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Quick Insight:
Cold Climate Heat Pumps

RESEARCH QUESTIONS

How can heat pumps support decarbonization of residential space heating in cold climates, what are the latest technology advances to enable cold-climate heat pumps, and what are their barriers to adoption?

INTRODUCTION

Air-source heat pumps provide both heating and cooling of homes and are commonly used in the southern portion of the United States due to the relatively mild winters. However, oil- and gas-fired furnaces are much more common than air-source heat pumps in colder climates since the heating capacity of heat pumps is reduced at lower outdoor temperatures where heating load is the highest. Yet as the industry transitions to a low-carbon energy future, heat pumps are expected to play a key role in decarbonizing space conditioning. Heat pumps have several advantages when compared with fossil heat, including high overall efficiency (i.e., higher energy output for the same energy input) and reduced local emissions (CO_2, NOx, and SOx). However, there are several challenges associated with heat pump installations in cold climate locations. This Quick Insight brief describes these challenges and provides insight into how heat pumps may be deployed for a low-carbon space heating solution in cold climates.

KEY POINTS

- Heat pumps offer a key solution for decarbonizing space conditioning in many climates, but face challenges with deployment in cold climates.
- The heating capacity and efficiency of air-source heat pumps decrease at lower outdoor temperatures. In typical applications, a heat pump will rely on supplemental heating (either electric resistance or fuel-based) on the coldest winter days.
- The balance point is the minimum outdoor temperature where the heat pump compressor and fans fully satisfy the heating load, below which supplemental heating must be used to maintain the desired indoor air temperature.
- While the heating capacity of baseline, single-speed heat pumps drops linearly with outdoor temperature, variable-speed systems are capable of providing a higher proportion of their maximum heating capacity at low outdoor temperatures.

- Certain variable-speed heat pumps can deliver 100% of rated heating capacity (measured at 47°F) down to 17°F outdoors, or even lower for some systems (e.g., -5°F). These models are referred to as high heating output or low-ambient heat pumps. EPRI has tested models from several manufacturers that meet this criterion.
- EPRI field testing has demonstrated that variable-speed heat pumps can significantly reduce heat pump electricity demand during winter by reducing dependence on supplemental heating. Certain models were demonstrated to meet the entire home heating load without supplemental heating down to 0°F outdoors, with continued heat pump compressor operation observed down to -20°F.
- Regardless of equipment type (single-speed, multi-speed or variable speed), selecting the appropriate heat pump size is important for proper operation and efficiency, and requires carefully estimating both the peak heating and peak cooling loads for the home.
- Variable-speed heat pumps provide the added benefit of continuously adjusting compressor and fan speeds to meet the required heating and cooling loads, resulting in high energy efficiency and excellent occupant comfort. For low-ambient heat pumps, this flexibility can be exploited to size the heat pump compressor to meet the vast majority of the winter home heating load (without supplemental heating) while limiting or eliminating "oversizing" during cooling operation in summer.

BACKGROUND

In essence, air-source heat pumps operate as air conditioners in summer but also operate in reverse during winter, when heat is moved from cold outdoor air to the indoor conditioned space by means of the vapor compression (refrigeration) cycle. (This paper focuses on air-source heat pumps due to their prevalence in the market, but it should be noted that ground-source and water-source heat pumps generally offer superior cold climate performance over air-source systems due to moderated temperature of the ground or water. For a brief summary of recent innovations in ground-source heat pump technology see EPRI's latest Scouting Update.[1]) Heat pump equipment has the same components as an air conditioner (compressor, expansion valve, indoor heat exchange coil and blower, outdoor heat exchanger and fan) plus a refrigerant reversing valve, allowing it to operate in heating or cooling mode as needed. Unlike conventional heating, a heat pump can move more energy than it consumes, with overall efficiency expressed in terms of coefficient of performance (COP) being greater than 1, often between COP of 2.5 and 3.5 at typical operating conditions.

CONVENTIONAL HEAT PUMP SIZING, SELECTION AND OPERATION

A heat pump's capacity and efficiency decrease as outdoor temperature drops due to the inherent thermodynamics of the vapor compression cycle. This means the heat pump is least efficient and has the least capacity when there is the greatest need for heating. For this reason, contractors currently install virtually all heat pumps with a supplemental (a.k.a. auxiliary or backup) heating source for use at low outdoor temperatures. Even in climates with mild winter conditions, a supplemental heating source is typically installed as a precaution in case of heat pump compressor failure, although it should be noted that redundancy is not provided for fuel-fired furnace heating systems. The most common sources of supplemental heat are electric resistance, natural gas, and propane heaters. These supplemental sources can deliver consistent heating capacity independent of the outdoor temperature but cannot exceed COP of 1. The choice of supplemental heating is an important design and installation consideration, one that can significantly affect the overall energy performance of the system.

