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Decarbonizing Campus Heating: Preliminary field Performance data of a Subcritical R744 Heat Pump for Ambient District Energy System

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Abstract

This applied research paper presents the first field-performance evaluation of a 1.5 MW reversible R744 (CO_2) air-source heat pump (ASHP) installed at the University of British Columbia Okanagan (UBCO)—the largest known CO_2 ASHP deployed for a district energy application in North America. The system is integrated into UBCO's ambient low-temperature district energy system (LDES), a bidirectional thermal network operating between 8 °C and 25 °C that supports energy sharing, high-efficiency nodal heat pumps, and campus-wide decarbonization.
Building on earlier theoretical studies, this work analyzes preliminary operating data collected during a one-week period in November shortly after system commissioning. The analysis evaluates subcritical heating performance, part-load behavior, and the control strategies used to optimize compressor staging, fan modulation, and pump operation. Measured COP values ranged from 3.7 to 4.3 under mild winter conditions, consistent with prior modeling and supporting an expected seasonal COP of approximately 3.5. Over the one-week period, the ASHP delivered more than 55,000 kWh of heat to the LDES, corresponding to approximately 25 t of CO_2 emissions avoided and nearly 6,000 m³ of natural gas savings relative to boiler-based operation.
Commissioning improvements—including optimized fan and pump modulation, refined staging logic, and stable defrost management—significantly enhanced part-load efficiency and operational stability. These early results demonstrate the practical viability of large-scale CO_2 ASHPs for ambient district energy networks and highlight their potential as scalable, low-carbon solutions for cold-climate district heating decarbonization.

Keywords: CO_2 air source heat pump, District energy system, Decarbonization;

1. Introduction

The decarbonization of district heating systems has emerged as a key strategy for reducing greenhouse gas emissions from the built environment. As cities transition away from fossil fuels, centralized heat pumps—particularly systems integrated into low-temperature thermal networks—offer a scalable pathway for electrification and improved energy efficiency. Ambient low-temperature district energy systems (LDES), which operate close to ground or outdoor air temperature, have gained increasing attention due to their ability to support bidirectional heat flow, integrate diverse thermal resources, and significantly reduce system-level thermal losses. By maintaining loop temperatures typically between 8 °C and 25 °C, LDES enable individual buildings to use high-efficiency nodal heat pumps while simultaneously sharing excess heating or cooling across the network.

Natural refrigerant heat pumps, and carbon dioxide (R744) systems in particular, have shown strong potential in LDES applications. CO_2 heat pumps operate efficiently at low return temperatures, exhibit favorable performance under large lift conditions, and avoid the environmental impacts associated with synthetic refrigerants such as Hydrofluorocarbons (HFCs) and Hydrofluoroolefins (HFOs), including Per- and

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Polyfluoroalkyl Substances (PFAS) and Trifluoroacetic Acid (TFA) formation. Previous theoretical work conducted for the University of British Columbia Okanagan (UBCO) campus demonstrated that a subcritical R744 air-source heat pump (ASHP) could supply more than 98% of the annual heating demand of the campus LDES while achieving an annual average COP of approximately 3.5 [1]. Additional analysis comparing R744 with leading synthetic-refrigerant ASHPs has shown that CO_2 systems outperform alternatives in applications where return temperatures remain below 49 °C or where large temperature differentials are achievable [2].

Building on these earlier studies, the present paper provides the first field-performance evaluation of the 1.5 MW reversible R744 ASHP installed at the UBCO central energy plant—the largest known CO_2 ASHP deployed for a district energy system in North America. The system was commissioned recently and will complete its first full year of heating and cooling operation in 2025-2026. This paper presents an overview of the UBCO district energy system, describes the configuration and operation of the R744 heat pump, and analyzes measured hourly performance, part-load behavior, and control strategies.

2. UBCO District Energy System

The University of British Columbia Okanagan campus operates a hybrid district energy network consisting of two interconnected thermal loops (Figure 1):

1. A medium-temperature district energy system (MDES) supplying 80 °C water to legacy buildings, and
2. An ambient low-temperature district energy system (LDES) supplying water between 8 °C and 25 °C to most academic buildings on campus.

