High Efficiency Heat Pumps Can Pave the Path for Building Decarbonization in Cold Climates

Preprint

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High Efficiency Heat Pumps Can Pave the Path for Building Decarbonization in Cold Climates

Gregory Shoukas, Eric Kozubal, Eric Bonnema, and Ramin Faramarzi,
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ABSTRACT

Heat pumps play an instrumental role in building decarbonization through recent advances in systems that employ variable-speed compressor technology and electronically commutated fan motors. Inherently, the heating capacity and efficiency of heat pumps decrease with falling outdoor temperatures; however, compared to single-speed heat pumps, variable speed systems can maintain higher heating and cooling efficiencies over a wider range of outdoor temperatures.

The goal of this multi-phase project was to determine the energy savings of a high-efficiency, variable-speed, air-source, split-system heat pump designed for cold climate applications. The first phase was a laboratory evaluation of heat pump performance under varying outdoor conditions in heating and cooling modes. The second phase translated laboratory-measured performance into lookup tables for an EnergyPlus hourly building simulation engine. Then, two sets of annual building simulations were performed using typical meteorological year weather from Chicago O'Hare International Airport for three different building types (single-family residence, strip mall, and low-rise office building). The first set simulated a standard efficiency heat pump while the second utilized phase two performance tables to model a high-efficiency heat pump.

The high-efficiency heat pump produced significant annual heating energy savings in all three buildings. The variable speed compressor and fan control also contributed to cooling energy savings. Simulated annual energy savings ranged from 22%–35% over respective baselines. Findings from this research are being considered by ComEd's energy efficiency program designers for an incentive for high-efficiency heat pumps.

Introduction

High-efficiency, variable speed heat pumps can yield the largest cost-effective carbon emissions reductions (Langevin 2019) through commercially available configurations such as minisplit, multisplit, and ducted split systems. These system configurations are most prevalent in residential applications but can be found on building rooftops in light commercial applications. Variable-speed heat pumps can ramp up the compressor speed and increase conditioning capacity to better match peak thermal loads during periods of extreme outdoor temperatures. At moderate building loads, the compressor speed is reduced to precisely meet the space conditioning requirements, improve part-load efficiency, and reduce on/off cycling and energy consumption. Prior work (Adhikari 2012) has reported 5%–14% annual heating, ventilating, and air conditioning (HVAC) energy savings comparing variable-speed and constant-speed air-source heat pumps using EnergyPlus to simulate residential apartment units in three Italian cities. This work first characterizes variable-speed heat pump performance via laboratory experiments, which is then input into EnergyPlus models. The estimated annual energy savings ranges from 22%–35% for three different building types.

This project utilized the HVAC Laboratory located at the National Renewable Energy Laboratory's (NREL) Thermal Test Facility (TTF) to experimentally characterize cooling and heating performance of a high-efficiency split-system heat pump under a wide range of steady-state outdoor climate conditions. The heat pump performance characterization from laboratory experiments was used to develop equipment performance tables as inputs to be used by the EnergyPlus® building simulation engine. Hourly building simulations were run using typical meteorological year 3 (TMY3) weather data for Chicago O'Hare International Airport, which is representative of ComEd's service territory. The simulated annual energy savings compared a high-efficiency, variable-speed heat pump with a standard efficiency, constant-speed unit operating in the following U.S. Department of Energy's (DOE) Building Energy Codes Program energy prototypes: (1) single-family home, (2) strip mall, and (3) low-rise office building.

First, we report on the approach and results of the laboratory experimentation. Second, we discuss the annual energy savings using EnergyPlus building simulations to compare the high-efficiency, variable-speed heat pump to a baseline heat pump for three prototype buildings.

Laboratory and Heat Pump Overview

At NREL, the TTF laboratory conditions multiple 100% outdoor air streams that are ducted to a test article. Through a computer-based measurement and data acquisition system, the lab controls and maintains precise air temperature, humidity, pressures, and flow rates to user-defined setpoints. Four laboratory air streams in total are used to control and measure the psychrometric conditions at the inlet and outlet of the heat pump's indoor and outdoor unit. Accurate, real-time measurements are recorded to determine the heat and mass transfer performance of the equipment.

The test unit used for this study was a five-ton Carrier Infinity Series heat pump with Greenspeed (variable-speed) intelligence. The heat pump's steady-state heating and cooling performance was evaluated over a wide, representative range of outdoor and indoor psychrometric conditions. The thermal capacity and coefficient of performance (COP), a unitless ratio of heating or cooling capacity over total power input, was measured over the range of experimental conditions discussed in the following section. Table 1 summarizes the manufacturer's performance ratings and specifications of the heat pump.

Characterization Methodology

Generally, testing methods and laboratory measurements are guided by American Society of Mechanical Engineers (ASME), American National Standards Institute (ANSI), ASHRAE, and Air Conditioning, Heating, & Refrigerating Institute (AHRI) standards. While this evaluation fundamentally followed these standards, it did not strictly conform to them. For example, standards ANSI/ASHRAE 37 (ASHRAE 2019) and AHRI 210/240 (AHRI 2023) provide a framework for measuring a single rating value such as seasonal energy efficiency ratio (SEER) or heating seasonal performance factor (HSPF). Although ratings provide a good comparative metric for consumers, they are insufficient for building energy simulations which require characterizing equipment performance over a broader range of operational conditions.

Table 1. Table of Manufacturer's Performance Specifications: Outdoor Unit (25VNA0060A)/ Air Handler Unit (FE4ANB006)/Thermostat (SYSTXCCITC01-B)

Manufacturer's Specifications	Cooling	Heating
Rated Capacity[a,b] [BTU/h]	56,000	55,500
SEER[a] [-], EER[a] [-]	18.0, 12.7	-
Compressor Speed [RPM]	1,800–4,250	1,800–7,000
Outdoor Unit Fan Speed [RPM]	500–900	500–900
Indoor Unit Fan Speed [RPM]	1,185–1,885	750–1,750
Expansion Device	Thermal expansion valve	Electronic expansion valve
HSPF[b] [-]	-	12.0
COP[b,c] [-] @ 47ºF and 17ºF	-	3.86 and 2.22

[a] Cooling standard: 80ºF dry-bulb (db) 67ºF wet-bulb (wb) indoor return air and 95ºF db air at the outdoor unit.
[b] High heating standard: 70ºF db indoor return air and 47ºF db 43ºF wb air at the outdoor unit.
[c] Low heating standard: 70ºF db indoor return air and 17ºF db 15ºF wb air at the outdoor unit.

