Field Validation of Next-Generation Rooftop Units: Balancing Performance, Fuel Flexibility and Reliability in Commercial Buildings

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ABSTRACT

Next-generation rooftop units (RTUs), including advanced heat pump and dual-fuel configurations, are emerging as a promising pathway to improving commercial building HVAC performance and reliability. However, widespread adoption requires demonstrated performance under diverse real-world operating conditions. This paper presents findings from ongoing field evaluations of commercially available and pre-production prototype heat pump RTUs developed under the U.S. Department of Energy's Commercial Building HVAC Technology Challenge as well as commercially available RTUs studied by the Minnesota Center for Energy and Environment (MNCEE). We are monitoring energy use, cooling and heating performance, thermal comfort, controls and operational reliability across several U.S. cold climates and a variety of commercial building types.

Field evaluations across five cold-climate commercial buildings show that next-generation HP RTUs deliver reliable heating at sub-freezing temperatures, sustain COPs near or below lockout thresholds, and reduce peak electrical demand through dual-fuel operation. Variable-speed compressors and modern control algorithms supported stable performance across diverse load conditions, while observed installation and commissioning issues – such as curb compatibility, equipment specifications, controls integration, and firmware updates – highlight practical considerations for broader deployment. These field-based results provide actionable guidance for owners, manufacturers, and utilities seeking to accelerate adoption of high-efficiency RTUs in cold-climate commercial buildings.

Introduction

Packaged Rooftop Units (RTUs) are a dominant HVAC technology in the U.S. commercial sector, accounting for space conditioning of approximately 37% to 40% of commercial buildings and over 50% of total commercial floor space (EIA, 2022). They are particularly prevalent in small- to medium-sized commercial buildings, including offices, retail, education, and warehouses (Caradonna et al., 2023). Natural gas is the primary space heating and water heating fuel source for half of all commercial buildings – representing roughly 70% of all commercial building floor space – and is the main commercial fuel source in the Northeast, Midwest, and West regions of the U.S (EIA, 2022). In addition to natural gas, nearly 10% of commercial buildings report using propane and fuel oils for space heating, leaving only 25% of all commercial buildings currently utilizing electricity as the primary source for space heating (EIA, 2022). For example, a 2017 study in Minnesota (Schuetter et al., 2017) found that 80% of commercial buildings in Minnesota were served by RTUs, and of those 97% used natural gas for heating with the remaining 3% attributed to electric resistance heat. This represents a much higher use of RTUs and a higher reliance on natural gas for heating in Minnesota than nationally. Minnesota is also a heating dominant region with major cities in climate zones 6A and 7A. While cooling efficiency has improved, heating efficiency for RTUs with gas furnace has stayed around 80%.

Heat pump RTUs (HP RTUs) are an efficient and effective option for commercial sector space conditioning. They are technologically similar to air-conditioning RTUs (AC RTUs) but provide the additional benefit of reverse-cycle HP heating. It is estimated that less than 15% of commercial buildings utilize heat pumps as heating equipment, and when they are in use, heat pumps are more commonly found in the warmer Southern region of the US (Caradonna et al., 2023; EIA, 2022). There is remarkable room for growth in the implementation of heat pump technology in commercial buildings, which offers several benefits including improved energy efficiency, operating cost savings and enhanced HVAC performance as well as a future-proof solution for cost-effective commercial building space conditioning.

The path to next-generation RTUs began with the U.S. Department of Energy (DOE) RTU Challenge (DOE, 2011), which pushed manufacturers to develop units exceeding then-current high-efficiency standards. Field evaluations of these early high-performance units demonstrated seasonal efficiency improvements of 18% to 31% over standard equipment (Wang & Katipamula, 2013). Further, the Advanced RTU Campaign (DOE, 2016) catalyzed market transformation to overcome barriers for high-efficiency RTU solutions, successfully aiding the commercial buildings market adoption of next-generation technologies. However, these early successes also highlighted real-world hurdles, including significant weight increases that required roof reinforcement and complexities in integrating proprietary manufacturer controls with existing Building Automation Systems (BAS) (Wang et al., 2015).

There are notable benefits and barriers to widespread market transformation of commercial heat pump technology. While variable-speed compressors and advanced fans have improved cooling efficiency, cold-climate heating remains the primary frontier for RTU innovation. Conventional air-source heat pumps (ASHPs) historically struggled with capacity degradation and efficiency losses in sub-freezing temperatures. The other barriers to commercial HP RTU adoption in northern regions include pre-existing biases against HP RTUs among contractors and building owners which permeate through the market, leading to low confidence in customer comfort. Contractors worry that heat pump RTU installations will take more time and result in added cost to site due to increased system complexity. Further, as technology is not common in northern region (e.g. Minnesota) product availability and long lead times can be a barrier too, as most distributors do not stock HP RTUs. In addition, most contractors and building owners do not have visibility to sites where HP RTUs are working well in cold northern climates.

DOE launched Commercial Building HVAC Accelerator (DOE, 2024a) to work with stakeholders, from commercial building owners and operators to manufacturers, to accelerate the development and adoption of next-generation RTUs to achieve energy efficient and cost-effective solutions for buildings. As part of the Commercial Building HVAC Accelerator, the Commercial Building HVAC Campaign (DOE, 2024b) aims to help commercial building owners and operators reduce operating costs by increasing the adoption of innovative high efficiency HVAC technologies. Further, through Commercial Building HVAC Technology Challenge (DOE, 2024c), the U.S. Department of Energy is challenging manufacturers to develop innovative RTUs that meet an advanced technology specification to help organizations meet their cost, energy, and reliability needs. Under the Challenge, leading OEMs have developed prototype HP RTUs capable of maintaining high capacity and efficiency at ambient temperatures as low as -10°F. Most manufacturers have already completed the laboratory evaluation phase of the Challenge, showcasing the technical feasibility for cold-climate operation and providing 100% heating capacity at 5°F and over 70% capacity at -10°F.