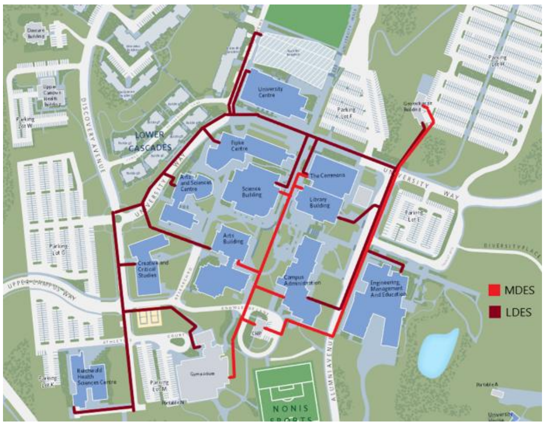

Figure 1: UBCO district energy system

The MDES is served primarily by natural-gas boilers and distributes heat to five older buildings with high-temperature hydronic systems. The LDES, introduced as part of UBCO's long-term decarbonization strategy, is designed to support energy sharing between buildings and maximize the use of heat pumps. Most new buildings on campus are equipped with distributed water-to-water heat pumps that extract or reject heat to the LDES depending on heating or cooling needs.

The LDES is connected to several thermal resources, including open-loop geothermal standing column wells and fluid coolers, which provide baseline heating and cooling capacity.

However, without active conditioning, seasonal drift can occur in ambient loops, particularly during prolonged heating periods where heat extraction exceeds natural recharge. To stabilize loop temperatures and reduce reliance on gas boilers, UBCO installed a central R744 ASHP—manufactured in Canada by Vitalis Equipment Technology Inc.—capable of both heating and cooling the LDES.

The heat pump provides base heating to the LDES during winter months while the boilers remain available for peak or backup operation. In summer, the heat pump operates in transcritical cooling mode when fluid coolers and geothermal sources cannot meet the entire cooling load. This configuration increases operational flexibility, reduces natural gas consumption, and significantly improves overall system efficiency due to the compatibility between CO_2 cycle characteristics and the low operating temperatures of the LDES.

By integrating a large reversible ASHP directly into the ambient loop, UBCO achieves a district-wide heat-sharing environment in which buildings simultaneously act as sources and sinks of thermal energy. The approach supports UBCO's campus-wide decarbonization goals and provides a replicable model for other institutions seeking cost-effective, low-carbon district energy solutions

3. UBCO Air Source Heat Pump

The ASHP installed at UBCO is a 1.5 MW nominal capacity, reversible R744 system operating in subcritical mode for heating and transcritical mode for cooling. The unit consists of two fully independent refrigerant circuits, each comprising:

- A compressor rack with five semi-hermetic CO_2 compressors,

- Three 300 kW air heat exchanger (AHX) modules with variable-speed fans,
- CO_2-to-water plate heat exchangers connected to the LDES

These three main elements are shown in Figure 2: the LDES heat exchangers are installed inside the building, while the compressor rack is housed in an enclosure 30 feet away from the air heat exchangers.

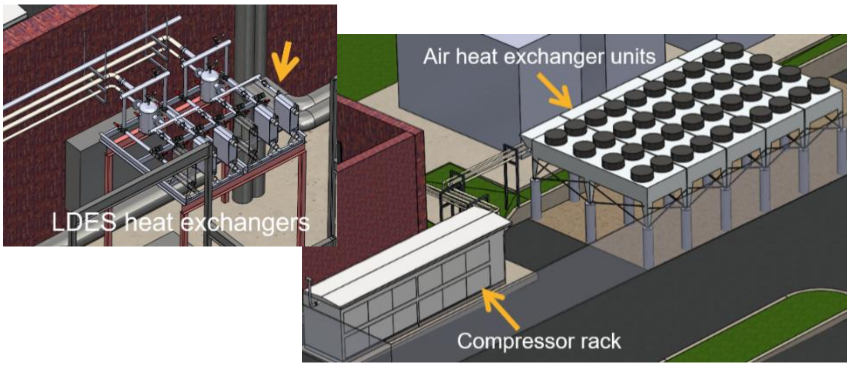

Figure 2: Three main elements of the UBCO ASHP

3.1. Heating Mode Operation

In heating mode, the R744 cycle operates fully subcritical due to the low LDES supply temperature (20 °C saturation discharge). CO_2 vapor is compressed to the desired discharge pressure, desuperheated slightly through the IHX to add superheat to the suction gas and then condensed in the CO_2-to-water heat exchangers to deliver heat to the ambient loop. After expansion through the expansion valves installed at each AHX coil, the refrigerant enters the AHX, where it absorbs heat from the outdoor air before returning to the compressor suction. The following process flow diagram along with P-h diagram for each mode presents the described process.

