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International Institute of Ammonia Refrigeration
1001 North Fairfax Street, Suite 503
Alexandria, VA 22314

703-312-4200 • info@iiar.org • www.iiar.org

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Technical Paper #17

Decarbonizing With District Energy Systems: When an R744 (CO_2) Heat Pump Is the Obvious Choice

Parham Eslami-Nejad, R744 Program Manager
Vitalis

Abstract

R744 (CO2) industrial air-source heat pumps (ASHPs) can serve as cost-effective and scalable alternatives to conventional heating and cooling systems. Leveraging the unique thermodynamic properties of CO2, a natural refrigerant, these systems deliver high efficiency and flexibility for certain temperature applications.

This article examines the performance of an R744 ASHP as primary heating equipment for buildings or as a first stage for nodal heat pumps in district-level applications. R744 heat pumps are renowned for delivering a significantly high temperature lift in a single stage and operating efficiently as a first stage for high-temperature heat pumps. In this article, the overall coefficient of performance (COP) of an R744 ASHP is compared against the most efficient commercially available ASHP solutions with synthetic refrigerant for different temperature applications.

A case study of the University of British Columbia Okanagan (UBCO) is also presented to illustrate a promising application of an R744 ASHP for conditioning a low-temperature district energy system (LDES) that serves nodal heat pumps throughout the campus, providing heating and cooling for buildings. It also demonstrates how the heat pump manufacturer integrates energy efficiency control algorithms for optimum operation of the system.

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Introduction

The electrification of heating can be efficiently achieved on a large scale through the use of central heat pumps, either for large buildings or clusters of buildings within districts. Among the various heat pump configurations, air-source heat pumps (ASHPs) stand out as a cost-effective solution. These systems extract heat from the outdoor air and consist of two primary components: the compressor rack, which generates heat and transfers it to a heat transfer fluid (air, water, brine, …), and the air heat exchangers, which absorb heat from the outdoor air.

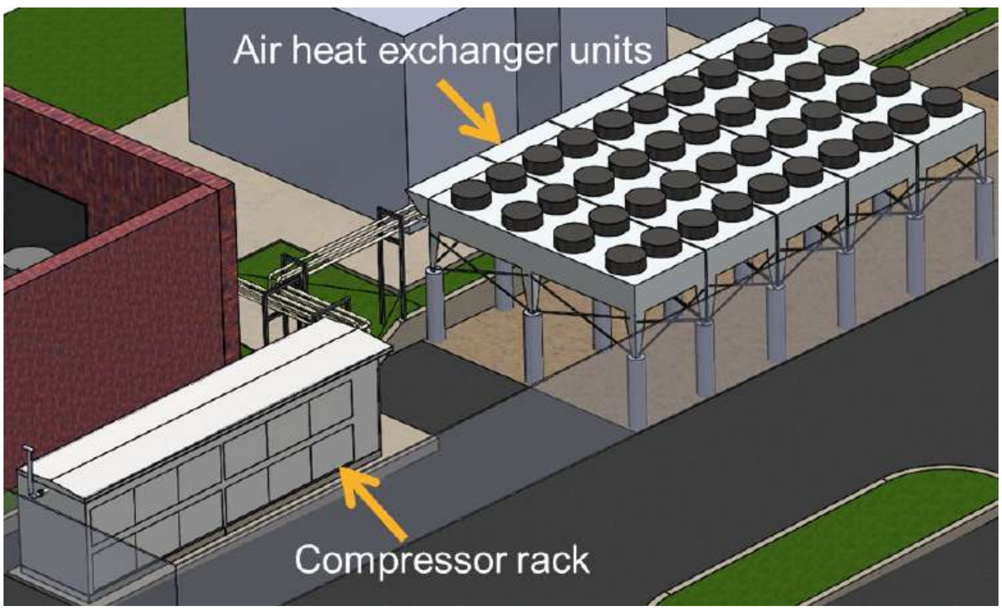

Figure 1. Air source heat pump.

Using industrial heat pumps to supply heat to a district energy system (DES) is a highly efficient approach for serving a network of buildings from a centralized plant. However, the efficiency of air-source heat pumps (ASHPs) in a DES depends significantly on the system's supply temperature and ambient air conditions. Since ASHPs extract heat from the surrounding air, lower ambient temperatures and higher DES supply temperatures both lead to reduced energy efficiency.