The heat pump's communicating thermostat can operate the equipment in four modes of heating or cooling operation: technician checkout, comfort (the default mode of operation), efficiency, and maximum. Depending on the thermostat mode, the indoor unit's variable fan speeds are controlled differently as the compressor speed modulates. Differences in the thermostat's mode of operation have implications for the exiting supply air state, the conditioning capacity, and energy consumption of the heat pump. The experimental work characterized the system in comfort and efficiency mode; however, the project budget and timeline only allowed for EnergyPlus modeling and estimated annual energy savings using efficiency mode data. We believe this represents the maximum possible energy savings relative to the baseline equipment.

During heat pump operation, we observed the compressor speed modulating once per minute to match the conditioning capacity to the building load. As the space temperature, measured by the thermostat, deviates further from the setpoint temperature, the equipment ramps up its speed to increase the conditioning capacity. As the space temperature converges to the setpoint, the compressor converges to a constant speed. The heat pump's embedded controls modulate the indoor fan speed accordingly based on the thermostat mode, measured space conditions, and the compressor speed. This load matching control strategy results in longer run times, minimizing building temperature swings and reducing the overall power consumption.

Operating the heat pump under its embedded control algorithms allows for the most realistic assessment of the heat pump operation, performance, and energy consumption over a range of speeds while supplying constant psychrometric conditions to the indoor and outdoor unit. To modulate the heat pump speed during experimentation via its inherent controls, a faux signal from the laboratory is connected to the thermostat. This signal emulates a (remote) room temperature sensor and acts as the primary space temperature input to which the thermostat reacts and varies the conditioning capacity. The laboratory uses a feedback control loop that slowly varies the emulated space temperature signal. When the measured compressor speed settles and gently oscillates around the desired setpoint, data can be collected. This feedback control strategy can be seen in Figure 1.

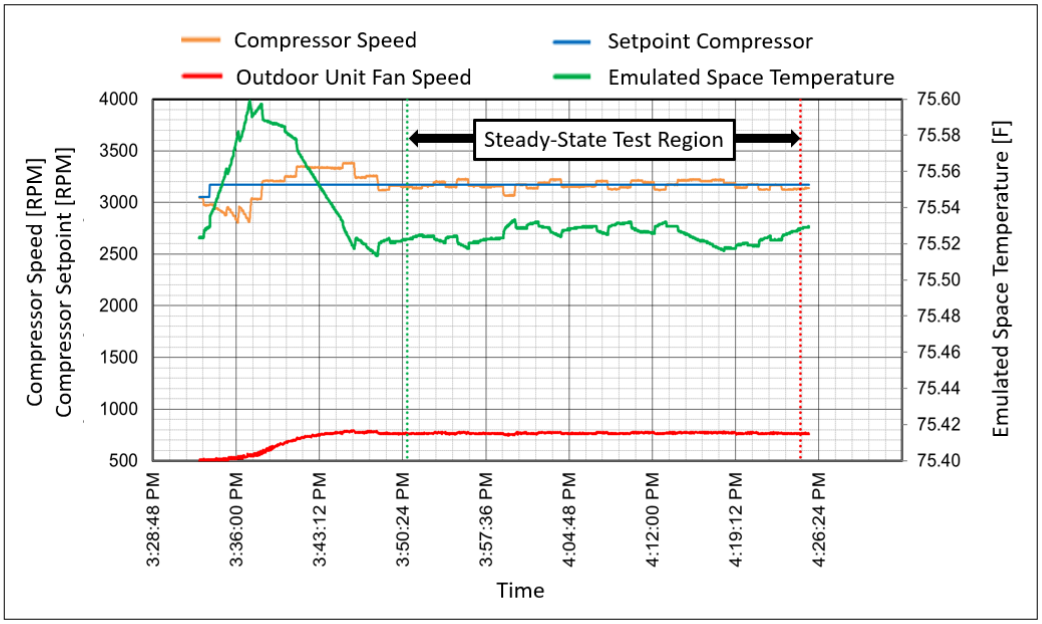

Figure 1. Controlling the compressor speed by emulating a room temperature signal on the thermostat

Laboratory Characterization

Assessing the performance of HVAC equipment requires varying numerous independent variables over a wide range of expected operational conditions. These factors dramatically affect the equipment capacity and energy consumption. Therefore, characterization over a wide range of conditions ensures that performance regressions developed from the data (used as EnergyPlus modeling inputs) remain valid even during extreme heating or cooling days.

Design of Experiment

Due the vast number of combinations that result from the independent variables required to evaluate the heat pump's performance, a full-factorial test matrix would not be practical. Instead, a statistical software package, JMP from SAS, was used to develop a custom design of experiment. The software determines a sparse test matrix, guided by classical design-of-experiment principles, which significantly reduces the number of test combinations needed to develop low-uncertainty response surface methodology (RSM) regressions.

Prior to developing a design of experiment, the equipment was run over a wide range of conditions to determine its operational boundaries in cooling and heating modes. Laboratory measurements determined the minimum and maximum compressor speeds are bounded by an outdoor air temperature sensor mounted on the outdoor unit. Compressor speeds outside of the minimum and maximum boundary were entered into JMP as variable constraints that must be excluded from the design of experiment. The heat pump's compressor operating boundaries can be seen in Figure 2.