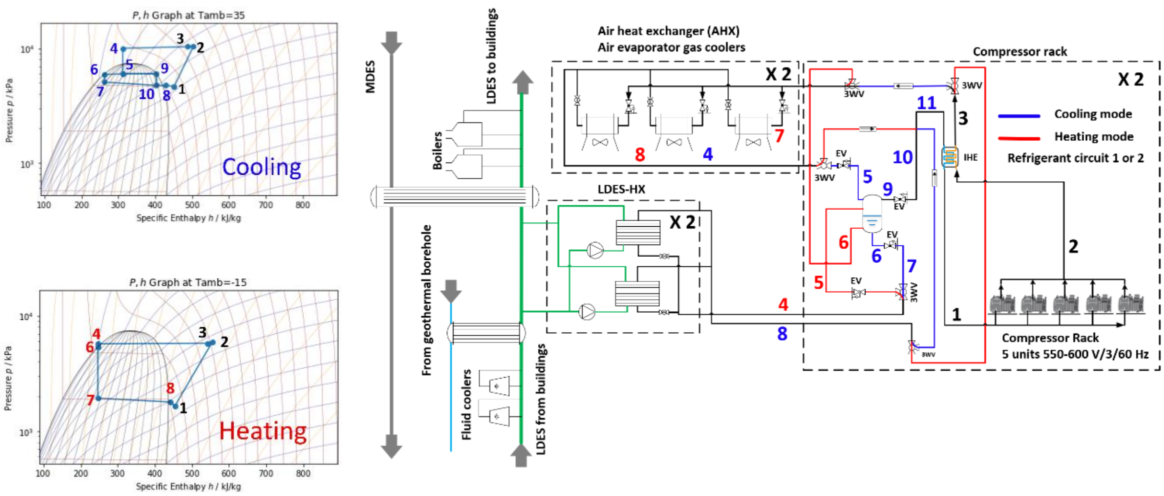

Figure 3: System PFD and P-h diagrams of cooling and heating mode of operation

The subcritical regime provides significant performance benefits at the low supply temperatures characteristic of LDES. At outdoor dry-bulb temperatures between –5 °C and 5 °C—where approximately 70% of annual LDES heating demand occurs—the unit achieves COP values between 3.0 and 4.7 under part-load operation. Each circuit can operate independently, and compressors are staged to match load while maintaining appropriate mass flow, refrigerant velocities, and fan operation.

3.2. Cooling Mode Operation

During summer operation, the heat pump operates in transcritical mode as shown in the P-h diagram in Figure 3. The AHX functions as a gas cooler, rejecting heat to the ambient air. The CO_2-to-water heat exchangers then cool the LDES, enabling building-level heat pumps to operate at high efficiency during peak cooling conditions. The system is optimized using discharge pressure controls and fan modulation strategies to maximize COP under varying ambient temperatures.

At 30 °C outdoor temperature, the system delivers approximately 1.2 MW of cooling capacity with a COP of around 2.9 at partial compressor staging. The gas cooler outlet temperature and optimum discharge pressure are continuously controlled to balance efficiency and capacity.

3.3. System Control and Part Load Optimization

One of the defining features of the UBCO ASHP is its advanced part-load management. The control algorithms leverage:

- Pre-calculated optimal fan speeds based on ambient conditions and required heat exchange,
- Pre-calculated pump speeds coordinated with compressor staging,
- Dynamic switching between one or two refrigerant circuits depending on load, and
- Real-time performance monitoring for improved tuning over the operating season.

Preliminary measured field data demonstrate that fan electricity consumption plays a critical role in determining system COP, particularly during spring and fall shoulder seasons when the heat pump operates at reduced capacity. The optimized control strategy implemented during commissioning significantly improved hourly performance and system responsiveness.

4. System operation data

The system is currently commissioned in heating mode with limited hours of operation in November. We hope that more heating mode operation data will be available when presenting the paper during the conference. Figure 4 shows the three elements previously described.

Figure 4: Installed ASHP at UBCO, Kelowna, BC, Canada

4.1. Winter mode operation

In this mode, the ASHP is prioritized and used for heating and is supplemented by gas boilers if the delivered heating capacity is insufficient. The source side of the heat pump is connected to air heat exchangers, and outdoor air is the only heat source used for the heat pump. During ASHP operation, the geothermal boreholes are not used.