With advancements in heat pump technology and the growing shift toward electrification of thermal systems, a new generation of district energy systems, known as low-temperature district energy systems (LDES), has emerged as a highly efficient solution. These systems utilize nodal heat pumps at individual buildings to meet heating demands while enabling thermal energy sharing across the network. This design ensures a consistent source temperature for the nodal heat pumps throughout the year, improving efficiency and offering greater flexibility for integrating diverse energy sources.

To ensure a stable temperature throughout the year, an R744 ASHP can be used to heat and cool the LDES. This approach is more cost-effective and versatile than relying on a network of geothermal boreholes, commonly referred to as a geo-loop.

This paper compares the coefficient of performance (COP) of an R744 ASHP with that of the most efficient commercially available ASHP alternatives with synthetic refrigerant across various temperature applications. The results highlight scenarios where the R744 ASHP emerges as a promising solution for central heating systems in DES.

A primary focus of this study is also the role of the R744 ASHP in efficiently decarbonizing low-temperature district energy systems. The paper also quantifies the energy savings and greenhouse gas (GHG) emissions reductions achieved through the implementation of a LDES utilizing an R744 ASHP.

System overview and methodology:

R744, classified as a natural refrigerant, is non-toxic, non-flammable, and environmentally safe. Unlike newer generations of synthetic refrigerants (HFOs), R744 poses no risk to watersheds and does not contribute to PFAS or TFA pollution in local ecosystems.

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Due to its relatively low critical temperature, R744 heat pumps can operate in two distinct modes depending on the required supply temperatures. For supply temperatures above 27°C (80°F), a transcritical cycle is typically required, involving both supercritical heat rejection and subcritical heat absorption. This mode encompasses nearly all heating applications. In contrast, for a few applications, R744 heat pumps may operate in subcritical mode, where both heat rejection and heat absorption occur below the critical point. Examples include heating low-temperature district energy systems or serving as the first stage of a high-temperature heat pump reducing refrigerant charge of A2, A3, and B2 refrigerants and enhancing safety.

This paper identifies five key heating applications based on the supply and return temperatures of the heating system. These applications represent common scenarios for heating single buildings or districts. For each application, the performance of the R744 ASHP is compared against the most efficient commercially available synthetic refrigerant alternative. These applications are as follows:

Application 1: Supply temperature 71°C (160°F) and return temperature 60°C (140°F)

Application 2: Supply temperature 60°C (140°F) and return temperature 49°C (120°F)

Application 3: Supply temperature 49°C (120°F) and return temperature 38°C (100°F)

Application 4: Supply temperature 38°C (100°F) and return temperature 27°C (80°F)

Application 5: Supply temperature 27°C (80°F) and return temperature 15.5°C (60°F) (LDES)

For R744, applications 1 to 4 are single-stage heat pumps operating in transcritical mode, employing mechanical desuperheating, parallel compression, or a simple transcritical cycle with a flash gas bypass valve, depending on the return temperature. These configurations are selected to efficiently and economically manage the flash gas. Application 5 is a subcritical single-stage R744 heat pump. All R744 heat pumps applications are not equipped with ejector technology or other advanced energy performance enhancement strategies beyond mechanical desuperheating or parallel compression. Adding an ejector could potentially increase the COP by up to 5%.

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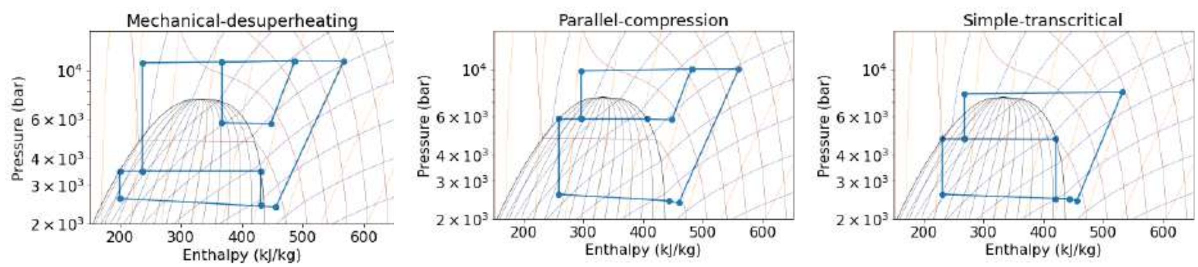
The P-H diagrams for the various transcritical R744 heat pump cycles used in this study are presented in Figure 2 at -5°C (23°F) ambient temperature. Applications 1 and 2 utilize mechanical desuperheating, application 3 employs parallel compression, while application 4 uses a simple transcritical cycle due to the relatively low return temperature and the resulting insignificant vapor quality after the first expansion. As previously mentioned, application 5 operates with a conventional subcritical cycle. The P-H diagram for the subcritical cycle will be presented in the next section.