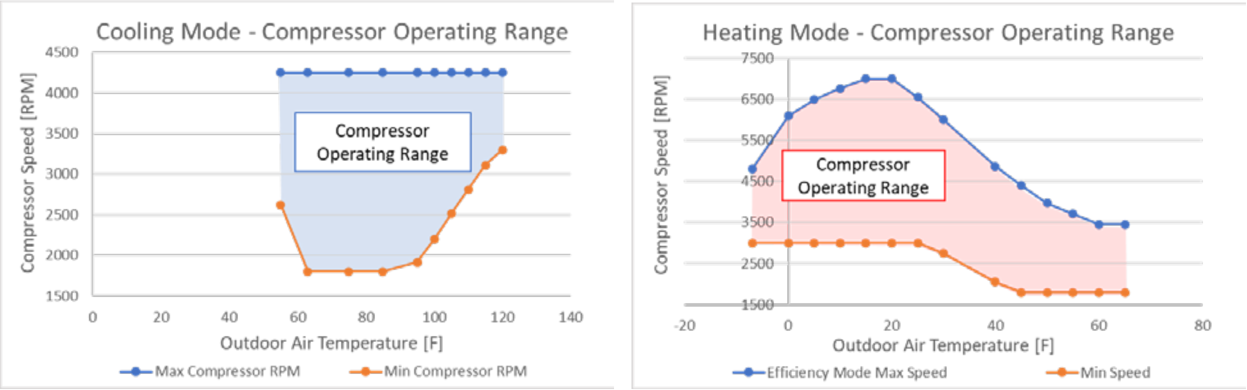

Figure 2. Variable speed limits of the heat pump compressor in cooling (left) and heating (right)

Cooling

The independent factors that affect the capacity, performance, and energy consumption of a heat pump operating in cooling mode are the outdoor dry-bulb air temperature, the indoor dry-bulb return air temperature, the indoor return air wet-bulb air temperature (humidity), and the speed of the compressor and fans. Instead of specifying the indoor humidity as a wet-bulb temperature, the test matrix captures the vapor content of the air using a dew point depression. The dew point depression is a temperature delta which, when subtracted from indoor dry-bulb temperature, results in the dew point temperature.

Two designs of experiments were developed to characterize the indoor unit under high humidity (relatively small dew point depressions) and low humidity (large dew point depressions). These tests are designated as wet-coil conditions and dry-coil conditions, respectively. The wet-coil conditions assess the performance of the system when the indoor unit provides both latent (dehumidification) and sensible cooling. Under these conditions, water vapor is removed from the air and condensate forms on the cooling coils. The dry-coil conditions assess the indoor coil performance when no dehumidification occurs. At sufficiently large dew point depressions, the moisture content of indoor return air is very low, and dehumidification will not occur. This results in a cooling coil condition that provides sensible cooling only.

The range of conditions from which the wet-coil and dry-coil design of experiment were developed can be seen in Table 2. JMP identified 28 wet-coil and 16 dry-coil variable combinations needed during laboratory evaluations that would provide sufficient data for low-uncertainty performance regressions.

Heating

The factors that affect the capacity, performance, and energy consumption of a heat pump in heating mode are the outdoor dry-bulb air temperature, the outdoor wet-bulb temperature (humidity), the indoor dry-bulb return air temperature, and the speed of the compressor and fans.

Depending on the outdoor humidity, frost formation occurs on the outdoor coil when the saturated refrigerant temperature is lower than the outdoor air dew point. Under these conditions, the water vapor from the air freezes on the outdoor coil which reduces the heat transfer and results in heating capacity degradation. Elimination of frost is important to maintain the highest heat transfer effectiveness across the outdoor coil. Periodically the unit initiates defrost cycles, lasting between 3.5 and 10 minutes, which temporarily reverse the operation of the equipment—

identical to a cooling cycle. Although the defrost cycle is essential for reliable heating operation, this poses two detrimental impacts: (1) energy is consumed to defrost the coil instead of heating the building, and (2) heat already supplied to the space by the heat pump is removed from the building and used to defrost the outdoor coil. This adds complexity to the performance characterization of the equipment in heating mode and must be accounted for in simulations.

Two designs of experiments were developed to characterize the heating performance. The first set of evaluations were designed to assess the heating capacity and energy consumption of the heat pump under low outdoor air humidity. This characterizes the heat pump performance under no or low coil frost operation which represents the highest achievable steady-state performance. The performance was assessed between defrost cycles to understand idealized performance before applying capacity and efficiency degradation factors resulting from defrost cycles. The independent variables and ranges for which this design of experiment was developed to characterize the heating performance are shown in Table 2. JMP identified 20 variable combinations needed for laboratory evaluation.

Table 2. Factors and Ranges Specified to Develop the Steady-State Cooling and Heating Design of Experiment Test Matrix

Independent Variable	Cooling Mode		Heating Mode
	Wet-Coil Indoor Unit	Dry-Coil Indoor Unit	Low-Humidity Outdoor Unit
Outdoor air dry-bulb temperature	55º–120ºF	55º–120ºF	-7º–60ºF
Indoor return air dry-bulb temperature	68º–82ºF	68º–82ºF	60º–76ºF
Indoor return air dew point depression temperature	5º–25ºF	>35ºF	n/a
Compressor speed[a]	1,850–4,250 RPM	1,850–4,250 RPM	1,800–7,000 RPM

[a] The compressor speed operational limits are bounded by the heat pumps embedded controls and mode of operation.

The second set of experiments was designed to better understand the heating capacity degradation as frost forms, and the energy penalties associated with defrost cycles. Seven outdoor dry-bulb air temperatures were selected ranging from 5ºF to 50ºF. High humidity levels were supplied to the outdoor unit at a dew point depression of only 2ºF below the dry-bulb temperature. The heat pump was operated at its minimum or maximum heating capacity over an 8- to 12-hour period such that 3 to 7 defrost cycles were incorporated into the data set. By integrating the entire period of performance, the continuously degrading heating capacity and varying energy usage provided an average capacity and COP. The average heating performance was compared with the idealized dry-coil performance to estimate degradation factors. This derating attempts to account for frost formation on the outdoor unit and the defrost cycles.