November 12, 2025: A full 24-hour operation under mild winter conditions was recorded, during which the ambient temperature ranged from 5 °C to 9 °C. The overall COP—including the compressor rack, AHX fans, and the LDES water pumps electricity consumptions—varied between 3.7 and 4.3. The COP drop observed at 2 p.m. was caused by a short heat pump shutdown due to the LDES supply temperature exceeding its upper limit.

UBCO calculates COP using a one-hour average heating capacity divided by the one-hour average total electrical consumption of all equipment. As a result, instantaneous performance changes are not reflected in the dataset presented earlier; however, the method provides an accurate representation of the heat pump's hourly performance.

During this period, only one refrigerant circuit was active, with a maximum of 2.5 compressors operating at the peak condition of 650 kW at 9 a.m. on November 12. As shown in the figures below, during the ramp-up in capacity, the COP decreased from 4.0 to 3.7 as the active compressor count increased from 1.5 to 2.5. This decline is attributed to a temporary reduction in suction saturation temperature required to maintain a minimum 6 K superheat at the AHX coil outlet. With longer operation under these conditions, the COP is expected to rise back toward values near 4.0.

The 50kW reduction in capacity observed between 6 p.m. and 7 p.m. is attributed to the defrost cycle. During this period, hot-gas defrost was activated to melt ice accumulation on the header and coil inlet, resulting in a temporary decrease in both capacity and COP of less than 10%. Notably, immediately after the defrost cycle, both COP and capacity recovered quickly, with the COP even improving despite the ambient temperature being approximately 2 °C lower than before the defrost event.

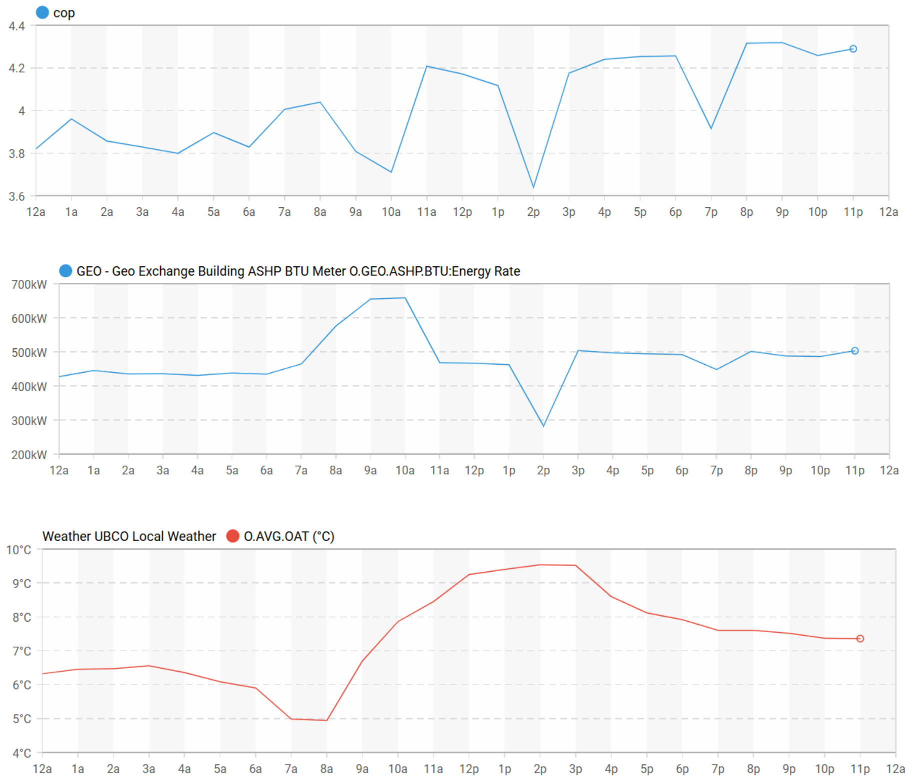

Figure 5: November 12 heating mode operation data (hourly averaged), UBCO, Kelowna, BC, Canada

November 14, 2025: Another operation period under mild winter conditions is presented in the following figure. On this day, the ASHP operated continuously from 7 a.m. to midnight, with its capacity adjusted several times and the system transitioned between one active circuit and two active circuits. The ASHP exceeded 1 MW of heating capacity between 11 a.m. and noon while operating both circuits—one with 2.5 compressors and the other with 2 compressors. During this period, the overall system COP remained above 4, typically around 4.3, demonstrating that capacity modulation was effectively managed using the pre-calculated fan and pump speed tables even with a few degree changes in ambient temperature.