In a similar effort, MNCEE started the Minnesota Efficient Technology Accelerator (ETA) in 2023, a statewide market transformation program which included the Next Gen RTU initiative to address the barriers to HP RTU adoption. This initiative focused on increasing the adoption of dual-fuel heat pump RTUs as well as RTUs with integrated or bolt on energy recovery ventilators. Next Gen RTUs work with a range of market actors, from building owners and contractors to distributors and OEMs, with an early focus on dual-fuel HP RTU demonstration to gather data on unit performance and showcasing a successful use case for HP RTUs in cold climates. MNCEE also partnered with an OEM to study the performance of a dual-fuel HP RTU in climate zone 4A with a particular focus on energy use, efficiency, and operating mode.

Despite lab-verified performance, the "performance gap" between controlled environments and real-world operations persists. Widespread adoption requires demonstrated performance under diverse real-world operating conditions to de-risk decisions for building portfolio owners, operators, utilities, and other stakeholders. This study provides findings from recent and ongoing field evaluations of commercially available and pre-production prototype HP RTUs (including dual-fuel configuration) developed under the Commercial Building HVAC Technology Challenge, monitored across different US cold climates and commercial building types. These different field evaluations and installation observations address the efficiency and reliability of HP RTUs in cold climates as well as occupant and installer experience. Together this work showcases the benefits and applicability of HP RTUs in cold climates. This paper addresses the core questions below:

- **Energy Performance**: How do next-generation HP RTUs perform in terms of observed energy use and electrical power demand across outdoor temperatures?
- **Heating Performance at Low Outdoor Air Temperature (OAT)**: How does measured COP vary with outdoor temperature, and what operational patterns (e.g., defrost occurrences) are observed in the field?
- **Reliability, Controls and Fuel flexibility**: What reliability issues and control behaviors were observed during field deployment of HP RTUs?
- **Installation, Commissioning and Building Integration**: What installation and commissioning challenges were encountered, and what lessons can inform broader deployment?

Field Evaluation Methodology

Technology Overview and Building Site Characteristics

Next-generation HP RTUs were installed or retrofitted at five buildings sites to evaluate in-field performance. Figure 1 shows site locations overlaid on the IECC climate zone map (PNNL, 2022). The selected climate zones are dominated by AC RTUs with gas furnaces, which use a direct expansion (DX) refrigeration system for cooling and a gas-fired furnace for heating, delivering conditioned air through ductwork in a single packed unit.

HP RTUs serve as an alternative technology evaluated in this study. Unlike AC RTUs, HP RTUs provide both cooling and heating via a DX refrigeration system, using a reversing valve to switch between modes. Because heat pump heating capacity declines with outdoor temperature, HP RTUs include a compressor lockout temperature below which the heat pump cannot operate. To meet the higher building load at low ambient temperature, HP RTUs incorporate backup heat, either electric resistance or gas furnace. When outdoor temperatures fall below a balance point or control logic-defined threshold, the system transitions to backup heating to maintain occupant comfort. Units with a gas furnace backup are known as dual-fuel or hybrid HP RTUs, which can switch between fuel sources based on outdoor air temperature, system efficiency, or utility rate signals, offering flexibility in energy efficiency, cost, and reliability.

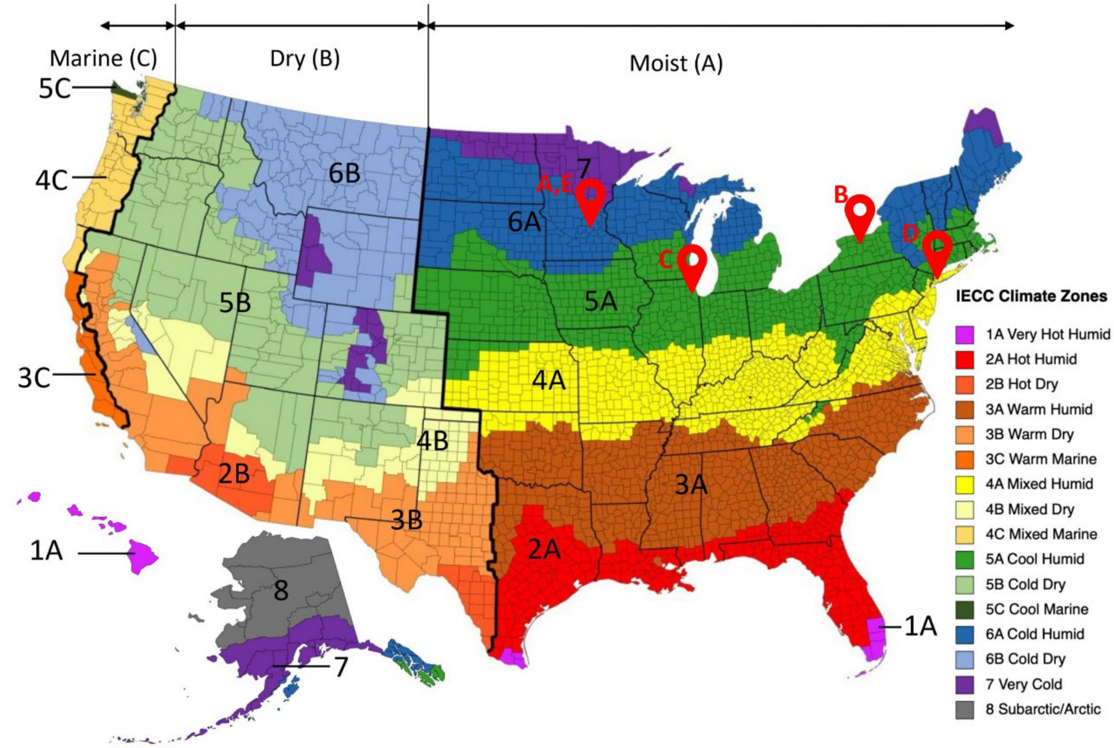

Figure 1. Site Locations on IECC Climate Zone Map

Next-generation HP RTUs evaluated in this field study fall into two categories: production units currently available on the market, and pre-production prototypes developed under DOE's Commercial Building HVAC Technology Challenge (DOE, 2024c). Table 1 summarizes the building site characteristics, total number of RTUs serving each building, and the number of next-generation units installed at each site. Sites B and C hosted prototype Challenge units, while the remaining sites evaluated commercially available next-generation HP RTUs. Sites were selected across cold climate regions, where low ambient temperatures present the greatest technical barriers for air-source heat pumps. Table 2 details the HP RTUs installed or retrofitted at each site, including cooling and heating capacity, backup heat type and capacity, compressor control type, lockout temperatures, and whether the unit is pre-production prototype. Table 2 also indicates whether backup heat can operate simultaneously with the compressor. Parallel operation allows the system to supplement heat pump output at low ambient temperatures where compressor capacity alone cannot meet building load. Unit sizes, control configurations, and lockout temperatures (the outdoor temperature at which the system fully transitions to backup heat) varied considerably across sites, the latter ranging from -15°F to 35°F. The range of lockout temperatures demonstrates how various HP RTUs perform under different conditions, showcasing the diversity in unit capabilities. The goal of this study is not to compare individual units, but to illustrate the breadth of performance across a wide spectrum of designs.