(a) (b) (c)

Figure 2. P-H diagrams.

For the first two applications, the alternative solution is a dual-stage heat pump or booster system designed to address the relatively high temperature lift between the heat absorption and heat rejection processes. However, for applications 3, 4, and 5, the alternative solution is a single-stage heat pump, similar to the R744 heat pump. The synthetic refrigerants in this study were selected from HFOs, HFCs, and HFO/HFC blends, including R32, R1234yf, R152a, R515B, and R410A, based on their efficiency and suitability for the application's temperature requirements.

The following figures compare the overall coefficient of performance (COP) of the R744 heat pump with that of the alternative solution using synthetic refrigerants for various temperature applications.

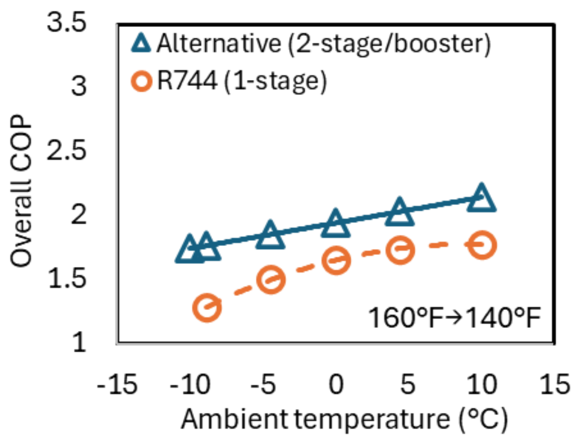


Figure 3. Application 1.

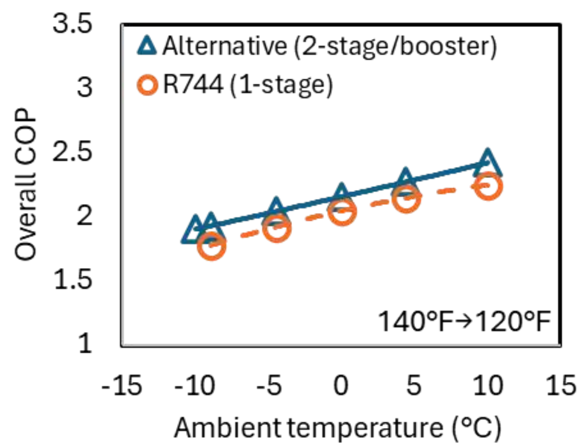


Figure 4. Application 2.

The COP is calculated using the following equation.

$$Overall\ COP = \frac{Heat\ delivered\ by\ the\ heat\ pump}{Work\ input\ to\ compressors\ and\ air\ heat\ exchanger\ fans}$$

For applications 1 and 2, the alternative solution outperforms the R744 heat pump across all ambient temperatures. However, in application 2, the overall COP of the R744 heat pump and the alternative solution is relatively close, with a difference of only 5% to 8%. The lower COP of the R744 ASHP in these applications is primarily due to the high return temperature, which makes the R744 transcritical cycle less efficient compared to the subcritical cycle of the alternative solution. For applications 3 to 5, as shown in Figures 5, 6 and 7, the R744 heat pump begins to demonstrate its performance advantages over the alternative solution.

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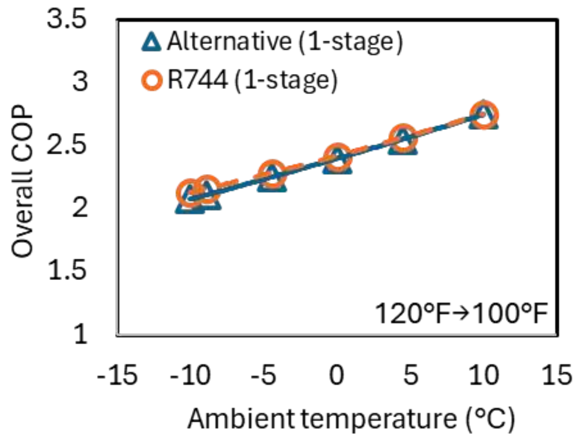

Figure 5. Application 3.