Test Setup

Because the HVAC at laboratory NREL can provide psychrometric properties of air at typical building return air conditions, the lab ducts are connected directly to the air handler. The vertically mounted air handling cabinet sits between insulated horizontal inlet and outlet plenums. Instrumentation is integrated within the plenums to measure the conditioning capacity across the air handling coil. Static pressure taps and a differential pressure transducer measure the external static pressure across the indoor unit (Wheeler and Pate 2016). The external static pressure imposed by the laboratory air streams are guided by the AHRI 210/240 standard. Temperature measurements are made using an averaging array of thermocouples (ANSI/ASHRAE 41.1-2013) while an air sampling rake connected to chilled mirror hygrometers draws sample air from the inlet and outlet air streams to measure dew points (ANSI/ASHRAE 41.6-2014). Inlet and outlet air mass flow rates are measured using the laboratory ASME flow nozzles to an uncertainty of less than 2% (ANSI/ASHRAE 41.2-2018). The indoor unit blower speed is measured using an optical tachometer mounted inside the air handling cabinet and positioned to view the rotating fan cage. The indoor unit and outdoor unit control boards are connected to a Carrier Infinity Touch communicating thermostat which orchestrates heating or cooling at precise compressor and fan speeds based on the manufacturer's embedded controls algorithms.

The outdoor unit is placed inside an insulated environmental chamber (Figure 3). The chamber is designed to maintain summer-like or winter-like outdoor air conditions. Conditioned air supplied to the inlet of the outdoor unit is controlled by mixing makeup air provided by the TTF laboratory with the heat pump's discharge air. The two air streams mix in the return plenum of the environmental chamber and are recirculated by a fan to the inlet plenum.

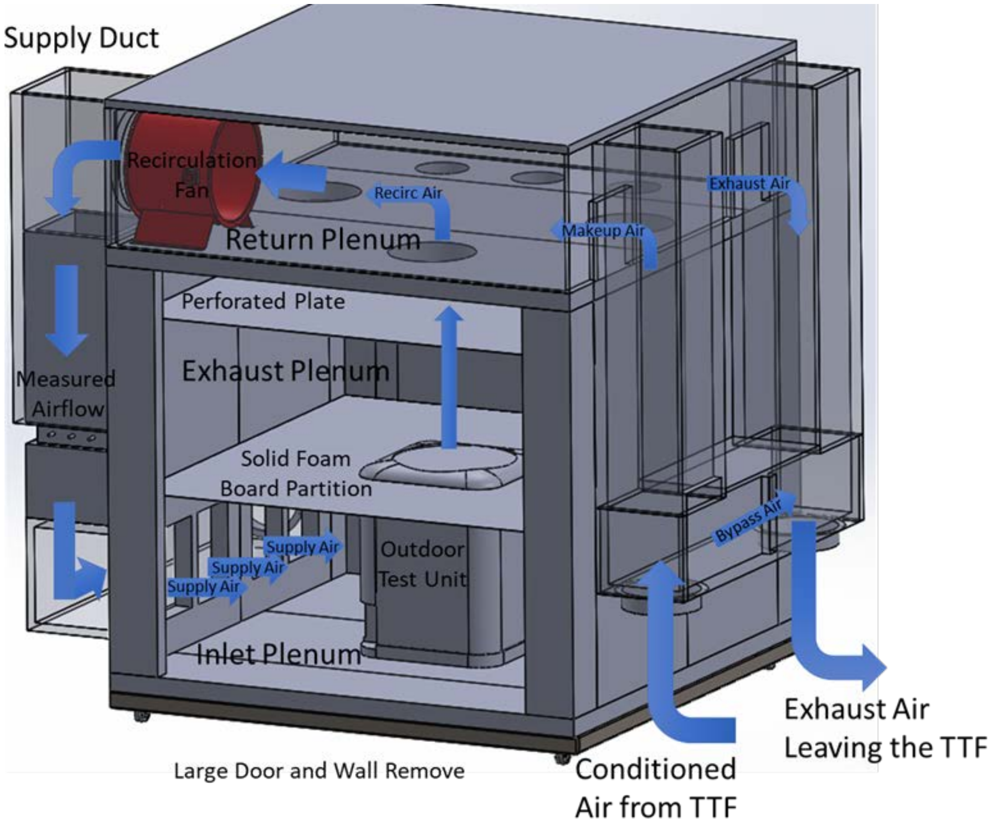

Figure 3. Environmental test chamber used to create an outdoor climate around the test article

In heating mode, recirculating the cold discharge air from the outdoor unit lowers the temperature inside the chamber and allows it to be cooled to subzero temperatures. In cooling mode, recirculating the hot discharge air from the outdoor unit raises the temperature inside of the chamber. To maintain a constant temperature in the chamber, the lab exhausts a portion of the recirculated air and provides counteracting warm or cool makeup air through a set of flow control dampers. Similarly, humidity levels are controlled at the heat pump inlet by adjusting the humidity ratio in the makeup airstream. This control strategy maintains constant air inlet conditions for steady-state heating or cooling characterization.

During the performance assessments, steady-state conditions of the laboratory and the heat pump operation must be achieved. This is verified by monitoring the measurements related to air temperatures, dew points, flow rates, and pressures as well as the heat pump compressor speed, fan speeds, and the refrigerant pressures. Once steady-state operation has been reached, over 200 measurements and calculated variables are collected once per second for a 20- to 45-minute interval. The data is then postprocessed to adjust for altitude effects (Wheeler, Kozubal, and Judkoff 2018).

Performance Regressions

The sparse set of postprocessed performance data, over the varied range of independent parameters, was input into the statistical software package, JMP. The software was used to develop second-order RSM models to empirically fit the analyzed data with respect to the independent variables. If any factors or cross terms in the regression were statistically insignificant, they were removed from the predictive RSM. In cooling mode, the dry-coil and wet-coil conditions were regressed independently to generate two discrete sets of regressions.