Electric resistance elements can be sized to meet the full heating load or to operate in tandem with the heat pump compressor. For typical residential applications, electric resistance is sized between 5–20 kW, depending on heat pump system size and climate. The electric resistance elements are often installed in multiple stages that can be energized as needed (e.g., two 10kW heating elements).

1 Deployment Innovations for Residential Ground-Source Heat Pumps. EPRI, Palo Alto, CA: 2018. 3002014792.

Oversizing electric resistance is relatively inexpensive in terms of first cost, except for added electrical branch circuit requirements, and can serve as a safety factor. There is some variation in how multiple electric resistance stages are energized depending on the control settings in the thermostat and heat pump. In general, heat pumps with electric resistance backup will attempt to use the heat pump compressor whenever heating is requested by the thermostat and will activate electric resistance when the heat pump compressor alone is unable to satisfy the indoor comfort settings. The exact staging of electric auxiliary heat depends on the controls and can depend on indoor temperature and outdoor temperature, but most often the first stage of auxiliary heat is energized when the thermostat detects reduced indoor temperature and additional stages are energized based on a simple timer (e.g., stage 2 activated after 10 minutes of continuous call for stage 1 auxiliary heating).

As outdoor temperatures approach freezing, frost will begin to build on the outdoor coil, degrading the performance of the heat pump. To maintain heat pump operation, the system will defrost the outdoor coil by reversing cycle (operate briefly in cooling mode) to warm the coil, typically while reducing indoor fan speed and energizing auxiliary heat to prevent cold air from being supplied indoors. The defrost cycle is normally terminated based a predefined period of time or a coil temperature measurement to indicate when the frost has been removed.

When the outdoor temperature drops to the point where the heat pump compressor cannot provide sufficient heating (for a heat pump with fossil fuel auxiliary heat) or when the compressor can no longer operate efficiently (e.g., for an all-electric heat pump), the system will switch over to auxiliary heating only. Like the control of staged supplemental heating described above, the transition to auxiliary (backup) heat can be determined by indoor temperature, outdoor temperature, or continuous heating runtime. The specific staging of auxiliary heating can often be fine-tuned by settings in the thermostat or heat pump, allowing for some trade off between customer comfort and efficiency.

In general, common practice is to size the heat pump to satisfy the full cooling load (i.e., summer design conditions at the site) and to size the supplemental heating for the full heating load (winter design conditions). A trained HVAC professional should use Air Conditioning Contractors of America (ACCA) Manual J to estimate the design heating and cooling load for the HVAC system, which factors in foundations, walls, roofs, insulation, windows, internal heat gains, etc.[2] For much of the U.S., the heating design load is larger than the cooling design load, meaning that a heat pump system is normally sized to use supplemental heat on the coldest days. For these applications, the minimum outdoor temperature where the heat pump compressor can fully satisfy the heating load is called the *balance point*, below which the system must rely on supplemental heating. The balance point varies for a given location due to building differences (insulation levels, number and type of windows, airtightness of the building shell, internal gains, etc.), design outdoor temperature choice (e.g., 99% or 99.6% design weather conditions), and the selected heat pump size, but a typical balance point in the southeastern region of the U.S. may be around 35°F to 40°F. Even in warm climates (e.g., ASHRAE Climate Zone 2, including most of Florida and the Gulf coast of the U.S.) a heat pump will typically activate supplemental heat on the coldest winter mornings.

A heat pump that uses gas for supplemental heating is referred to as a *dual-fuel* system. Unlike staging with electric resistance heat, existing dual-fuel systems can only operate with either the heat pump compressor or the supplemental gas furnace enabled. The switch from heat pump compressor to furnace operation is commonly set at the balance point, the lowest temperature where the heat pump compressor can meet the entire heating load. Below the balance point, the dual-fuel system will utilize the furnace to provide heating. This changeover temperature is typically programmed by the installing contractor and requires an outdoor temperature sensor.