Table 1. Field Study Building Site Characteristics

Site	Location	Climate Zone	Building Type	Total number of RTUs	Field Study HP RTUs	Monitoring Period
A	Chaska, MN	6A	Retail Store	33	3	1 year
B	Penfield, NY	5A	Retail Store	22	1	3 months
C	Bensenville, IL	5A	Warehouse Office	4	1	3 months
D	Queens, NY	4A	Office building	6	2	1 year
E	Minneapolis, MN	6A	Office building	23	1	5 months

Table 2. Next-generation Heat Pump RTUs Info at different Building Sites

Site ID	Unit ID	Backup Heat (Simultaneous Operation)	Cooling Capacity [MBH]	HP Heating Capacity [MBH]	Compressor Control	Backup Heating Capacity [MBH]	Lockout Temperature	Pre-Production Prototype
A	RTU -8	Gas Furnace (No)	108	97	Variable	168	0°F	No
A	RTU -12	Gas Furnace (No)	120	114	3-stage	177	35°F	No
A	RTU -16	Gas Furnace (No)	114	102	2-stage	194	35°F	No
B	RTU -11	Gas Furnace (Yes)	120	156	Variable	200	-15°F	Yes
C	RTU -1	Electric (Yes)	142	312	Variable	245	-15°F	Yes
D	RTU -2F	Gas Furnace (Yes)	183.7	160	Variable	240	0°F	No
D	RTU -3F	Gas Furnace (Yes)	183.7	160	Variable	240	0°F	No
E	RTU -11	Electric (Yes)	53.5	52.5	2-stage	81.9	-10°F	No

Site A and B are retail stores with grocery section located in climate zones 6A and 5A, respectively, with HP RTUs serving the sales floor. At site A, three existing AC RTUs with gas furnaces were retrofitted with market-available dual-fuel HP RTUs from three different manufacturers. The retrofit units had different footprints than the existing units, which required custom curb adapters for each installation. Outside air dampers on all three units were kept closed throughout the study, operating them as recirculation units only. Site C is office space for a warehouse in climate zone 5A. Sites B and C host pre-production HP RTUs developed under the Challenge.

Site D is a four-story office building in climate zone 4A where two AC RTUs with gas furnaces were retrofitted with variable-speed dual-fuel HP RTUs. The replacements did not require infrastructure upgrades, as the structural capacity of the roof and the existing electrical service were compatible with the new units. The other four units serving the building have already been upgraded to dual-fuel HP RTUs and are shown in Figure 2(A). Site E is an office building that serves as headquarters for a furniture company in climate zone 6A. The building features rooftop solar panels that produce 120% of expected electrical consumption, which factored into the owner's decision to install an all-electric HP RTU, as solar generation offsets operating costs (Figure 2(B)). The RTU serves the building’s gym and brings in outside air to ventilate the space. It supports simultaneous operation of the compressor and backup electric resistance. The primary mechanical heating heat would attempt to satisfy the space setpoint, but the backup heat would engage after a user-adjustable delay if the setpoint remains unmet.

(A) Site D (B) Site E

Figure 2. (A) Site D dual-fuel HP RTUs with monitoring equipment installed (B) Site E All-electric heat pump RTU with solar panels in the background

Instrumentation & Data Acquisition

Each unit was instrumented to evaluate field performance using a combination of direct sensors and control status data sourced either directly from the unit or building automation system (BAS). Instrumentation varied somewhat across sites due to differences in building and unit configurations. Figure 3 shows the key instrumentation installed on a dual-fuel HP RTU to measure air-side capacity, electric power consumption, gas usage, and ambient conditions. Table 3 summarizes the key measurements needed by category or performance metric.

For site A, all sensors except the weather station were connected to the BAS, which also served as the data acquisition system. A standalone data acquisition system with a cellular modem was installed to collect data from the rooftop weather station. Unit controls, onboard sensors, and control signals were integrated with the store BAS via BACnet. At sites B and C, all sensors including the weather station were connected to a standalone data acquisition system, with existing BAS points leveraged where possible to improve data reliability. Across all sites, data were logged at 1-minute intervals and transmitted to a secure cloud-based platform for storage and analysis.

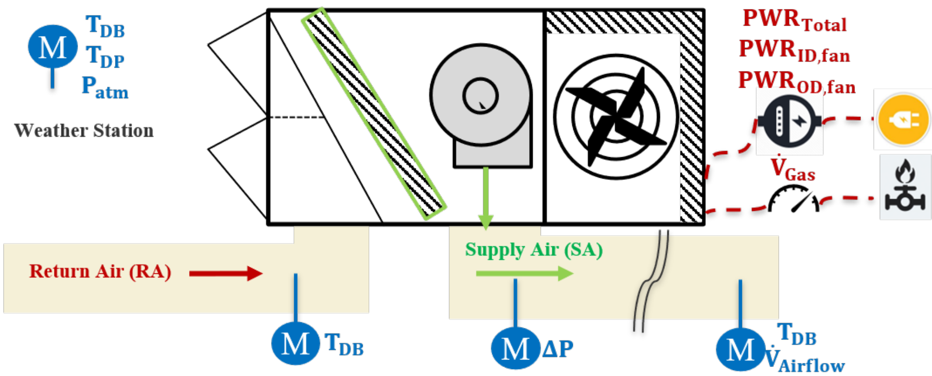

Figure 3. Schematic showing key instrumentation to measure dual-fuel system performance

