal decrease in outdoor temperature.

This raises concerns about the model's ability to extrapolate COPs beyond the site's observed operating range. Despite this methodological concern for sites with high lockout temperatures, we believe this extrapolation provides "rough estimates" of the "cost-equivalent lockout temperature" and the "COP at lockout temperature", which are the only two results from this estimation strategy reported in the study.

Figure 15. Modeled COPs for sites with variable-speed compressors.



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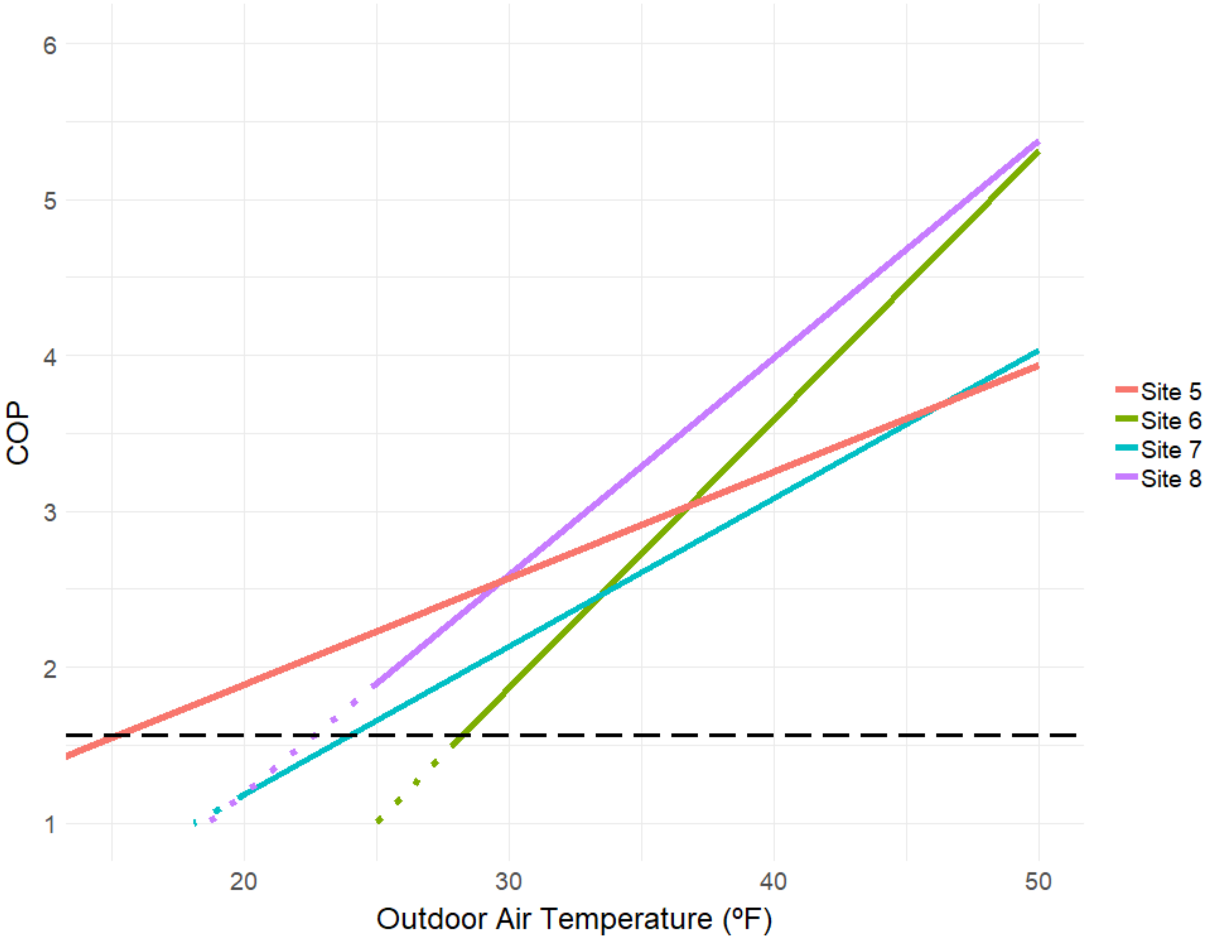
[42] The product data for this site can be found in this installation manual. EDB was assumed to be 70ºF and used an average COP of each of the three stages provided in each testing temperature. AHRI: 9966881.