The RSM regressions were then used to develop an extensive lookup table created for input into the EnergyPlus simulation environment. The table is an explicit interpolation of the heat pump's indoor coil conditioning capacity and COP to any combination of factors within the range of conditions specified in Table 2. For example, the predicted heat pump cooling performance parameters are based on the compressor speed, outdoor dry-bulb air temperature, indoor dry-bulb return air temperature, and indoor return air wet-bulb temperature. For a set of conditions, if the sensible heat ratio was predicted to be a value of one or more, the dry-coil performance regressions were used in place of the wet-coil performance.

Using the predictive performance regressions, the idealized heating capacity and COP over the full range of compressor speeds at indoor return air temperatures between 68ºF and 76ºF are shown in Figure 4. As the compressor speed decreases, the heating capacity decreases and the heat pump COP increases. As the indoor return air temperature increases and the outdoor air temperature decreases, more compressor lift is required. Under these conditions, both the heating capacity and the COP decreases because the heat pump consumes more power.

Thirteen tests were performed under high-humidity conditions to make defrost cycle degradation adjustments to the idealized heating lookup table. The average heating capacity, evaluated over an 8- to 12-hour period, was divided by the idealized lookup table values to determine a derating factor less than one. Multiplying the derating factor by the low-frost performance lookup table value provides an effective heating capacity and COP that accounts for energy penalties associated with coil frost. The effective values capture the estimated energy usage during the heating cycle, the defrost cycle, plus the cooling effect (negative capacity) from the space that provides the heat needed to thaw the outdoor coil.

The data revealed that three piecewise regressions for fitting degradation factors were needed due to a cusp in the data, as shown in Figure 5. At an outdoor air temperature of 25ºF, a discontinuity exists due to a difference in the heat pump's embedded control logic. It is stated in the manufacturer's service manual that the unit ends the defrost cycle at a warmer outdoor coil temperature when the outdoor air temperature is above 25ºF.

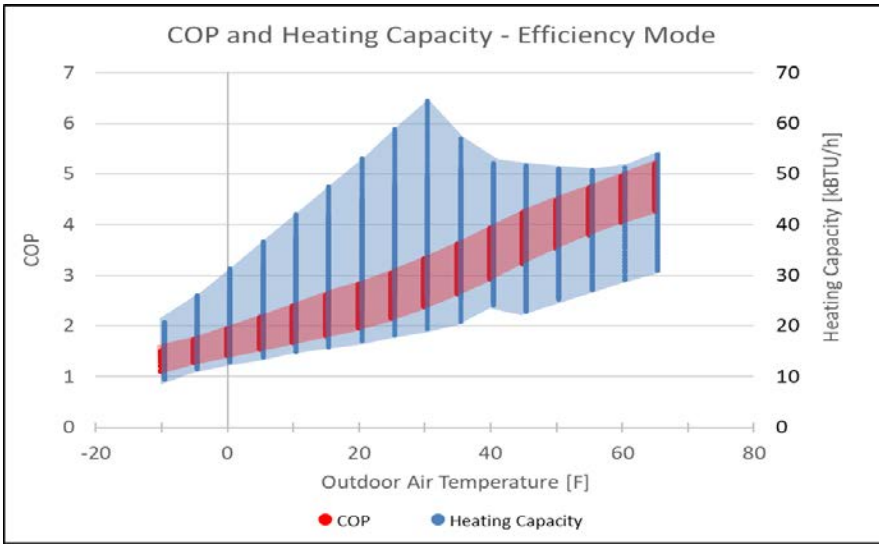

Figure 4. Expected range of varying heating capacity and COP versus outdoor air temperatures at sea level

Above 25ºF, two distinct curves represent the system operating at its minimum and maximum compressor speed. The system experiences the most rapid frost accumulation, largest capacity degradation, and runs the most defrost cycles when operating at the maximum compressor speed near freezing outdoor air temperatures. This is where the air contains the most moisture and heat pump's outdoor coil is guaranteed to be below the frost point.

At outdoor conditions below 25ºF, the capacity derating appears to be independent of the compressor speed. Despite the heat pump operating at its coldest coil temperatures, the system initiates less frequent and shorter duration defrost cycles due to slower rates of frost formation. This is due to exceptionally low dew point air containing little water vapor. Based on the embedded controls of the heat pump, the shorter defrost cycles are followed by longer heating intervals, typically lasting 90 to 120 minutes.

Upon developing this regression, it was apparent that more experimental runs were needed to better refine these trends. A few estimates were included to better approximate a regression below 25ºF.

During the thirteen defrost cycle experiments, a total of 56 individual defrost cycles occurred. Each defrost cycle was analyzed to relate the capacity degradation with a derated COP. As expected, the COP degrades proportionally to the capacity degradation, because the COP is a ratio of the capacity to the heat pump input energy. This relationship can be seen in Figure 6.

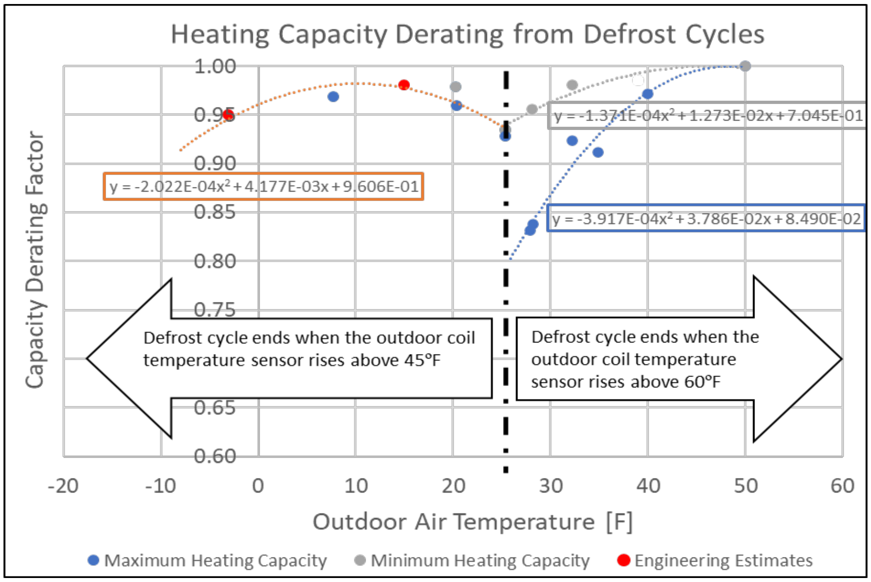

Figure 5. Estimated capacity derating factors regressions to account for defrost cycles