2 https://www.acca.org/standards/technical-manuals

CHALLENGES IN COLD CLIMATE DEPLOYMENT

Heat pump applications in cold climates face several design challenges. The heating capacity and operating efficiency of a heat pump drops as outdoor temperature falls. For conventional heat pumps with electric auxiliary heat, resistive heating elements are used to supplement the declining heat pump capacity, driving up electricity use and operating costs. In regions with high penetration of heat pumps, auxiliary electric heating drives peak load on the grid and can be a primary contributor to system peak demand.

Second, colder climate zones often have a greater mismatch of cooling and heating requirements. As noted earlier, most heat pumps are frequently sized to satisfy cooling design conditions, which minimizes up-front cost while ensuring efficient operation. Yet for most climate zones in the U.S., this means that the heat pump does not have sufficient capacity to meet a significant portion of the load in the heating season. Table 1 illustrates the difference between heating design conditions for climate zones with similar cooling design conditions, with only a 3°F difference in cooling but 23°F difference in heating. On the other hand, if the heat pump is sized to satisfy heating design conditions, it may be oversized for the cooling season, which can lead to poor dehumidification and inefficient operation due to excessive cycling. In addition, over-sizing a heat pump in this manner raises first costs, which is a major barrier for residential customers.

Third, some models of heat pumps may not be designed to operate at extremely low temperatures (e.g., below 0°F), and may experience problems with low refrigerant flow, poor lubrication, and compressor overheating. These operational problems are dependent on the manufacturer design and will likely not impact products specified for cold climate applications.

ADVANCEMENTS IN COLD CLIMATE HEAT PUMPS

One method for addressing significant differences between the design heating and cooling loads is to utilize a multi-speed heat pump. These systems allow the compressor to operate at two or more discrete capacity stages to better match the range of heating and cooling requirements. The most common offering is a two-speed system, but systems with up to 5 distinct stages are available. If the system is sized slightly larger to meet more of the heating load with compressor operation, the lower capacity stage(s) can be employed in the summer to maintain good energy efficiency and indoor air dehumidification.

While multi-speed systems are readily available and address one challenge, advances in heat pump technology are being developed to improve the cold-weather heating performance of heat pumps and to enable reliable heat pump use in colder climates. One principal technology that has allowed heat pumps to improve performance at lower ambient temperature is variable-speed, inverter-driven compressors. Variable-speed equipment offers several advantages for overall heat pump performance, and in cold climate applications the main benefit is the ability to increase compressor speed at low outdoor temperatures to compensate for the decrease in delivered heating capacity. Variable-speed compressors also allow the heat pump to modulate capacity which alleviates cycling losses normally encountered with oversized single-speed equipment during cooling and shoulder weather seasons. The Northeast Energy Efficiency Partnerships (NEEP) maintains a specification for cold climate heat pumps, detailing requirements for operation.[3] This "cold-climate" specification requires publishing heating capacity and efficiency performance data down to 5°F (with COP >1.75 at max operating speed), and the compressor must be variable-capacity (three or more distinct speeds).

Table 1 – Heating Design Conditions by Climate Zone

ASHRAE Climate Zone	Representative City	Heating Design Condition (99.6%)	Cooling Design Condition (0.4%)
3A – Warm, humid	Atlanta, GA	22°F	94°F
5A – Cold, humid	Chicago, IL	-1°F	91°F

3 https://neep.org/sites/default/files/media-files/cold_climate_air-source_heat_pump_specification-version_3.0_final.pdf

In addition to the advancements in variable-speed technology, there have been numerous efforts in developing advanced vapor compression cycles that can provide improved heating performance in cold climates. In particular, vapor-injected compression has seen adoption in certain products in recent years, with multiple offerings from different manufacturers utilizing this technique. Vapor injection, or flash-injection, returns lower temperature refrigerant vapor to a midpoint in the compression cycle, which keeps the compressor cool while allowing high-speed operation without deterioration due to friction or overheating. This effectively allows the system to operate similar to a multi-stage compression cycle with just one compressor and improves the system heating capacity.

As described previously, air-source heat pump operation leads to frost buildup on the outdoor coil as the outdoor temperature drops below approximately 40°F. Virtually all air-source heat pumps utilize "reverse cycle" defrost, where the heat pump reverts to cooling (air conditioner) mode for a brief period to heat the outdoor coil for frost removal. In most cases, supplemental heat (e.g., electric resistance elements or gas heater) is energized during the defrost cycle to avoid cold air being delivered to the conditioned space. For heat pumps installed in cold climates, frost buildup and required defrosts are more frequent. At least one equipment manufacturer offers a heat pump where auxiliary heat during defrost is not required. This product incorporates certain components and controls that allow the indoor fan to be turned off completely during defrost; therefore, no auxiliary heat is needed to temper cold air normally produced during conventional reverse-cycle defrost. For all-electric air-source heat pumps, this feature is particularly beneficial in that it eliminates electric resistance operation during defrosting. This variable-speed heat pump also incorporates vapor-injection compression for improved cold-weather performance; therefore, when properly applied these heat pumps may be installed in cold climates without any auxiliary heat source.