Figure 16. Modeled COPs for sites with fixed-speed compressors.



APPENDIX C: MODE CHARACTERIZATION BY SITE

Mode Definition Table:

Six different modes of operation were defined for the dual fuel air-source heat pumps in this study. The criteria for defining each mode is presented in Table 13[43] Columns with “N/A” indicate that the mode is not defined according to the corresponding variable.

Table 13. Defining modes of operation.

Mode	Propane Consumption	HP Power	Furnace and Fan Power	Refrigerant Temperature
Standby	0	Below 117 Watts	Below 22 Watts	N/A
Fan-only	0	Below 117 Watts	Above 22 Watts	N/A
Furnace-Only	Above 0	Below 117 Watts	N/A	N/A
Defrost	Above 0	Above 117 Watts	N/A	N/A
Heat Pump Heating	0	Above 117 Watts	N/A	Above 55 F
Cooling	0	Above 117 Watts	N/A	Below 55 F

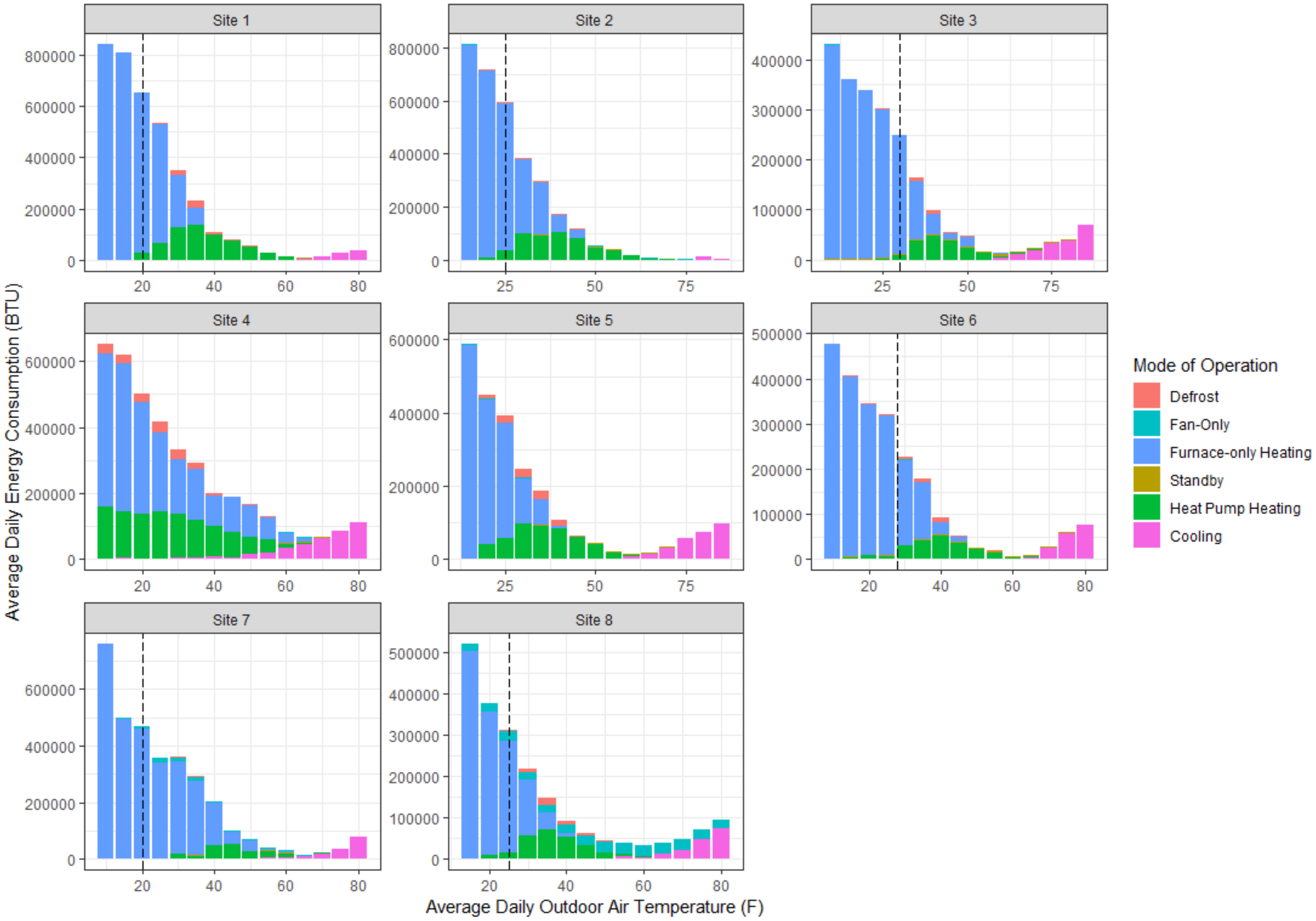
---

[43] These mode definition rules could not define 0.016% of minutes in the data. This likely occurs when the dfASHP changes modes close to the end of a minute interval. This can cause, for example, higher than standby electric consumption in a minute that also has a propane pulse.

Mode Characterization for Each Site

The characterizations of each site by mode can be found below:

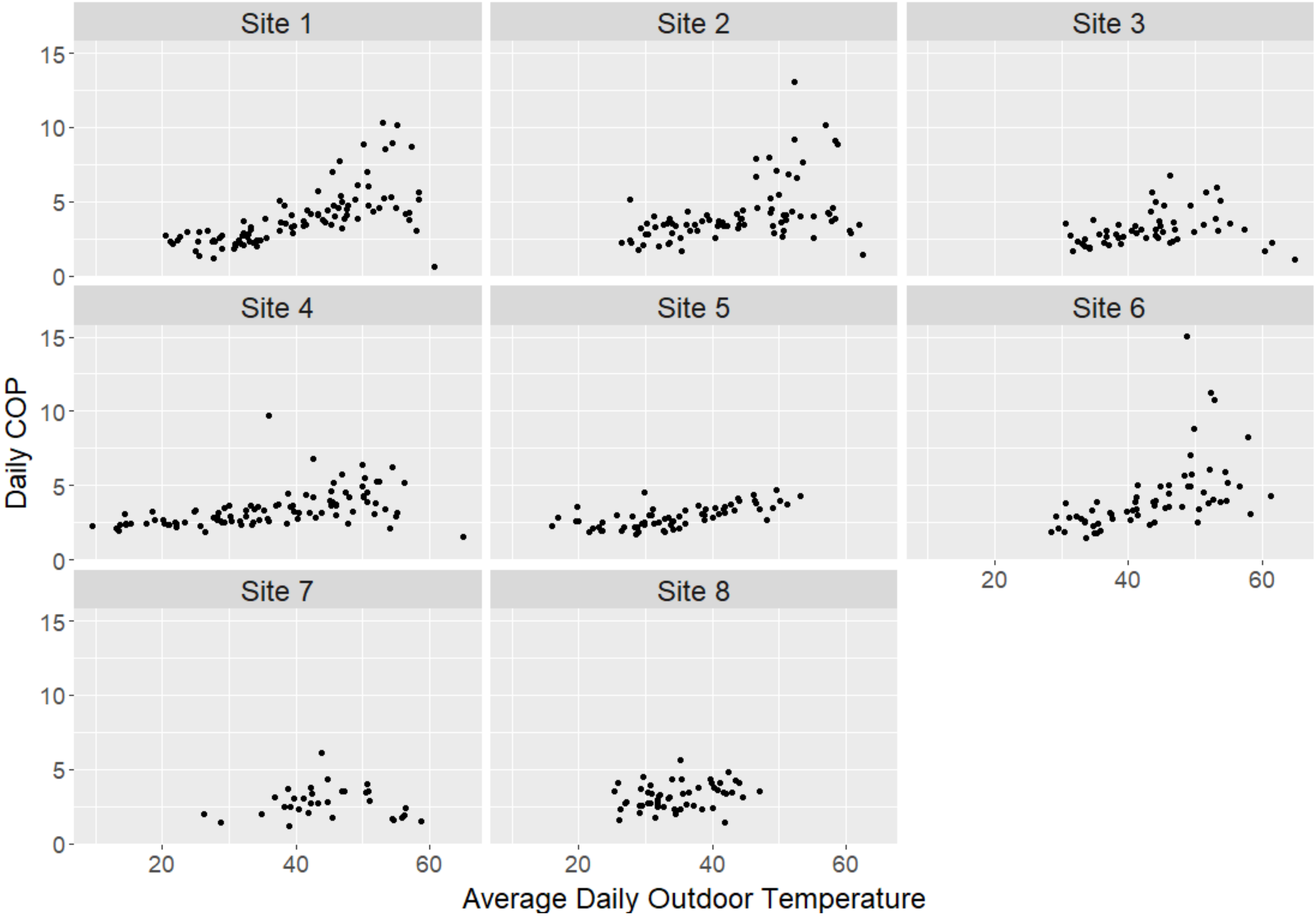
Figure 17. Average daily energy consumption by mode across outdoor temperatures.