Table 3. List of Key Measurements in each Category

Category/Performance Metrics	Measurements
Capacity	Supply and return air temperature Airflow External static pressure
Electrical Power	Total RTU power Indoor fan and outdoor fan power Backup heat (if electrical)
Gas Usage	Natural gas flow rate to backup heating modules
Outdoor Conditions	Outdoor air dry-bulb temperature Dew point temperature Barometric pressure
Runtime & Staging	Compressor and gas heat runtime Staging levels Defrost mode Fuel-switching events (Unit onboard controls or data from BAS)
Controls	Setpoints Mode changes Occupancy schedules, Control signals (Unit onboard controls or BAS Data)
Occupant Comfort	Zone air temperature

At sites D and E, two independent data loggers were deployed for each RTU: one measuring overall electrical input power and the other measuring air temperatures and actuator statuses. Only dry bulb temperatures were collected at these sites, so analysis was limited to sensible capacity during the heating season. Both loggers transmitted data logged at 1-second intervals via cellular modem to a server for processing and analysis. Monitoring was completely independent of unit controls, system controls, or BAS, so time-series data were labeled with operating modes according to rules based on combinations of actuator states.

Accurate airflow measurement is critical for evaluating the air-side thermal performance of HVAC systems. Airflow was characterized by temporarily installing TrueFlow airflow plates and testing each unit across multiple fan speeds. Measured airflow rates were then correlated to supply fan current, power, or fan speed in revolutions per minute (RPM), depending on available measurements, to estimate airflow throughout the monitoring period. This approach facilitated description of RTU performance in terms of operating modes, delivered capacity, and COP. More details can be found in Baumgardner et al. (2025) and CEE (2025). Further, methodological limitation affects cooling COP comparability across sites: Sites B and C were equipped with full psychrometric instrumentation, whereas Sites A, D, and E collected only dry bulb temperature data, excluding latent cooling effects from the analysis. This omission biases cooling COP calculations at these locations. It should be emphasized that the study was designed primarily to evaluate heating performance across diverse site and not to compare different unit performance between sites.

Measured Field Performance

To demonstrate the comprehensive operation of HP RTUs, Figure 4Figure 4 through Figure 7 illustrate the distribution of RTU operating modes across ambient temperature bins along with total time in each bin at different sites. These figures are key for field characterization of unit operational behavior, rather than direct unit-to-unit comparison. The motivation for this analysis is to understand how RTU controls respond to varying outdoor conditions and occupancy schedules, switching between heating, cooling, supplemental heat, and fan-only operation in real-world settings.

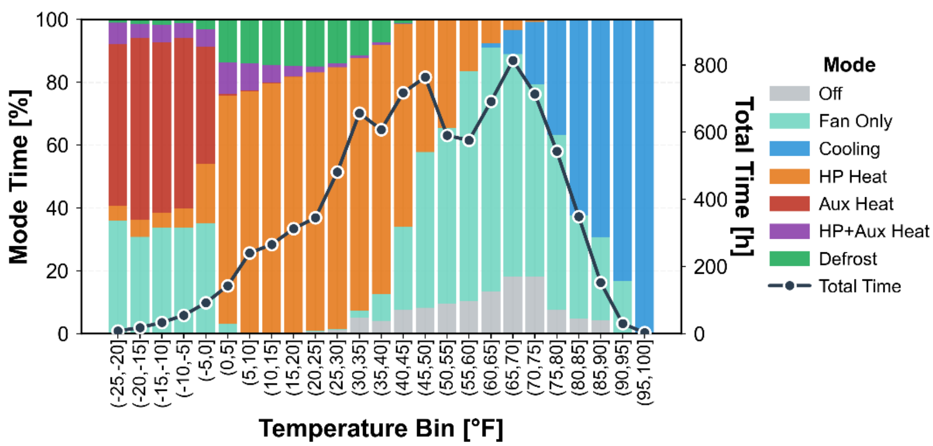

Figure 4. Percent of time in each mode at ambient temperature bins for Site A RTU-8

Figure 4 (Site A) displays RTU-8's mode distribution, reflecting both heating and cooling demand, influenced by ambient temperature, setpoints and occupancy schedules. In shoulder months, units show significant Fan Only operation, as OAT decreases, fraction of HP and HP + Aux increases, and below lockout temperature 0°F demand is mainly met by Auxiliary gas backup heat. Off mode is mainly driven by occupancy schedule in cooling period where ZAT SP is raised. Figure 5 and Figure 7 (Sites B and E) focus on heating modes, as data collection was only during heating season. At Site B, unit operated in heat pump mode till the minimum observed OAT which was above the lockout temperature. Also at low OAT, additional load was met by supplemental heat running simultaneously to heat pump when the COP remained above

1, illustrating a lack of economic incentive to disable the heat pump and confirming the operational flexibility of these RTUs. Figure 6 (Site E) further details mode distributions for both cooling and heating, reinforcing the trend that as outdoor temperature falls, heating modes dominate. This unit was able to meet the building heating with heat pump only in observed OAT range. It is important to note that all these unit showed heat pump operation well below the typical lockout temperature of 35°F.

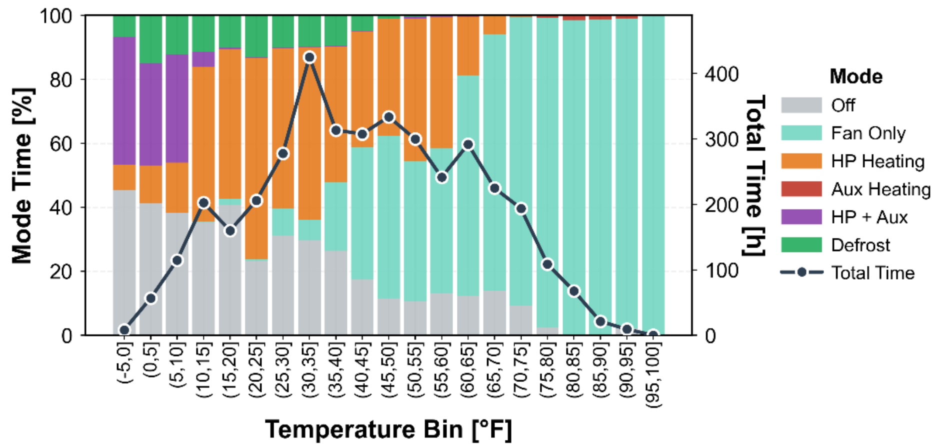

Figure 5. Percent of time in each mode at ambient temperature bins for Site B RTU-1