EPRI RESEARCH ON COLD CLIMATE HEAT PUMPS

EPRI has evaluated various aspects of variable-capacity heat pump (VCHP) technology through its Customer Technologies research area (Program 170). These efforts have characterized the energy efficiency, electrification, demand response, and power quality impacts of these units through laboratory assessments[4,5] and field demonstrations.[6,7] These studies have evaluated the efficiency of variable-capacity technology in both heating and cooling mode and provided independent verification of the low-temperature heating performance of these devices.

In particular, the heating performance of variable-capacity heat pumps at low ambient temperatures was studied in a laboratory setting and compared with a baseline heat pump technology.[4] The study compared three different heat pumps in a controlled laboratory setting: a single-speed system (HSPF 7.7), a variable-speed system (HSPF 9.7), and a variable-speed system (HSPF 9.5) designed to maintain capacity at low outdoor temperatures (herein referred to as low-ambient heat pump). While all three systems showed a reduction in system capacity as ambient temperature decreases, the low-ambient heat pump was able to provide 70% of its maximum capacity at 5°F. This can be seen in Figure 1 and is much higher than that of the single speed system (~30%) and the variable speed system (~55% of maximum capacity) at this same outdoor temperature. Due to the higher compressor speed, the low-ambient system had greater power consumption and thus a lower COP compared to the variable-speed system at temperatures below 30°F, as shown in Figure 2. However, the increased heating capacity provided by the low-ambient model can offset less efficient auxiliary heat and this benefit is not captured in Figure 2. This lab study demonstrated that heat pumps, when designed properly, can be deployed in much colder climates than where they have traditionally been used.

4 Laboratory Testing of the Heating Capacity of Air-Source Heat Pumps at Low Outdoor Temperature Conditions. EPRI, Palo Alto, CA: 2010. 1020130.
5 Laboratory Testing of Residential Variable Speed Heat Pump. EPRI, Palo Alto, CA: 2013. 3002002288.
6 Elimination of Electric Strip Heat Dependence with Advanced Inverter Driven Heat Pumps. EPRI, Palo Alto, CA: 2015. 3002004964.
7 Variable Capacity Heat Pump Applications: Elimination of Backup Electric Resistance Heat. EPRI, Palo Alto, CA: 2018. 3002014920.

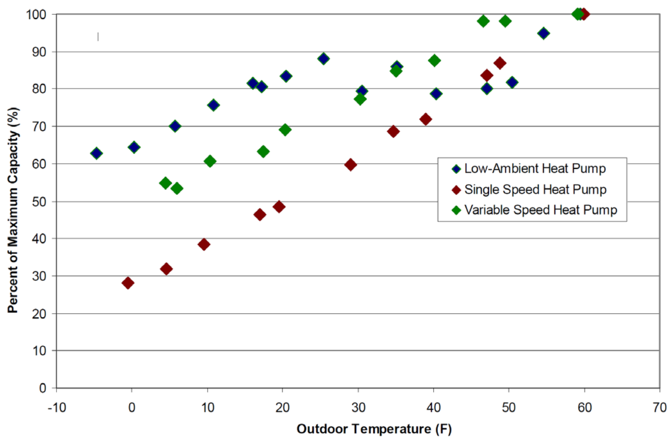

Figure 1. Heating capacity as a percentage of maximum capacity at different outdoor temperatures in EPRI lab testing