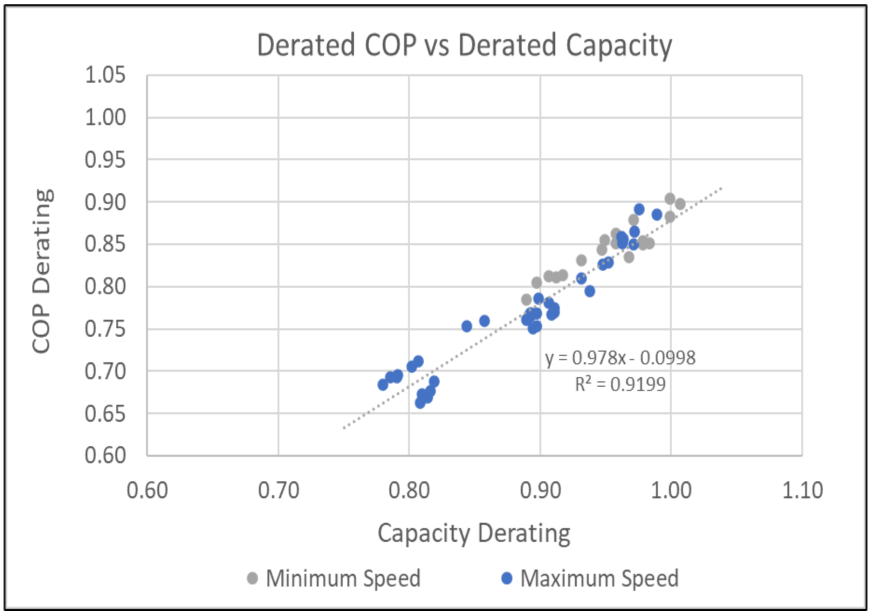

Figure 6. COP derating as a function of the capacity derating factor

The capacity degradation factor and COP derating is an integrated approach accounting for multiple variables that diminish the system's heating performance and increase energy consumption. By multiplying these factors with the ideal, frost-free performance data that represent the highest achievable system performance, the capacity and COP are adjusted to account for intermittent defrost operation. This method was developed for this project and attempts to estimate heat pump frost formation at high humidity levels. However, performance degradation and energy consumption can be even more severe under adverse winter weather conditions such as snow, sleet, and rain—especially near outdoor air temperatures of 32ºF. Such conditions are better assessed in field monitoring projects and could contribute significantly to higher annual energy use than these factors estimate.

EnergyPlus Modeling

EnergyPlus 9.5 is the software used for simulating the advanced heat pump model compared to a traditional heat pump. EnergyPlus is a free, open-source, cross-platform, whole-building hourly energy simulation program that engineers, architects, and researchers use to model both energy consumption (of heating, cooling, ventilation, lighting, and plug and process loads) and water use in buildings. The console-based program reads input from and writes output to text files.

Modeling Setup

The performance of both a traditional and the advanced heat pump is simulated for three DOE prototype buildings: a single-family home, a strip mall, and a low-rise office building. These prototype building models aid the development of building energy codes and standards and are available on the DOE website.[1]

The buildings follow either ANSI/ASHRAE/Illuminating Engineering Society of North America (IESNA) 90.1-2013 (for commercial) or International Energy Conservation Code 2021 (for residential) recommendations for IECC climate zone 5A. A brief description of the features of these buildings is shown in Table 3. The HVAC operation, occupancy, equipment, lighting, and ventilation schedules are also defined by default in these building models. Note that the baseline HVAC systems for the two commercial DOE prototype buildings utilize a rooftop unit (RTU) heat pump. Despite the difference in form factor, the variable speed, split-system heat pump data was used to assess the potential energy savings in applications where split systems can service light commercial buildings. All three buildings are simulated for the city of Chicago, using the TMY3 weather file for Chicago O'Hare International Airport.

For simulating the advanced heat pump, the experimental data for efficiency mode were translated into an EnergyPlus-readable format. This was done through the following process:

- The experimental data was translated from its raw form into `Table:Lookup` objects. These objects map the independent variables (such as the outdoor air dry-bulb temperature and the entering wet-bulb temperature of the coil) to the cooling and heating capacity of the heat pump. The lookup table object was specified to use cubic interpolation independently for each input variable. For performance points outside the table's defined grid space, a constant extrapolation method is set independently for each dimension.
- The `Table:Lookup` objects define the cooling capacity as a function of temperature (*CoolCapfT*) and heating capacity as a function of temperature (*HeatCapfT*). Ten discretizations are specified for each heating and cooling coil. For each discretization, a reference rated cooling/heating capacity, COP, and rated air flow rate are specified. Each table is representative of a particular speed of operation of the heat pump.
- The same procedure is repeated to create `Table:Lookup` objects to define Energy Input Ratio as a function of temperature curves (*EIRfT*). The Energy Input Ratio is the inverse of COP. The independent variables for the tables are once again the entering wet-bulb temperature and the outdoor air dry-bulb temperature. As before, 10 such discretizations are specified for the heating and cooling coils.