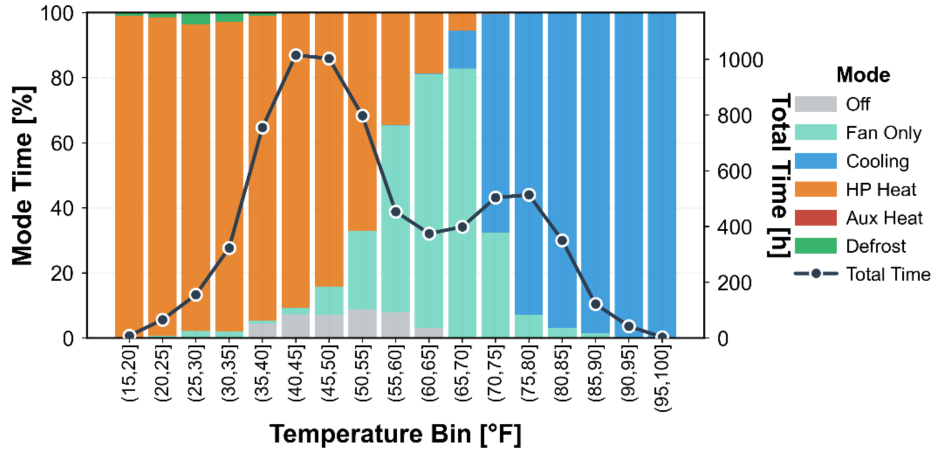

Figure 6. Percent of time in each mode at ambient temperature bins for Site D RTU-2F

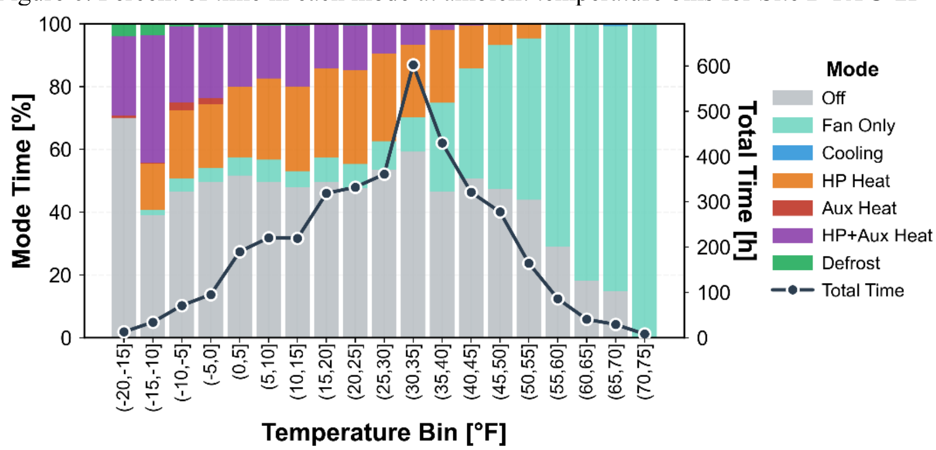

Figure 7. Percent of time in each mode at different ambient temperature bins for Site E RTU-11

Figure 8 shows the average power across operating modes over a wide range of outdoor temperature bins for one RTU 2F at site D. At the coldest observed temperatures (15~30°F), the electrical power required to operate the heat pump was about double the power required at milder outdoor conditions (60~75°F), underscoring the value of fuel flexibility inherent in dual-fuel HP RTUs. Switching to gas heating at extremely cold temperatures can meaningfully reduce electrical demand charges.

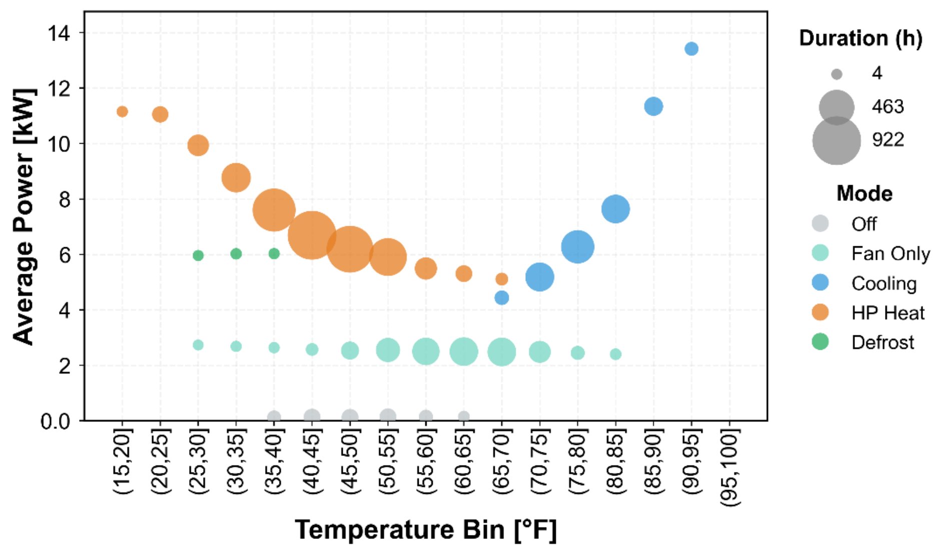

Figure 8. Average power by mode at different ambient temperature bins for Site D RTU 2F

Figure 9 shows the average COP and hours during heat pump operation different temperature bins for Site B RTU, demonstrating strong COP retention at low ambient temperatures, with the unit maintaining a COP near 1.7 even in the 0–10°F bin. As outdoor temperature increases, COP rises predictably, exceeding 2.0 by approximately 30°F and reaching above 3.0 in bins warmer than 50°F. This COP retention at low temperatures, indicates robust performance relative to conventional expectations for air-source heat pumps operating in cold-climate applications.