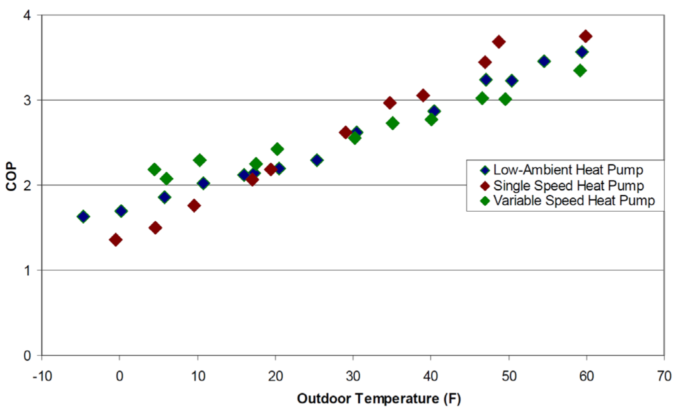

Figure 2. COP at different outdoor temperatures in EPRI lab testing

EPRI field demonstrations have further studied the capability of VCHPs to reduce peak electric demand from heat pumps in winter. Utilities in warmer southern climates can face system peak demand during winter months due to the predominance of heat pumps in these mild climates, and this situation may more broadly apply as electric heat pumps installations increase in colder climates. EPRI partnered with Duke Energy to evaluate how VCHPs address the "needle peak" caused on the few mornings where temperatures in its central Florida territory fell below the balance point, activating supplemental electric heating across the region.[6,7] This two-part study showed the potential for variable-capacity equipment to reduce the demand from heat pumps through reduced dependence on supplemental electric resistance heating. In addition, an over-sized (relative to cooling load) variable-capacity model was found to provide satisfactory heating performance at these temperatures without supplemental heating. Despite being over-sized for cooling load, the system at the latter site provided the needed dehumidification—typically an issue with over-sizing conventional single-speed heat pumps—due to its ability to modulate speeds.

The Phase II study with Duke Energy evaluated a high heating output VCHP and a cost-competitive VCHP at two other sites in central Florida.[7] Like the over-sized unit from the first study, both systems were intended to eliminate the need for supplemental heating in this climate. The results of this study demonstrated a reduction in winter peak demand of 8.5 kW at 34°F and 5.8 kW at 26°F compared to baseline equipment while providing significant energy savings through summer and winter seasons. When cost-effectiveness was considered (in terms of Total Resource Cost test), the cost-competitive and high-heating output models demonstrated in this follow-up study were found to be more cost-effective in this climate than oversizing VCHP equipment as demonstrated in the first study.

AVAILABLE PRODUCTS FROM MANUFACTURERS

Manufacturers have started to offer heat pump products capable of sustained and productive operation well below 5°F. This is driven by advancements in the technology, electrification, and polar vortex events in recent years. Table 2 shows a variety of air-source heat pump products that are currently available, with most offerings capable of delivering 100% of the rated heating capacity at 5°F outdoors and some are able to operate at temperatures down to -31°F. Most of the products listed use either advanced vapor-injection controls, compressor speed controls, or both to provide near full capacity at cold outdoor temperatures.

ON-GOING EPRI WORK AND NEXT STEPS

As part of its ongoing research into emerging heat pump technologies, EPRI is currently conducting a field demonstration of VCHP technology in residential applications. This collaborative project seeks to evaluate the various aspects of this technology—including energy efficiency, occupant

Table 2 – Example Cold Climate Heat Pump Performance

	% of Rated Heating Capacity at Low Outdoor Temperature [a]	Minimum Operating Temperature
Daikin – Aurora	100% @ 5°F	-13°F
Mitsubishi – HYPER-HEAT	100% @ -5°F	-13°F
Carrier – Infinity Greenspeed	100% @ 17°F	-15°F
Rheem – RP20	100% @ 17°F	7°F
BOSCH – MAX performance [b]	100% @ -5°F	-22°F
Fujitsu – Halcyon XLTH [b]	100% @ -5°F	-15°F
Gree – Vireo+ Ultra [b]	100% @ 17°F	-31°F
Lennox – MLA [b]	100% @ 0°F	-22°F
Samsung – Smart Whisper Max Heat [b]	100% @ 5°F	-13°F
GE – Endure [b]	85% @ -22°F 100% @ -15°F	-31°F

[a] Heat pumps rated at 47°F outdoors, [b] Ductless unit.

comfort, low-temperature heating, demand response, and cost-effectiveness—and involves utilities from across the U.S., representing a variety of climate zones with field sites in Pennsylvania, Nebraska, Colorado, New Mexico, and Washington. Preliminary project results indicate that VCHP equipment can meet space conditioning needs in cold climates with significant energy savings and enhanced occupant comfort compared to the conventional heating and cooling systems that were replaced.

As part of this field-testing project, the performance of one VCHP model was monitored at extremely low outdoor temperatures. During an unseasonably cold polar vortex in February 2021, the heat pump compressor continued to provide space heating at outdoor temperatures as low as -20°F. At several sites in Nebraska, the VCHP equipment was able to meet the home's heating needs without supplemental heating down to around 0°F. Below this point auxiliary heating (electric resistance) began to supplement the heat pump compressor to satisfy the load. Below -20°F the equipment was observed to transition to supplemental heating only to meet the thermostat setpoint temperature.