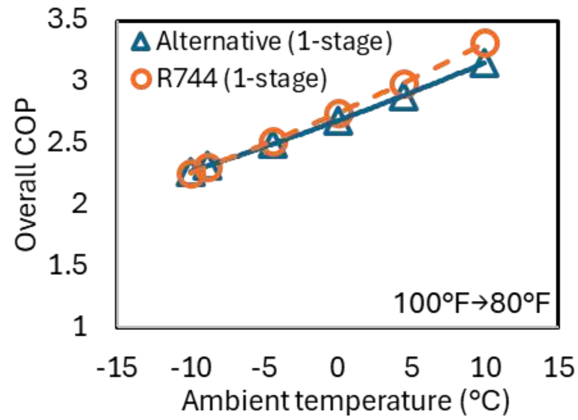

Figure 6. Application 4.

Application 5, in particular, is a promising use case for the R744 ASHP in LDES.

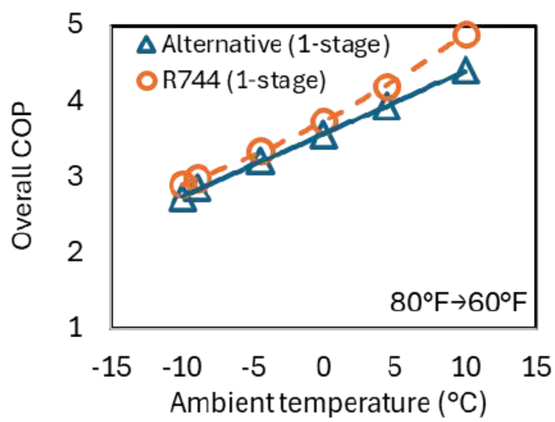

Figure 7. Application 5.

Ground-assisted ambient-temperature thermal network, commonly referred to as geo-loops, with nodal heat pumps are often selected for DES due to their enhanced thermal performance and conceptual simplicity. However, the high upfront costs and complex installation processes associated with geo-loops present significant challenges. In contrast, the R744 ASHP-assisted DES offers a cost-effective and scalable alternative by actively conditioning the LDES, providing precise temperature

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control and maintaining optimized system performance throughout the year. Figure 7 compares the overall COP of the R744 ASHP with an alternative synthetic-refrigerant-based ASHP solution for application 5. The next section also presents a case study showcasing the benefits of R744 air-source heat pumps for this application in districts.

Another key advantage of the R744 heat pump is its lower sensitivity to supply temperature in applications with high return temperatures. This is due to the optimal pressure control mechanism implemented in R744 heat pumps, which is governed by the return temperature rather than the supply temperature. As a result, R744 heat pumps can deliver high supply temperatures even with lower return temperatures, without incurring a significant performance penalty.

As illustrated in the following figures, the performance difference between R744 heat pumps and alternative systems using synthetic refrigerants becomes more pronounced—exceeding 10%—when a high temperature differential between supply and return temperatures is maintained.