APPENDIX D: DAILY COP ESTIMATES FOR EACH SITE

The daily COP estimates for each site are reported below:

Figure 18. Daily COP estimates by site.



APPENDIX E: DATA COLLECTION

Furnace Efficiency

We intended to assess furnace efficiency according to a steady state efficiency test of the furnace. However, all sites in the study had condensing furnaces and the site technicians did not collect condensate, which is required to accurately measure furnace efficiency of condensing furnaces. For this reason, the furnace’s rated efficiency was used instead of the steady-state efficiencies during this study.

Missing Data

We had to eliminate some monitoring data for one site due to an issue in data collection.

In Site 5, a plumbing leak corrupted our data logger that collected propane pulse measurements during the end of the second monitoring period. It was not possible to sufficiently characterize modes without propane pulse data, so these days were removed. The missing data period occurred between April 30 and June 5, 2019 and resulted in 17 percent of days lost for this site.

APPENDIX F: PARTICIPANT EXPERIENCE

Clear communication with participating GLE members about the purpose of the monitoring project and their role in the data collection process was important for data reliability and ensuring that members have a positive experience. The “Welcome Letter” that was sent to each participant to communicate expectations for participants is below. Also, the participant survey played an important role in our analysis of member’s experience with dual fuel air-source heat pumps and provided context to interpret results in other sections. The member survey is available in the “Survey” section.

Welcome Letter

January 22, 2019

Dear Member Name:

Thank you for agreeing to participate in Energy Optimization’s Heat Pump Pilot and allowing us to collect data on the energy consumption of your dual fuel, air-source heat pump. This letter explains the purpose of this project, what will be measured, your role as a participant, and the timeline.

Purpose of this Pilot Project
This project will help us better understand the energy use and costs to operate different types of heat pumps. Information collected from your home will become part of a report to member utilities of the Energy Optimization Collaborative, but with no name or address information. If you’re interested, we may also develop a case study that describes your personal experience with your heat pump and the results from our analysis.

What will be measured?
We will install monitoring devices to measure the following:

1. Electric consumption of your heat pump and blower motor
2. Propane consumption of your furnace
3. Indoor and outdoor temperatures

Please note that all monitoring equipment contains on-board memory, and no data communications link (e.g. Wi-Fi) will be enabled. During the first visit, we will also perform an efficiency test on your furnace.

What’s my role as a participant?
You will be responsible for working with project staff to schedule three visits to your home, being present for each home visit, completing a survey, and suspending the use of wood stoves or outdoor wood boilers for the duration of the monitoring period. Wood stoves and outdoor wood boilers are problematic for this project because they add supplementary heat to the house. This makes it difficult to accurately compare energy consumption of the electric heat pump and propane furnace.

Additionally, as a participant, you agree to let our team take photos of your heating system and our monitoring equipment and their immediate surroundings.

As a token of our appreciation for your participation in this project, we will give you a $500 Visa gift card upon project completion.

Timeline

This heat pump data collection project will occur between February and May 2019. Below is a rough timeline of what you can expect.

- **January 28-February 1, 2019**: You will receive a call to schedule an appointment for the installation of monitoring equipment February 4- 8, 2019.
- **February 4-February 8, 2019**: Three-hour home visit by member of Energy Optimization team and HVAC contractor to install monitoring equipment
- **March 2019**: One-hour home visit by member of Energy Optimization team to check on monitoring equipment and collect initial data. You will also receive a survey that can be filled out during the visit or completed and mailed back after the visit.
- **End of May 2019 (depending on weather)**: Two-hour home visit by member of Energy Optimization team to collect monitoring equipment. Once the survey has been returned and monitoring equipment has been collected, a $500 Visa gift card will be mailed to you.
- **June 2019**: Upon your request, Energy Optimization team member will provide you with results of the research findings of your heat pump's performance.

Please note that the pilot study period runs February-May 2019. Energy Optimization staff will promptly repair or compensate you for any incidental damage to your home or its contents that might occur during the pilot study period as a result of your participation in this project but will not be responsible for any future equipment maintenance or repair.