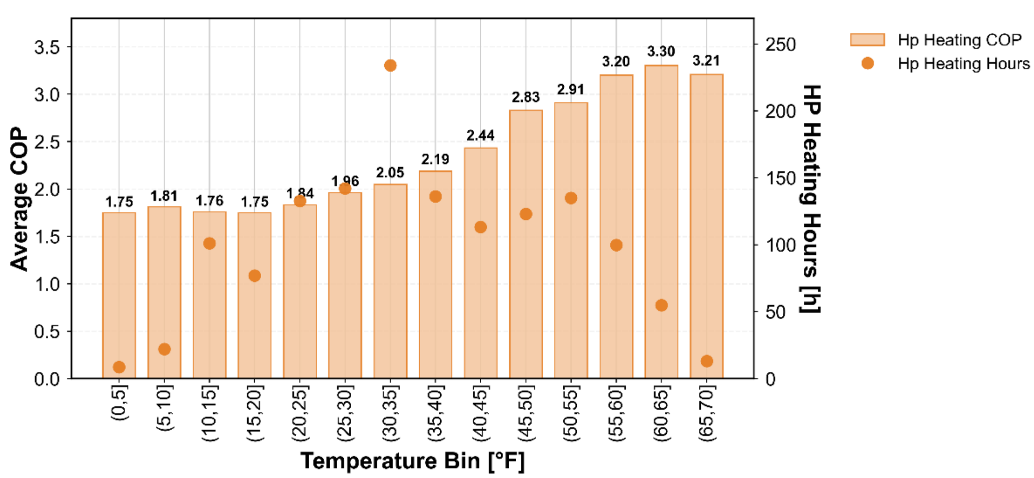

Figure 9. Average COP and heat pump operating hours at different ambient temperature bins for Site B RTU-1

Building on the mode-distribution and performance trends shown above, Figure 10 further quantifies how these operational patterns translate into temperature-dependent energy use. At Site A, heat pump heating is the dominant contributor in the 5-50°F range, confirming that the unit relies primarily on mechanical heating through most of the heating season. As outdoor temperatures fall below approximately 0°F, auxiliary gas heat begins to supply a larger share of total energy. During simultaneous operation above lockout temperature, auxiliary heat usage is mainly during defrost and just after defrosting in HP+Aux mode. At warmer temperatures, the energy distribution shifts toward cooling and fan-only operation. Together, this mode-resolved energy trend provide additional context for interpreting COP, cycling behavior, and low-temperature performance across the full range of field-observed conditions.

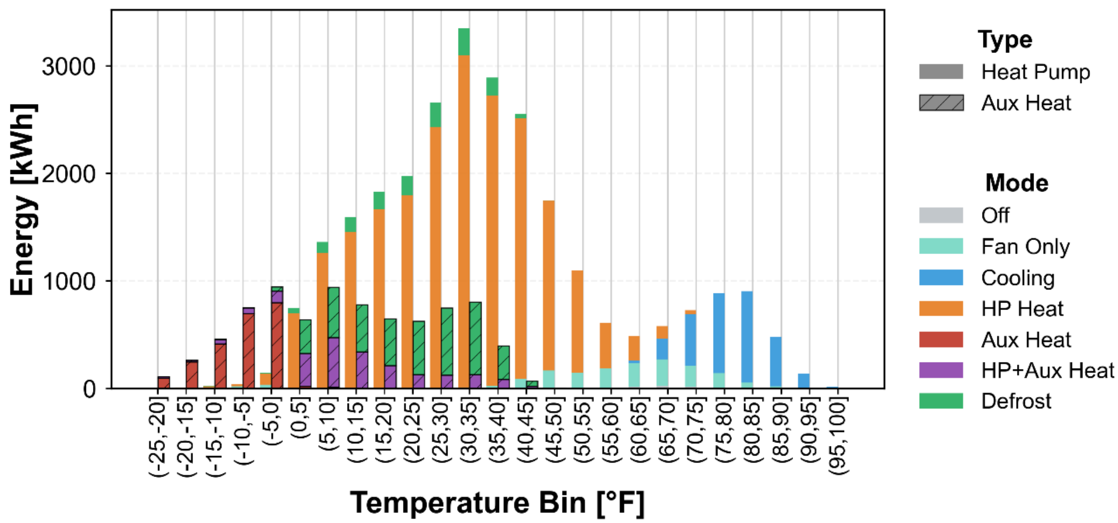

Figure 10. Heat pump and auxiliary backup heat energy use by operating mode across outdoor temperature bins for Site A RTU-8

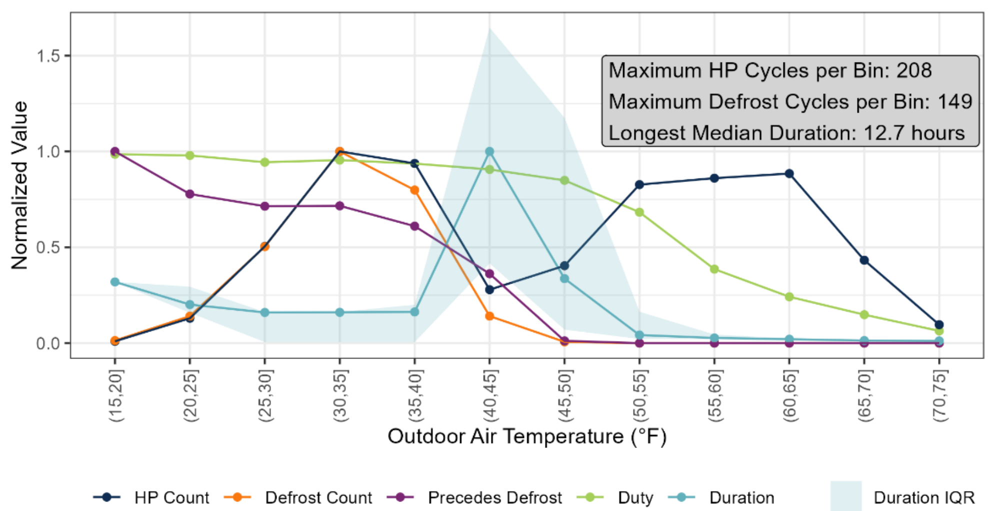

Figure 11. Heating-season cycling metrics versus outdoor air temperature for Site D RTU-2F (cycle count, duty, duration, defrost incidence)

Extending the operational analysis to cycling behavior, Figure 11 characterizes heating-season heat pump cycles by outdoor temperature, using the study's actuator-based definition of a "heat pump cycle" (supply fan **on**, compressor **on**, gas valve **off**, reversing valve directing hot gas to the indoor coil). "Precedes defrost" quantifies the fraction of cycles that terminate because a defrost is initiated, while "defrost count" indicates the frequency of defrost starts. In the 40–45°F bin, cycle duration and duty peak, with minimal defrost incidence, suggesting an alignment between zone heating load and compressor modulation that allows extended, nearly continuous operation without space overheating or frost accumulation. At lower temperatures (< 35°F), defrost-related terminations increase and median cycle durations shorten, reflecting both rising load and coil frost formation; at higher temperatures (> 55°F), duty and cycle counts fall as heating demand diminishes.