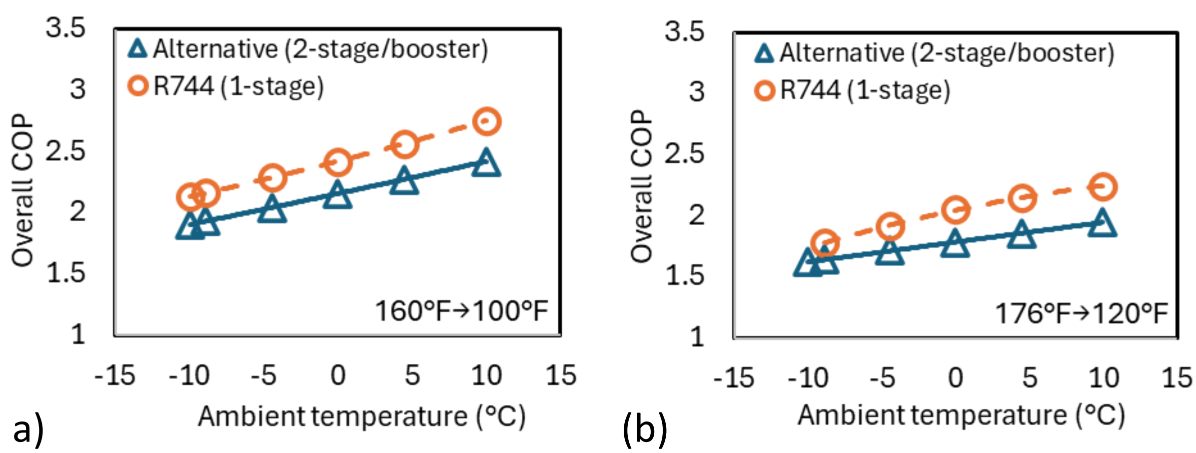

Figure 8. High ΔT applications.

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To determine if an R744 ASHP is a suitable solution for heating applications, either of the following conditions should be met:

1. The return temperature is below 49°C (120°F).
2. The temperature difference between supply and return exceeds 30°C (54°F) for applications requiring supply temperatures below 90°C (194°F).

In district energy systems, maintaining a high temperature difference between supply and return is often feasible due to the varied required heating temperatures of different buildings, which depend on the design of their heat distribution systems.

Case Study

UBCO District Energy System

As shown in the previous section, one of the promising applications is to heat the LDES using the R744 ASHP (application 5). In this section, the energy saving and GHG emission reduction is quantified for the energy system of the University of British Columbia Okanagan (UBCO) campus. The UBCO district energy system includes an ambient low-temperature district energy system designed for energy sharing, with supply temperatures maintained in a range of 8°C to 25°C. To decarbonize the district energy system, it is proposed that air-source heat pumps be utilized to meet the base heating load requirements for the central plant. This solution provides significant improvements in efficiency and operational flexibility. The LDES delivers ambient-temperature water to most academic buildings in the campus. Distributed heat pumps within the buildings further utilize this ambient-temperature water as a source for both heating and cooling.

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System characteristics

The LDES presents a unique opportunity for implementing the most efficient application of the R744 ASHP to replace condensing boilers. Operating the R744 ASHP in subcritical mode at saturation discharge temperature of 20°C enhances operational efficiency. The system's flexibility allows for capacity adjustments based on changing thermal demands, optimizing operational efficiency and cost savings. Utilizing multiple compressors and heat exchangers ensures scalability and modularity, facilitating easy expansion or modifications to meet future energy needs as well.

As mentioned earlier, an air-source R744 heat pump is employed to condition the LDES. Due to the loop's temperature, the heat pump operates in a subcritical thermodynamic cycle in heating mode. The heat pump incorporates two fully independent and identical refrigerant circuits. Figure 9 illustrates the process flow diagram (PFD) of one refrigerant circuit of the heat pump for heating mode. As depicted in Figure 9, each refrigerant circuit comprises two main modules: the air heat exchangers (outdoor evaporator module) and the compressor rack with CO2-to-water heat exchangers. To assess the system's energy performance, a model has been developed for the R744 heat pump that includes both modules and their associated components.

The cycle begins at the compressor suction (1), where CO2 is compressed into high-pressure and high- temperature CO2 (2). This compressed CO2 then passes through the high-pressure side of the internal heat exchanger (IHX), which provides superheat at the compressor suction. In heating mode, CO2 flows to the CO2-to-water heat exchanger to supply heat to the LDES (3). Subsequently, the CO2 passes through the back-pressure regulator (4). Liquid CO2 then absorbs heat from the outside air in heating mode (5), causing it to evaporate (6). The evaporated CO2 then returns to the compressors via the low-pressure side of the IHX, where it gains additional superheat before recommencing the cycle.