If you have any specific questions regarding the pilot, please reach out directly to the Energy Optimization team at 877.296.4319 and ask for Troy.

Please sign and mail slip below with the pre-addressed postage paid envelope

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☐ I acknowledge receipt of this letter and understand my roles and responsibilities for this field monitoring project.

Signature: ____________________________ Date: ___________________

Name: ________________________________

Survey Questions

Introduction:

Thank you for your willingness to participate in the Energy Optimization Program’s Heat Pump Field Study. We want to learn about your experience with heat pumps to help us make program recommendations to members of Great Lakes Energy Cooperative. The results of this survey are for research purposes and individual responses will remain anonymous.

Background on Your Heat Pump:

1. You recently purchased a new HVAC system. What prompted you to make this purchase?

   ____
   ____
   ____

2. What other HVAC systems did you consider at the time of your purchase?

   ____
   ____
   ____

3. Why did you choose a heat pump?

   ____
   ____
   ____
   ____

4. Overall, how satisfied are you with your decision to purchase a heat pump?

   ☐ Very Satisfied
   ☐ Somewhat Satisfied
   ☐ Not Satisfied or Dissatisfied
   ☐ Somewhat Dissatisfied
   ☐ Very Dissatisfied

5. What are your favorite aspects of owning a heat pump?

____
____
____

6. Have there been any drawbacks to owning a heat pump?

   ☐ Yes
   ☐ No

   If "yes", please explain:

   ____
   ____
   ____

7. After the installation of you heat pump, did your HVAC contractor provide any recommendations on how to program your thermostat?

   ☐ Yes
   ☐ No
   ☐ I do not have a programmable thermostat

   If "yes", what did your contractor recommend?

   ____
   ____
   ____

8. Did your HVAC contractor discuss the "lockout" temperature (the outdoor temperature that triggers the system to switch fuels) with you during the installation of your heat pump?

   ☐ Yes
   ☐ No
   ☐ I do not remember

   If "yes", what did the contractor tell you about the "lockout" temperature?

   ____
   ____
   ____

9. What other heating sources do you use regularly in your home? Select all that apply.

   ☐ Wood burning stove
   ☐ Fireplace
   ☐ Plug-in electric space heater
   ☐ Other: describe____________________

Your Comfort:

10. How satisfied are you with the heating from your heat pump?

    ☐ Very Satisfied
    ☐ Somewhat Satisfied
    ☐ Not Satisfied or Dissatisfied
    ☐ Somewhat Dissatisfied
    ☐ Very Dissatisfied

11. How has your comfort ***in the winter*** changed since installing your heat pump? Are you…

    ☐ Much more comfortable
    ☐ More comfortable
    ☐ About the same
    ☐ Less comfortable
    ☐ Much less comfortable

    If "much more comfortable" OR "more comfortable", describe specifically how you are more comfortable:

    ____
    ____
    ____

    If "much less comfortable" OR "less comfortable", describe specifically how you are less comfortable:

    ____
    ____
    ____

12. Do you notice any disruptive noises from the outdoor unit of your heat pump during operation?

    ☐ Yes
    ☐ No

13. Where is the outdoor unit of your heat pump located? (some examples may include: "outside my bedroom", "outside the garage", or "outside the kitchen")

    ____
    ____
    ____

Your Propane Consumption:

14. How do you think owning a heat pump has affected your propane consumption?

- ☐ I consume significantly less propane
- ☐ I consume somewhat less propane
- ☐ I consume about the same amount of propane
- ☐ I consume somewhat more propane
- ☐ I consume significantly more propane

15. Before owning your heat pump, how many times did you fill your propane tank per year?

- ☐ Not Applicable. I have always had a heat pump in my current house
- ☐ 4 or more
- ☐ 3
- ☐ 2
- ☐ 1
- ☐ 0

If you answered "1,2,3,4 or more" to Q15, In the year before you installed your heat pump, which months did you fill your propane tank (check all that apply)

- ☐ January
- ☐ February
- ☐ March
- ☐ April
- ☐ May
- ☐ June
- ☐ July
- ☐ August
- ☐ September
- ☐ October
- ☐ November
- ☐ December
- ☐ I don't remember

16. After owning your heat pump, how many times did you refill your propane tank per year?

- ☐ 4 or more
- ☐ 3
- ☐ 2
- ☐ 1
- ☐ 0

If you answered “1,2,3,4 or more” to Q16, In the year after you installed your heat pump, which months did you fill your propane tank (check all that apply)