Dual-fuel heat pump RTUs provide a dependable and efficient heating solution for commercial buildings. At Site E, an energy analysis showed that the dual-fuel heat pump RTU consumed 33% less total energy than a standard RTU equipped with a gas furnace. In addition, the unit reduced peak electrical demand by an average of 18 kW per month compared to an all-electric heat pump, offering meaningful savings during periods when utility rates are highest. Beyond energy performance, dual-fuel RTUs offer operational flexibility by enabling fuel switching between electric heat pump operation and gas-furnace backup. This capability allows the system to maximize heat pump efficiency at milder outdoor temperatures and transition to gas heating when ambient conditions drive higher electrical consumption or when gas heating is more cost-effective. Having two available heating sources enhances reliability and ensures that comfort is maintained throughout the heating season, particularly in cold-climate applications.

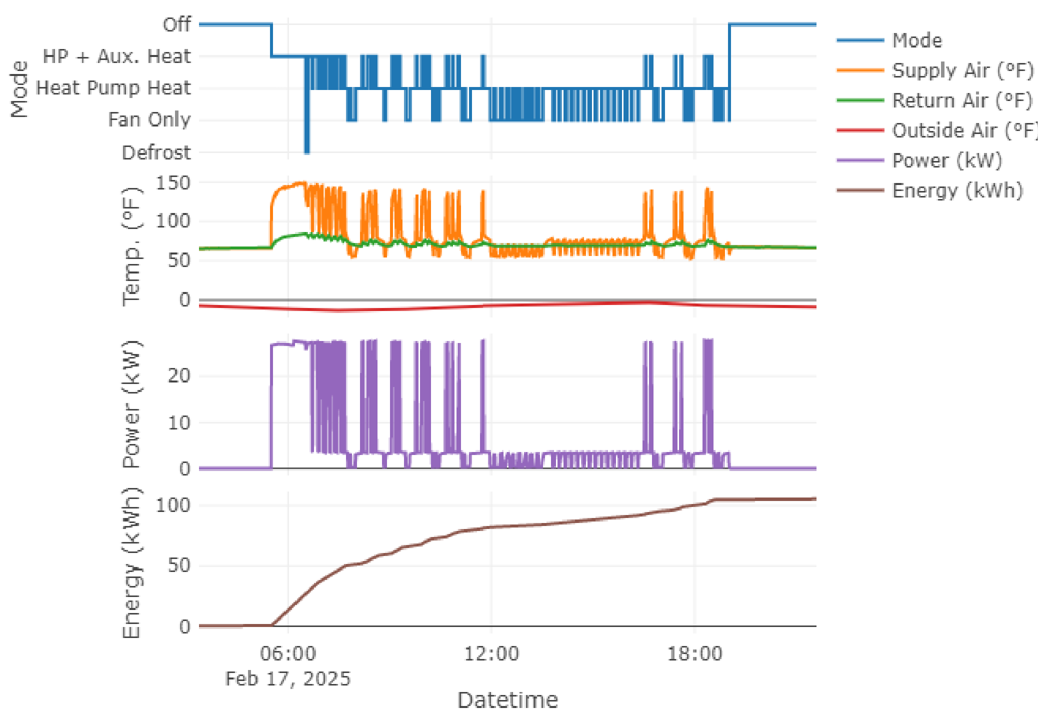

Figure 12. Timeseries of the Cumulative Energy Consumption for Site E (Baumgardner et al., 2025)

The all-electric heat pump RTU at site E operated with a nighttime temperature setback of a few degrees, which generated a substantial morning heating load when transitioning back to the occupied setpoint (Figure 12). During periods of low ambient temperature in February, the unit did not have sufficient heat pump capacity to meet this warm-up demand and therefore operated in simultaneous mode, engaging both mechanical heating and backup electric resistance until the zone temperature recovered. As a result, the unit consumed approximately 75% of its total daily energy by midday during these recovery periods, and its COP decreased from 1.6 (heat pump only) to 1.4 (heat pump plus resistance heat). To mitigate large morning energy spikes, follow-on research and field evaluations are underway to assess performance with the overnight setback removed.

Installation and Operational Observations

Beyond the performance metrics presented above, field deployment yielded several operational insights. During the commissioning phase, a number of issues were encountered that, while not directly related to the heat pump functionality, reflect broader challenges common in commercial HVAC installations.

- **Weight and Curb Adapter**: Installation of HP RTUs often requires careful consideration of unit weight and compatibility with existing rooftop curbs. In the field, some sites needed to install curb adapters to accommodate the new heat pump units, as the base dimensions and weight differed from the original RTUs. This can add complexity, time, and cost to retrofit projects, and should be anticipated during project planning. Not every installation will require a curb adapter, but site assessments should include a check for potential structural modifications to ensure proper fit and support.
- **Control Set up and Integration**: Integrating HP RTUs into existing building control systems can present challenges, especially when dialing in optimal settings for both comfort and efficiency. Commissioning often involves updating control firmware, configuring novel defrost algorithms, and ensuring seamless communication between new units and legacy systems. The transition may require additional troubleshooting or coordination with HVAC partners to align controls with site-specific operational goals. Proper integration is crucial for maximizing heat pump performance and occupant comfort and may require iterative adjustments post-installation.
- **Incorrect Equipment Specifications:** At site A, an RTU was delivered with a voltage rating that did not match the building owner's specifications. This mismatch required field modifications, including rewiring the power supply from the breaker panel to accommodate the unit — a time-consuming and avoidable issue stemming from gaps in manufacturer-to-contractor communication. More broadly, electrical infrastructure upgrades can be costly when retrofitted units have higher electrical requirements than the units they replace.
- **Control System Failures:** An RTU at site A experienced startup failure due to a faulty control board, which needed to be replaced by the manufacturer. Control board malfunctions are a common commissioning hurdle, often caused by factory defects or shipping damage.
- **Software and Algorithm Updates:** Some RTUs required control firmware updates to implement novel defrost algorithms. Software-related delays are increasingly common as manufacturers integrate more advanced, but less field-tested, control strategies.
- **Out-of-the-Box Functionality:** At site A, only one manufacturer delivered a unit that functioned as expected upon installation without requiring significant troubleshooting or rework. This underscores inconsistent quality control and the lack of standardized commissioning readiness checks across manufacturers.
- **Continued Maintenance on Existing Systems**: At site E, interior vents with significant debris buildup were not cleaned prior to RTU installation, reducing system airflow and heat pump efficiency until remediated.