Figure 3 shows measured data from one site in Columbus, NE. This new construction home (3,600 sq.ft.) is conditioned with a 4-ton variable-speed heat pump. Total electric power demand was approximately 8 kW on a morning with low temperature of -16°F due to the cycling of 5 kW of supplemental heat. The heat pump compressor alone kept the supply air temperature above 80°F and the system delivered over 100°F supply air when auxiliary heating was activated to supplement the heat pump compressor operation.

As described previously, heat pump defrosting introduces an efficiency penalty in the heating season—about 10–15% during frost-forming weather. Building on prior work[8,9,10], EPRI is currently conducting a study to evaluate alternative defrost methods and defrosting strategies for use with refrigerant-to-air heat exchanger coils in order to reduce the negative effects of conventional defrost methods, improve energy efficiency and overall system performance, and evaluate peak demand saving opportunities.[11] Testing includes evaluation of advanced controls and use of frost-prevention coil coatings by simulating frost accumulation and system operation during individual heat exchanger testing. By test-

8 https://www.epri.com/research/products/000000000001021641
9 https://www.epri.com/research/products/000000003002001997
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11 https://www.epri.com/research/products/000000003002011562

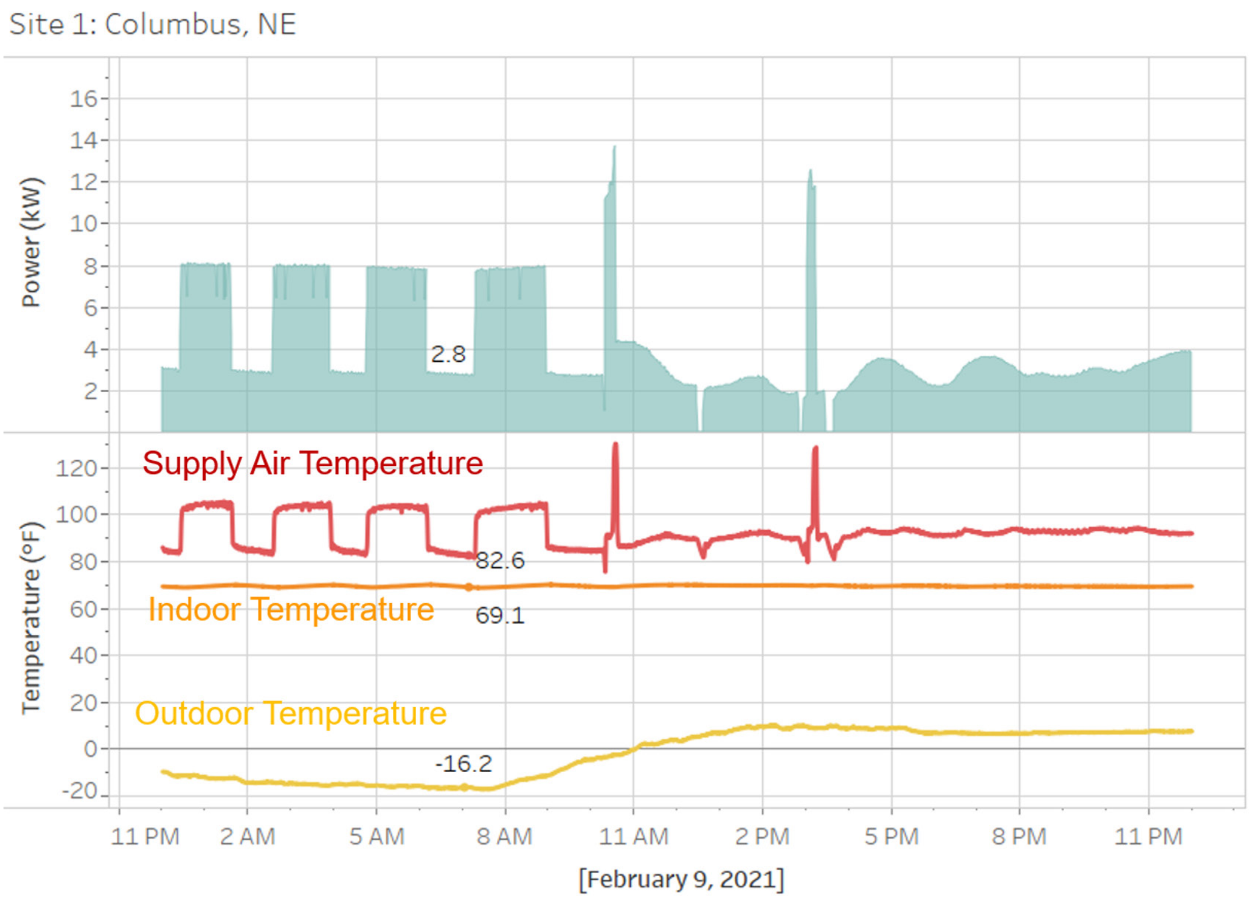

Figure 3. Variable-Capacity Heat Pump Performance on a Cold Winter Day

ing individual coils rather than a full assembly, the effects of frost accumulation/defrost can be isolated and eliminate the need to override existing controls in an assembled heat pump or refrigeration system. Testing is being conducted using coil samples that are representative of commercially-available fin/tube patterns.

Further enhancements to the conventional vapor compression cycle may improve heating performance across the full range of operating conditions, and particularly during cold winter conditions. Apart from vapor-injection compression, which has already seen adoption, other concepts that are being explored include:[12]

- Ejector-compressor hybrid cycle
  An ejector (nozzle) is used to entrain refrigerant gas leaving the evaporator using liquid refrigerant exiting the condenser coil. This process, combined with a liquid/vapor separator, allows the compressor to operate with a lower pressure ratio, thereby increasing its capacity and operating efficiency.[13] Ejectors can be fixed geometry, or variable geometry to improve performance by adjusting based on current operating conditions.
- Solar-assisted heat pump with ice slurry tank
  This system relies on an ice slurry storage tank to provide a constant temperature source around 30°F for heat

12 IEA HPC (2017) Annex 41 Final Report – Cold Climate Heat Pumps: Improving low ambient temperature performance of air-source heat pumps, IEA Heat pump center