- ☐ January
- ☐ February
- ☐ March
- ☐ April
- ☐ May
- ☐ June
- ☐ July
- ☐ August
- ☐ September
- ☐ October
- ☐ November
- ☐ December
- ☐ I don’t remember

Other Engagement Opportunities:

Great Lakes Energy Cooperative offers an “Efficient Heat Rate Credit”, which is a $0.03 per kWh discount on electricity used by a qualified air-source heat pump during the months of November-May. While Great Lakes Energy provides a complementary subtractive meter to measure electricity consumption of the heat pump, participating members are responsible for the one-time installation cost. Licensed electricians will typically charge $700-$1,000 to install the wiring needed for the subtractive meter.

17. Are you currently enrolled in Great Lakes Energy’s Efficient Heat Rate Credit?
    - ☐ Yes
    - ☐ No

18. ***If you selected “yes” in Q17***, what were the main reasons that you decided to enroll in the rate credit?

    ____
    ____
    ____

19. ***If you selected “no” in Q17***, were you aware of the rate credit at the time of purchasing your heat pump?

    - ☐ Yes
    - ☐ No

20. ***If you selected “yes” to Q 19***, why did you choose **not** to enroll in the Efficient Heat Rate Credit?

    ____
    ____
    ____

21. ***If you selected "no" in Q 19***, would you have enrolled in the rate credit had you been aware it existed?

☐ Yes
☐ No

22. Whether you are enrolled in the "Efficient Rate Credit" or not, what changes could be made to the rate credit that would make it a more attractive offer?

____
____
____

Heat pump water heaters apply the same technology to heat water that your heat pump uses to heat and cool your house. Heat pump water heaters can be more than 3 times more efficient than a conventional electric water heater. Heat pump water heaters are also sometimes referred to as "hybrid electric water heaters".

23. Prior to the explanation above, had you ever heard of a heat pump water heater?

☐ Yes
☐ No

24. Would you consider purchasing a heat pump water heater?

☐ Yes
☐ No

Explain why or why not:

____
____
____

Thank you for completing the survey. If you have any questions or comments, please contact Dianna Cacko at DCacko@weccusa.org or 734-957-2850

Best wishes,
The Energy Optimization Team

APPENDIX G: PARTICIPANT SYSTEM AND HOME DETAILS

Additional information on the dual fuel air-source heat pumps and homes that they were installed in are described in Table 14 below.

Table 14. Additional system and site information.

Site	Heat Pump		Furnace		Home Characteristics	
	AHRI	Model Name	AHRI	Model Name	Square Feet	Year Built
1	8761154	American Standard Platinum 18	9962862	American Standard Platinum 95	2,426	1998
2	10085012	Lennox Signature XP25 Series	4792116	Dave Lennox Signature	2,400	1860
3	8761441	Trane XV181	9962857	Trane XC95M	1,400	2018
4	8203840	Bryant Evolution Extreme	5053233	Bryant Evolution	2,200	2000
5	10095179	Trane XR17	9973381	Trane S9X2	1,700	1996
6	9966881	Bryant Evolution V	4706200	Bryant Evolution	2,000	2004
7	8683364	American Standard Silver 16	10265051	American Standard Gold 95v	2,400	2018
8	8586148	Bryant Legacy Line	7126209	Bryant Preferred Series	2,500	2016

APPENDIX H: CLIMATE ZONES

Each site in the field study had their monitoring data annualized based on the nearest weather station to the site according to a typical meteorological year.[44] The sections below associate each site with their TMY weather station, illustrate the differences between weather stations in the field study, and compare Grand Rapid's weather data to another city with more extreme weather conditions in MECA territory.

Climate Zones Used in Study

Table 15 associates each site with the weather station used to annualize their monitoring data.

Table 15. Weather station by site.

Site	Weather Station
1	Muskegon
2	Grand Rapids
3	Manistee
4	Grand Rapids
5	Grand Rapids
6	Grand Rapids
7	Muskegon
8	Muskegon

Figure 19 shows the distribution of hours in each temperature bin across a typical meteorological year for each weather station. The results show that all three weather stations in the field study had similar temperature data.