- **User/Occupant Feedback**: The site manager at Site E reported "...having a HVAC partner that is aligned on your company goals is a crucial part in this, but once the product was selected there were little to no issues with conversion from the old unit to the new heat pump. While there were no significant roadblocks with install, we did identify that installing a curb adaptor on the roof was necessary for this project. Moving forward we now expect this ahead of installations but understand it may not apply to every install. Once the heat pump was installed, we had to dial in our controls, but that is the case with any new installation." occupants at sites D and E reported no change in comfort compared to previous RTUs. Site E owners expressed satisfaction with unit performance and plans to expand HP RTU installations at their facilities after the completion of the field studies, while site D had already retrofitted its remaining RTUs to HP RTUs. Similarly, Site A and B owners are currently deciding which RTU configuration works best for their retrofits.

These challenges are representative of typical issues in the commercial HVAC market. They highlight the importance of thorough site assessments, effective communication between manufacturers and contractors, and robust commissioning practices to ensure successful retrofits and optimal system performance. Addressing these operational hurdles – such as equipment compatibility, control integration, and site preparation – can streamline installation processes, minimize delays, and improve satisfaction for both building owners and occupants. As heat pump RTUs become more prevalent, proactive planning and collaboration among stakeholders will be key to overcoming common barriers and achieving reliable, efficient outcomes in commercial HVAC projects.

Conclusions and Discussion

This multi-site field evaluation confirms that next-generation heat pump rooftop units (HP RTUs) can significantly reduce energy use and peak electrical demand in cold-climate commercial buildings while maintaining occupant comfort. At Site E, for example, a dual-fuel HP RTU consumed roughly 33% less total energy than a comparable standard gas RTU and reduced monthly peak electrical demand by approximately 18 kW relative to an all-electric heat pump. These results underscore the strong potential of advanced HP RTUs – particularly dual-fuel configurations that shift to gas heating during the coldest conditions – to deliver high efficiency while mitigating winter peak loads. Realizing these benefits in practice, however, depends on careful control configuration and robust commissioning, as field operation introduces complexities not captured in laboratory testing.

Across the five sites, heat pump performance generally aligned with expectations but was moderated by real-world operating conditions. Units provided reliable heating at subfreezing outdoor temperatures, with one prototype maintaining a COP near 1.7 in the 0–10 °F range and all units operating in heat pump mode to or below their respective lockout temperatures. Efficiency increased rapidly at milder conditions, reaching COP values above 3.0, but was periodically reduced by factors such as on/off cycling at low loads, defrosting in the 25–35 °F range, and engagement of backup heat during extreme cold or high transient loads. At one site, recovery from an overnight thermostat setback led an all-electric unit to briefly operate with both the compressor and resistance heat, lowering the effective COP from approximately 1.6 to 1.4 during the warm-up period. These observations highlight how cycling, defrost, and supplemental heating can temporarily suppress efficiency even in high-performance systems, reinforcing the importance of control strategies that minimize unnecessary backup heat use and avoid sharp morning recovery demands.

Field deployment also revealed practical challenges that are broadly relevant to commercial HVAC retrofits. Equipment compatibility and site preparation were recurring considerations, and controls integration emerged as a key determinant of successful performance. Several units required firmware updates or control board replacements during startup, and one unit was delivered with an incorrect voltage rating that required on-site electrical modifications. These experiences emphasize the need for rigorous pre-installation verification, clear communication between manufacturers and contractors, and standardized commissioning protocols. Addressing such issues proactively can reduce installation delays, streamline retrofits, and help ensure that systems operate as intended.

The implications of these findings extend to all major stakeholders. Building owners and facility managers can take confidence that modern HP RTUs can deliver substantial energy savings without compromising comfort. Notably, no comfort complaints were reported at monitored sites, and successful pilot installations have prompted some owners to plan broader HP RTU deployments. For manufacturers and HVAC contractors, the results point to opportunities to strengthen quality control, improve factory commissioning, and provide clearer guidance for field setup and control tuning. Utilities and energy program designers should also note the meaningful peak-demand reductions enabled by dual-fuel systems, which make next-generation HP RTUs attractive candidates for incentive programs and grid reliability strategies in cold climates.

Finally, this study's scope and limitations should be acknowledged. The results are based on a small number of RTUs across several sites, including two prototypes monitored for only a few months, and primarily reflect heating-season performance rather than multi-year operation. Differences in instrumentation also limited the ability to compare cooling performance across all sites. Rather than ranking individual products, the intent was to characterize the range of achievable performance under real operating conditions. Ongoing research is expanding monitoring duration and site diversity and is evaluating refined control approaches – such as reducing or eliminating nighttime setbacks – to further mitigate peak loads and efficiency losses. Together with continued collaboration among building owners, manufacturers, contractors, and utilities, these efforts will be critical to translating demonstrated field benefits into broader adoption of next-generation HP RTUs in cold-climate commercial buildings.

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AI-assisted Tools: Disclosures and Responsibility

AI-assisted tools used: Gemini and GitHub Copilot.
Used for: Data analysis, copyediting.
Extent: Light editing, Checking and modifying code for data analysis.
Human review: The authors reviewed and verified all content, calculations, and citations.