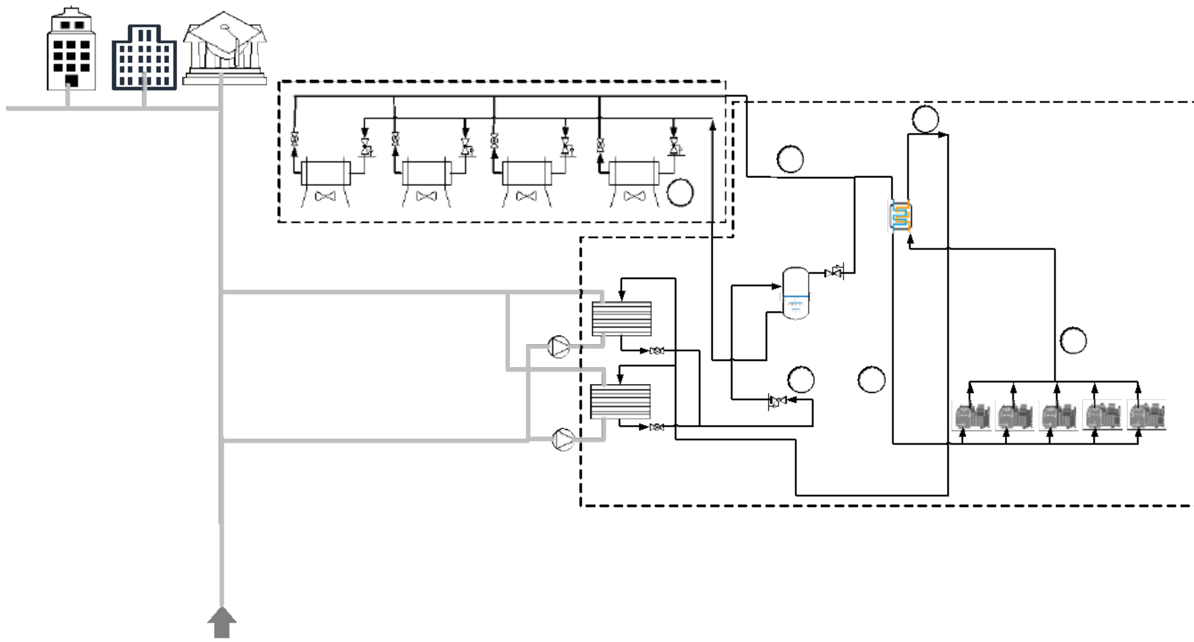

Figure 9. Process flow diagram of the R744 reversible ASHP.

Figure 10 presents the P-H diagram of the cycle with state points which are all marked on the PFD as well.

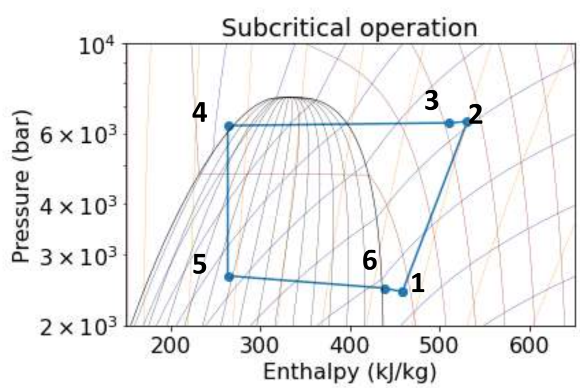

Figure 10. P-H diagram, subcritical cycle.

Each refrigerant circuit utilizes five 6-cylinder 575V/3/60Hz compressors with a total displacement of 272 m^3/hr. The compressor is modeled using the correlation provided by the manufacturer. Each refrigerant circuit is connected to three 300kW flat air heat exchanger (AHX) units, each with two coils and eight fans. The power consumption of the AHX fans varies with ambient temperature and the amount of required heat exchanged capacity.

Each refrigerant circuit has 20 fans in operation and 4 reserved when running in heating mode. The required heat exchange capacity is calculated from the energy balance of the cycle. Maximum pressure drops of the heat exchangers and CO2 pressure losses in pipes are considered in the pressure drop calculation of the system. For more details regarding the component models, fan electricity consumptions, and pressure drop calculations please refer to a conference paper presented at the 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, College Park, Maryland, USA 2024 *[P. Eslami-Nejad et al. Decarbonizing District Energy: Leveraging CO2 Heat Pumps at UBC Okanagan (Theoretical evaluation)]*

UBCO LDES Load Demands

Based on the heating and cooling demand data of the UBCO LDES, the total heating required from the ASHP are calculated as 14,267 GJ.