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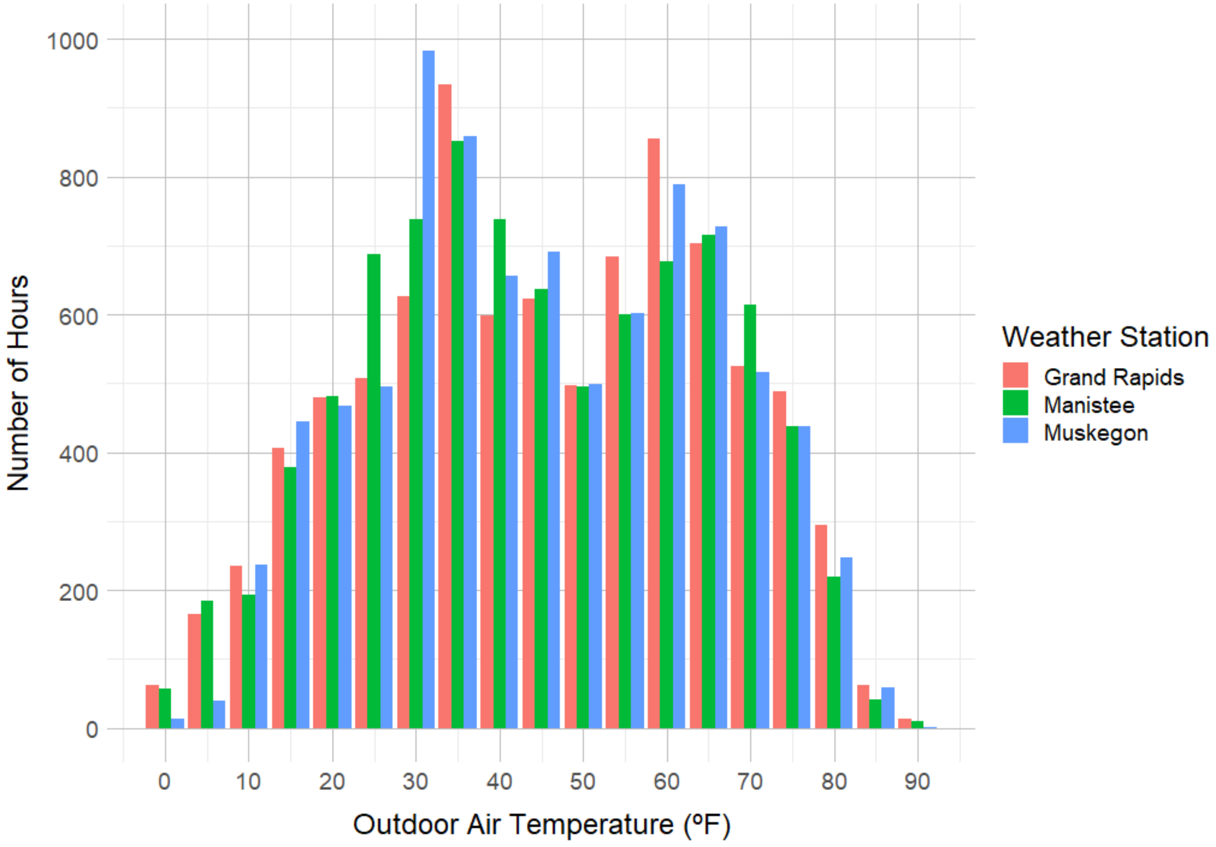
[44] The source for our weather data is: https://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

Figure 19. Number of annual hours for each weather station at different outdoor air temperatures.



Climate Zone Sensitivity

The field study participants are all in the greater Grand Rapids area, which does not represent all climate zones in EO-Collaborative utility territories. To address the potential sensitivity of applying the results from this field study to other areas in EO-Collaborative utility territories, we looked at the differences in annual temperature data between Grand Rapids and Sault Ste. Marie. Sault Ste. Marie was chosen to represent the colder extreme of the EO-Collaborative utility territories. Figure 20 shows more hours at very low temperatures, below 15ºF, and less high temperature hours (above 65 ºF) in Sault Ste. Marie than Grand Rapids. However, the two climates have a similar number of hours in the moderate heating temperatures of 20ºF-65ºF where the heat pumps in the field study typically operated. This suggests that heat pump heating performance results from this study may not be very sensitive to other more extreme climates in EO-Collaborative utility territories, but there would likely be less cooling hours.

Figure 20. Number of annual hours in Grand Rapids and Sault Ste. Marie at different outdoor air temperatures.