No defrost cycles were triggered on November 14, and therefore the COP remained relatively unchanged throughout the entire operating period.

During the first week of operation following system commissioning, from November 10 to November 16, the ASHP operated for over 100 hours and delivered more than 55,000 kWh of heating to the LDES. This corresponds to a reduction of approximately 25 metric tons of CO_2 emissions based on the electricity grid intensity of British Columbia and a savings of nearly 6,000 m³ of natural gas for UBCO.

5. Conclusion

Preliminary field data from the first months of operation of the 1.5 MW R744 air-source heat pump at UBCO confirm the technical viability and strong performance of large CO_2 heat pumps for ambient low-temperature district energy systems. The measured results align closely with prior modeling, demonstrating achievable COP values in the range of 3.7–4.3 under mild winter conditions and validating an expected seasonal COP of approximately 3.5. The system delivered over 55,000 kWh of heat during its first operational week alone, corresponding to 25t of CO_2 emissions avoided and approximately 6,000 m³ of natural gas savings.

Commissioning insights—including optimized fan and pump speed control, improved circuit staging, and stable defrost management—played a critical role in achieving high part-load efficiency and responsive operation. The system's ability to modulate capacity effectively between one and two circuits, while maintaining COP values above 4, demonstrates the robustness of the control strategy under varying ambient and load conditions.

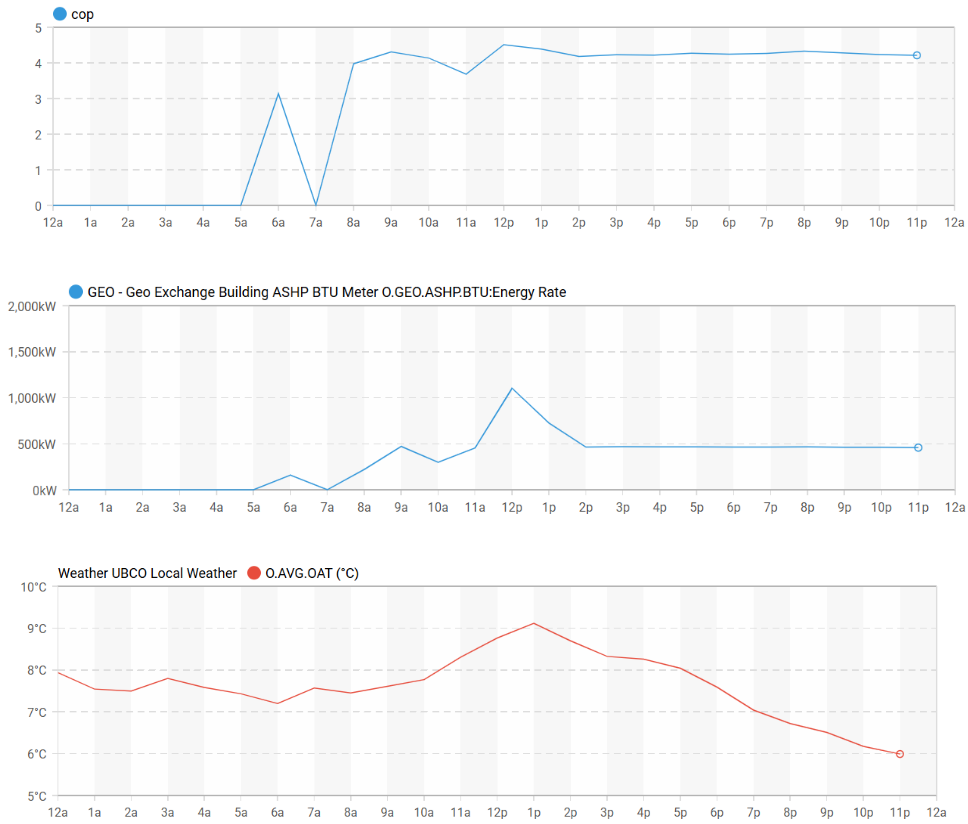

Figure 6: November 14 heating mode operation data (hourly averaged), UBCO, Kelowna, BC, Canada

This case study provides one of the first real-world demonstrations of a utility-scale CO_2 ASHP conditioning an ambient-temperature district loop, highlighting its suitability for cold-climate district energy applications. As additional operational data become available throughout the 2025–26 heating season, further opportunities for optimization are expected. Overall, the results underscore that R744 ASHPs offer a scalable, low-emission, high-efficiency pathway for campus and community-scale decarbonization.

References

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