13 Li H., Cao F., Bu X., Wang L., Wang X., 2014, Performance characteristics of R1234yf ejector-expansion refrigeration cycle, *Applied Energy*, Volume 121, S. 98-101

pump operation, well above outdoor air temperatures experienced by air-source heat pumps operating in cold and very cold climates.[14] Solar collectors inject thermal heat into the tank during daytime hours, thus melting the ice slurry mixture. An electric water-to-water heat pump transfers energy from the ice tank to a warm water tank (e.g., 95°F) which can be used to provide space heating, temper outdoor ventilation air or preheat domestic hot water. Due to the large amount of energy stored in the phase change of water (144 BTU/lb), the ice tank can be relatively small.

- **Ground-source heat pump with CO_2**
  Ground source heat pumps take advantage of the relatively constant ground temperature to provide high efficiency heating and cooling throughout the year, particularly advantageous compared to air-source heat pumps which experience performance degradation during especially cold or hot weather conditions. However, there is a high upfront cost to install the ground heat exchanger. Carbon dioxide (CO_2), an environmentally-friendly refrigerant, has excellent thermophysical properties which may allow a smaller ground heat exchanger and lower system first cost.[15]

- **Frost-free heat pump**
  This system uses a desiccant-coated heat exchanger to dehumidify air before it enters the evaporator coil to reduce or eliminate frosting.[16] Refrigerant valve positions are adjusted and air flow across the coils is redirected to regenerate the desiccant once loaded with moisture. The concept is currently being investigated for application to air-source heat pumps (for space or water heating) and household refrigerator/freezers.

- **Oil-flooded compression with regeneration**
  Lubrication oil or other non-volatile liquid is injected during the refrigerant compression process, transferring the heat of compression to the oil instead of the refrigerant. A regenerative heat exchanger is also used to subcool the liquid refrigerant leaving the condenser coil. This methodology results in increased capacity and efficiency, and lower refrigerant discharge temperatures which allows compressor operation down to lower outdoor temperatures.[17]

- **Parallel (tandem) compressors**
  Two single-speed compressors of equal capacity are configured in parallel to obtain higher heating capacity at low outdoor temperatures, while also providing good performance at part-load conditions (e.g., cooling mode or moderate outdoor temperatures in heating mode).[18] Different compressor types and heat exchanger sizes can be used to achieve improved performance, with the goal of being a cost-effective alternative to variable-speed compressor systems and with simpler controls.