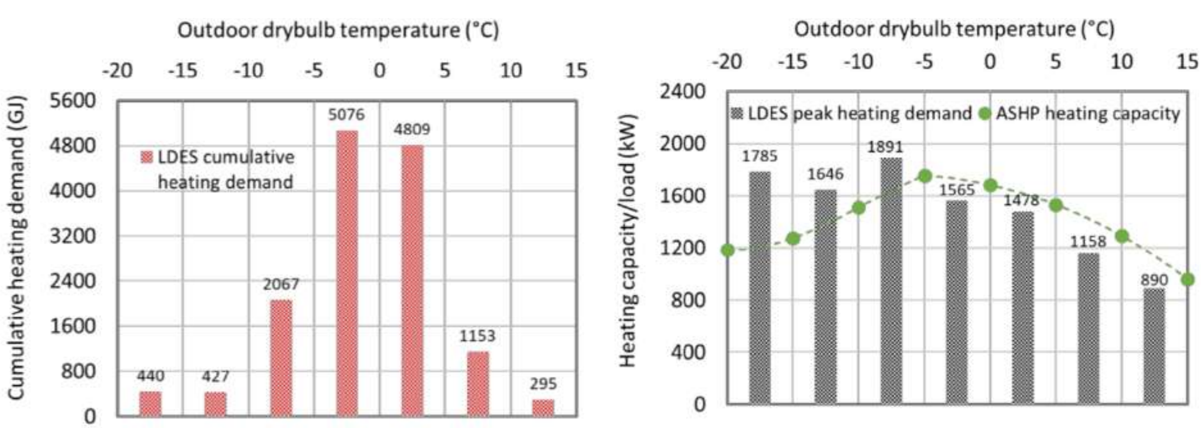

Figure 11. ASHP capacity and LDES cumulative (left) and peak (right) heating demand.

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Figure 11 (left) shows the total heating demand in GJ at different ambient temperatures. As shown in this figure, almost 70% (9,885 GJ out of 14,267 GJ) of the demand occurs at temperatures between -5°C and 5°C. Figure 11 (right) presents the peak heating capacity required in kW. According to this figure, the system can fulfill the entire LDES demand at -5°C outdoor dry bulb (ODB) temperature or higher, where 80% of the heating demand occurs. Figure 11 (right) also illustrates the heating capacity of the ASHP with the necessary turndown to meet the LDES peak demand. The system features 10 compressors with a nominal capacity of 1.5 MW at -10°C ODB temperature.

Table 1 outlines the performance and operating conditions of the ASHP in heating mode. For all these conditions, the condensing temperature of the ASHP is 20°C (57 bar, subcritical operation). The system delivers maximum capacity at -5°C ODB temperature with 10 active compressors, achieving an overall COP of 3.4. COP values range from 2.2 at -20°C to 7.3 at 15°C ODB temperatures. At higher ODB temperatures, as LDES demand diminishes, capacity is reduced by switching off compressors. The maximum nominal evaporator capacity is designed at 1500 kW.

ODB(°C)	Evaporator temperature (°C)	Maximum heating capacity (kW)	Maximum absorbed heat (kW)	Maximum absorbed power (kW)	Compressors working	COP
-20	-25	1176	758	547	9.5	2.2
-15	-23	1270	842	487	9.5	2.6
-10	-18	1497	1055	498	9.5	3.0
-5	-14	1694	1247	501	9.5	3.4
0	-10	1623	1253	412	8	3.9
5	-5	1524	1235	327	6.5	4.7
10	0	1207	1022	207	4.5	5.8
15	5	908	797	125	3	7.3

Table 1. ASHP performance data in heating.

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Results

Using the model, the part-load operation of the ASHP has been evaluated and summarized in the following tables. Table 2 presents part-load operation in heating. The highlighted cells represent the most probable operation points of the ASHP based on the heating and cooling demand data of the LDES from previous years.