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[1] https://www.energycodes.gov/prototype-building-models

- The curves described above are referenced by `Coil:Cooling:DX:VariableSpeed` and `Coil:Heating:DX:VariableSpeed` objects. These objects in EnergyPlus simulate different speed-rated performance of the cooling and heating coils specified. In this simulation, 10 different speeds are specified—the maximum allowable.
- The two coils are wrapped in a parent `AirLoopHVAC:UnitaryHeatPump:AirToAir` object to complete the setup of the variable-speed heat pump model. The heating coil is complemented by a supplemental backup electric heating coil to satisfy any deficiency in meeting the building load.

Table 3. Summary of DOE prototype buildings simulated

Parameters	Single-Family Home	Strip Mall	Low-Rise Office
Total building area (sf)	3,565	22,500	5,502
Window-wall ratio (%)	14%	11%	21%
Hours of operation	24/7	Store 1: 9:00-24:00 Store 2: 9:00-21:00 Store 3: 9:00-19:00	Weekdays: 8:00-17:00
Baseline HVAC system description	Single-stage heat pump with direct expansion (DX) cooling, reverse DX electric heating, and supplemental electric heat	Single-stage heat pump RTU with DX cooling, reverse DX electric heating, and supplemental electric heat	Single-stage heat pump RTU with DX cooling, reverse DX electric heating, and supplemental electric heat
Heating efficiency	7.9 HSPF	7.5 HSPF	7.5 HSPF
Cooling efficiency	13.0 SEER	12.0 SEER	12.0 SEER
Supply fan efficiency	0.4 W/cfm	0.5 W/cfm	0.5 W/cfm

For all the DOE prototype buildings referenced above, simulations were run for both a baseline case (using typical, predefined heat pump curves) and an advanced case. The results and savings of these simulations are discussed in the following section.

Model Results

This section discusses the energy modeling results for the baseline models retrofitted with a high-efficiency heat pump.

Figure 7 shows the whole-building energy savings for a single-family home retrofitted with the high-efficiency heat pump model as compared to a baseline model with a standard-efficiency heat pump unit.

The single-family home prototype shows relatively lower savings (22.1%) than the other two building models represented here (29.3% for strip mall, 28% for office). This is due to the following reasons:

- The single-family home model has relatively low supply fan savings (13.1%). This is because in the baseline model for this building type, the supply fans cycle only when heating and cooling is required, and they are turned off otherwise. In the other two commercial buildings, the fans are required by code to be operational during business hours to meet ventilation and indoor air quality requirements.

- The magnitude of internal loads, which need to be met by the HVAC system, are also smaller in a residential building model as compared to the other two commercial building prototypes.

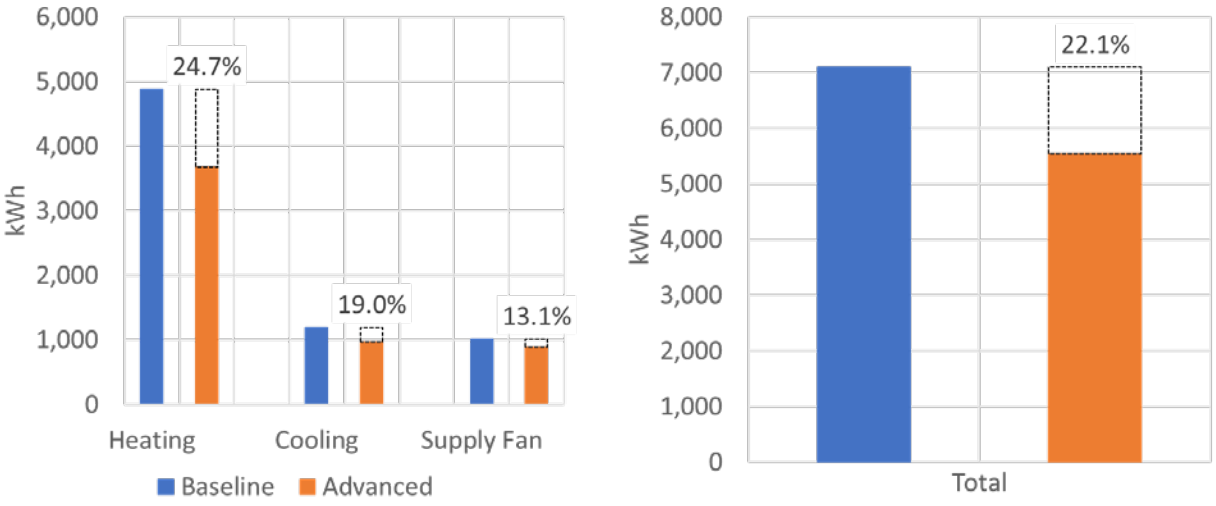

Figure 7. HVAC energy use comparison for a single-family home with the high-efficiency heat pump model. The figure on the left shows the end-use savings breakdown, and the figure on the right shows the total site energy use for the baseline and high-efficiency heat pump models.

Figure 8 shows the savings for the strip mall building prototype with a high-efficiency heat pump.