- **Refrigerant mixture with strategic temperature glides**
  Single-component refrigerants or azeotropic blends boil at a constant temperature for a given pressure. On the other hand, zeotropic mixtures have a temperature glide, meaning the evaporating/condensing temperature (at constant pressure) changes as the ratio of gas-to-liquid varies. Significant efficiency gains may be realized by matching the temperature glide of the refrigerant blend to that of the heat transfer medium (air or water).[19]

14 Tamasauskas, J., Poirier, M., Zmeureanu, R., and Sunye, R., Modeling and Optimization of a Solar Assisted Heat Pump Using Ice Slurry as a Latent Storage Material Solar Energy, *Solar Energy*, 86(11), pp. 3316-3325, (2012).

15 Badache, M., Ouzzane, M., Eslami-Nejad, P., Aidoun, Z., Experimental study of a carbon dioxide direct-expansion ground source heat pump (CO2-DX-GSHP), *Applied Thermal Engineering*, Volume 130, 5 February 2018, Pages 1480-1488.

16 Zhang L. et al. A new method for preventing air-source heat pumps and refrigerators from frosting. Paper no. O.1.6.3 in the Proceedings of the 12th IEA Heat Pump Conference 2017, May 15-18, 2017, Rotterdam, Netherlands.

17 Ramaraj, S., Braun, J.E., Groll, E.A, and Horton, W.T., "Performance analysis of liquid flooded compression with regeneration for cold climate heat pumps," *Int'l J. Refrigeration*, Vol. 68, August 2016, Pages 50–58.

18 Shen B., O. A. Abdelaziz, C. K. Rice, V. D. Baxter, and H. Pham, 2016, "Cold Climate Heat Pumps Using Tandem Compressor", Conference Paper (OR-16-C039) in Proceedings of 2016 ASHRAE Winter Conference, Orlando, FL, Jan 23-27,2016.

19 Hakkaki-Fard, A., Z. Aidoun, P. Eslami-Nejad, (2016). Evaluation of refrigerant mixtures in three different cold climates residential air-source heat pumps, *ASHRAE Transactions*, Vol 122, Part 2, June 2016.

Many of these proposed concepts are in the early stages of development, with efforts in modeling performance or initial prototype testing. EPRI will continue to monitor these emerging technologies as they mature and start to commercialize.

The "ultimate" heat pump would provide extremely high-efficiency performance and superior occupant comfort across the entire range of heating and cooling conditions, with no impact on the environment (e.g., zero global warming potential [GWP] refrigerant), and at an affordable first cost to the consumer. In addition to the challenges and technologies already mentioned, another needed area of advancement is extending the operating range of variable-speed systems. Existing heat pumps may operate from around 30 to 40% speed up to 100%+ when maximum heating or cooling capacity is needed. When the heating/cooling load drops below the minimum operating speed, the compressor cycles on and off like a conventional single-speed system which results in significant efficiency loss and may also negatively impact indoor comfort conditions.

Operation at lower compressor speeds can be challenging, particularly with current compressor designs where lubrication oil is mixed with refrigerant and distributed throughout the entire piping network. At low operating speeds the velocity of the refrigerant through the piping is low, so the heavier oil may not circulate back to the compressor sufficiently. In addition to energy inefficiencies, frequent cycling during cooling operation may lead to poor dehumidification and occupant discomfort. In order to avoid potential issues in the summer, contractors often install smaller heat pump compressors to avoid cycling but compensate with larger inefficient supplemental heaters to provide adequate heat during cold winter weather. Significantly reducing the lowest operating speed for variable-speed heat pumps represents a large opportunity to both improve overall performance and extend this equipment's applicability and cost effectiveness to cold-climate regions.

There is some development effort in oil-less compressor designs which are common in large centrifugal systems, ~100 tons and larger. Further R&D is needed toward reducing oil-less compressor technology to smaller sizes appropriate for residential and small commercial heat pumps. Oil-less designs offer promise for improving speed control and range, efficiency and reliability.

This document describes the current state of technology, some recent advances, and on-going research related to residential air-source heat pumps applicable to cold climate regions. Utilities interested in engaging in further evaluation of these technologies may consider participating in one of EPRI's collaborative supplemental projects in this area:

- Meeting Residential and Small Commercial Customer Needs for Space Conditioning (Supplemental Project Notice [SPN]: 3002009414)
- Evaluation of Frost-Prevention Measures for HVAC&R Equipment Performance Improvement (SPN: 3002011562)
- Heat Pump Working Council (HPWC) (SPN: 3002019816)

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Customer Technologies

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