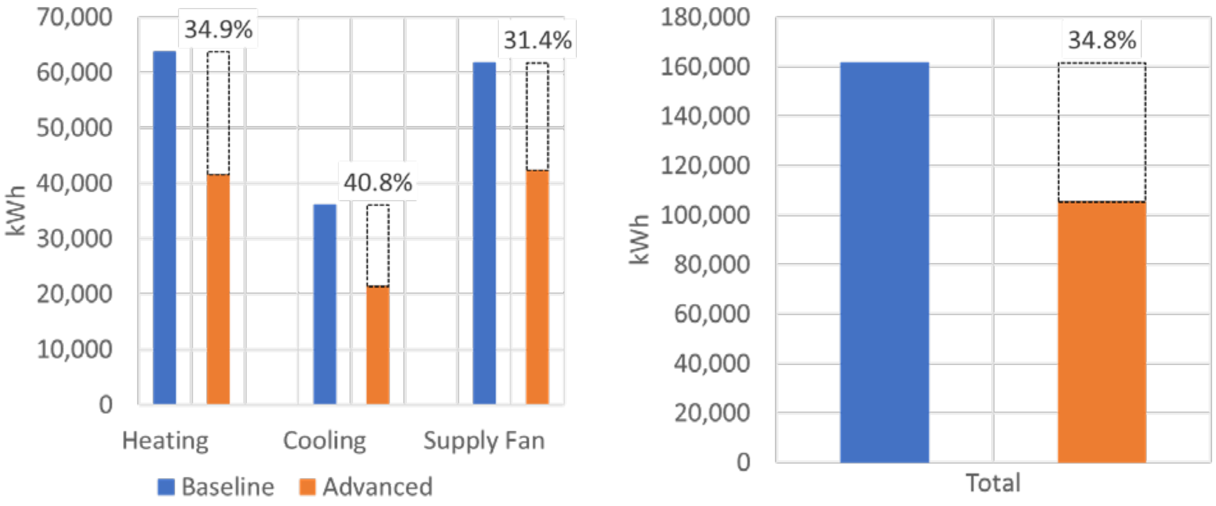

Figure 8. HVAC energy use comparison for a strip mall with the high-efficiency heat pump model. The figure on the left shows the end-use energy consumption breakdown, and the figure on the right shows the total site energy use for the baseline and high-efficiency heat pump models.

The strip mall prototype model shows the highest energy savings over its respective baseline, both in terms of percentage and in terms of absolute energy savings. The reasons for this include:

- The increased absolute energy savings are likely due to the large square footage of the strip mall (see Modeling Setup). More conditioned area means more loads to be met, and therefore higher energy usage (and subsequently higher absolute savings) for the building.
- A strip mall has significantly higher ventilation requirements to accommodate considerably more occupied hours and loads that need to be satisfied by the HVAC system. This translates to increased operating time for both the baseline system and advanced heat pump model.
- The load for the strip mall occurs coincidentally with lower ambient temperatures (due to longer operating hours). This would result in greater use of the baseline system's strip heating coil, leading to higher baseline energy usage. The increased performance of the advanced heat pump (especially at lower ambient temperature) would help minimize the use of the strip heater in the unit, and therefore realize more savings.

Figure 9 shows the savings for the low-rise office building prototype with a high-efficiency heat pump.

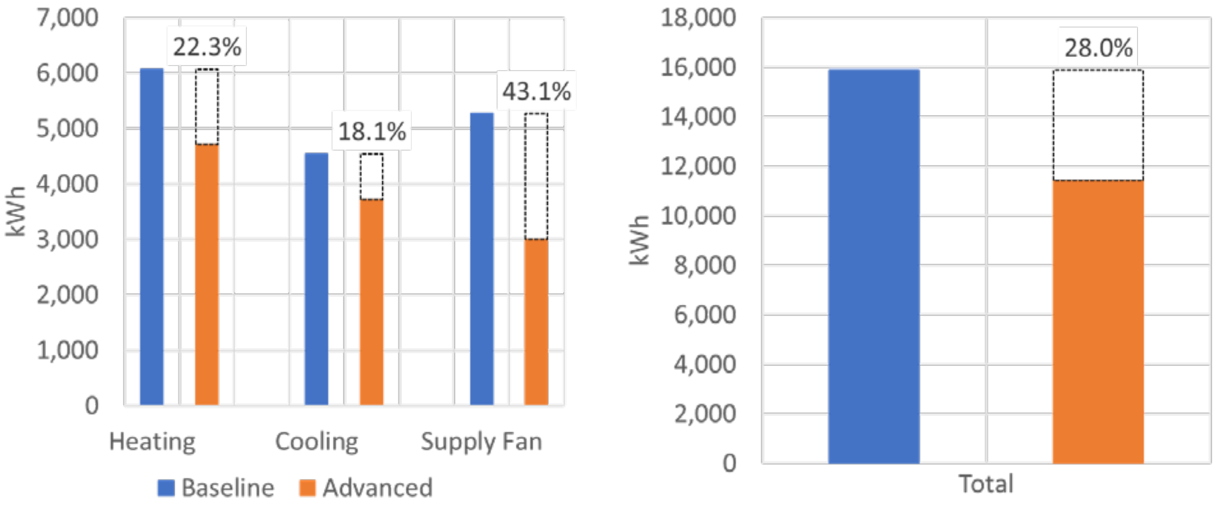

Figure 9. HVAC energy use comparison for low-rise office building with the high-efficiency heat pump model. The figure on the left shows the annual end-use energy consumption breakdown, and the figure on the right shows the total site annual energy use for the baseline and the high-efficiency heat pump model.

The low-rise office building's energy savings are comparable to the strip mall prototype. The lower ventilation requirements of the low-rise office buildings and reduced hours of operation contribute to slightly lower overall savings when compared to the strip mall prototype.

Conclusions

Table 4 shows a summary of the energy savings for the three different prototypes simulations. The higher COP of the high-efficiency heat pump under Chicago's low winter temperatures resulted in significant heating energy savings in all three buildings The higher compressor COP also contributed to moderate annual cooling energy savings. The high-efficiency supply fan motor and variable-speed controls of the high-efficiency heat pump provided additional fan energy savings for all three building models.

Table 4. Summary of DOE prototype buildings simulated

Parameters	Single-Family Home	Strip Mall	Low-Rise Office
Heating energy savings	24.7%	34.9%	22.3%
Cooling energy savings	19.0%	40.8%	18.1%
Supply fan energy savings	13.1%	31.4%	43.1%
Total (heating, cooling, and supply fan) energy savings	22.1%	34.8%	28.0%

The strip mall building shows the highest whole-building energy savings (29.3%) over its respective baseline. The low-rise office building's savings are similar (28%), while the single-family home has a slightly reduced energy savings due to lower internal loads and the lack of prescriptive ventilation requirements. Overall, all buildings show significant energy savings over their respective baseline and make a strong case for the use of these heat pumps. Upon presenting this experimental work and the simulation results, ComEd's next steps are to identify future rebate incentives for early customer adoption of this technology in their utility territory.

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