ASHP total delivered heat (kW)								
T_ambient (°C)	-20	-15	-10	-5	0	5	10	15
# Compressors								
10	1122	1220	1461	1670				
9.5	1068	1162	1391	1590				
9	1014	1103	1321	1510	1720			
8.5	959	1043	1250	1430	1629			
8	904	984	1179	1348	1537	1779		
7.5	849	924	1108	1267	1444	1672		
7	794	864	1036	1185	1350	1564	1791	
6.5	738	803	963	1102	1256	1455	1666	
6	682	743	891	1019	1162	1346	1541	1746
5.5	626	682	818	936	1067	1236	1415	1603
5	561	610	731	835	971	1125	1289	1459
4.5	507	551	661	755	860	1014	1161	1315
4	452	492	590	674	768	890	1034	1170
3.5	397	432	518	592	675	782	895	1025
3	341	371	445	510	581	673	771	873
2.5			372	426	486	563	644	730
2				342	390	451	517	585
1.5							388	440

Table 2. ASHP capacity at part load.

ASHP heating overall COP								
T_ambient (°C)	-20	-15	-10	-5	0	5	10	15
# Compressors								
10	2.2	2.5	2.9	3.2				
9.5	2.3	2.6	2.9	3.3				
9	2.3	2.6	2.9	3.3	3.7			
8.5	2.4	2.6	3.0	3.3	3.7			
8	2.4	2.6	3.0	3.4	3.8	4.2		
7.5	2.4	2.6	3.0	3.4	3.8	4.3		
7	2.4	2.6	3.0	3.4	3.9	4.4	4.7	
6.5	2.5	2.6	3.0	3.4	3.9	4.5	4.9	
6	2.5	2.6	3.0	3.4	3.9	4.5	5.2	5.0
5.5	2.5	2.6	3.0	3.4	3.9	4.6	5.3	5.6
5	2.2	2.5	2.8	3.2	3.9	4.6	5.5	6.0
4.5	2.3	2.5	2.9	3.2	3.6	4.6	5.6	6.3
4	2.3	2.5	2.9	3.3	3.7	4.1	5.7	6.6
3.5	2.3	2.5	2.9	3.3	3.7	4.3	4.6	6.8
3	2.4	2.5	2.9	3.3	3.7	4.4	5.0	4.9
2.5			2.9	3.3	3.7	4.4	5.3	5.8
2				3.2	3.7	4.4	5.4	6.3
1.5							5.4	6.5

Table 3. ASHP overall COP at part load.

The highlighted orange cell indicates the average LDES heating demand at each 5°C ODB temperature interval. The first column on the left shows the number of active compressors required to generate the capacity listed in the corresponding row at different ODB temperatures. Empty cells indicate an ASHP capacity shortage or too-small turndown. Depending on the refrigerant velocity in pipes and the capacity of heat exchangers, the system will have either one or two active refrigerant circuits. Based on the power consumptions of the AHX fans and the compressor rack, the overall COP of the ASHP is calculated for the part-load operation of the system and is listed in Table 3. As shown in Table 3, at each ambient temperature, the COP increases as the number of active compressors decreases, then suddenly drops before

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continuing its increasing trend. This fluctuation is due to changes in the number of active refrigerant circuits and the electricity draw of the AHX fans.

A unique approach has been implemented to ensure the system operates consistently under optimal conditions, minimizing unnecessary electricity consumption from fans and pumps. Using performance curves for water pumps and fans, along with specifications for the heat exchanger and air coils, the optimal operating speeds have been pre-calculated and programmed for all fans and pumps in the system.

Pump speed (%)								
T_ambient (°C)	-20	-15	-10	-5	0	5	10	15
# Compressors								
10	68%	77%	88%	98%				
9.5	65%	72%	83%	95%				
9	62%	67%	80%	90%	100%			
8.5	58%	63%	77%	85%	97%			
8	55%	60%	73%	82%	92%	100%		
7.5	52%	55%	68%	77%	87%	95%		
7	48%	52%	65%	73%	82%	88%	100%	
6.5	45%	48%	60%	68%	77%	83%	95%	
6	42%	45%	55%	63%	73%	78%	87%	100%
5.5	38%	42%	50%	58%	68%	73%	82%	90%
5	70%	77%	88%	98%	62%	68%	75%	83%
4.5	62%	67%	80%	90%	100%	63%	68%	78%
4	55%	60%	73%	82%	92%	100%	63%	72%
3.5	48%	52%	65%	73%	82%	88%	100%	65%
3	42%	45%	55%	63%	73%	78%	87%	100%
2.5			45%	52%	60%	68%	75%	83%
2				42%	48%	58%	63%	72%
1.5							48%	55%

Table 4. Pump speed.

Fan speed (%)								
T_ambient (°C)	-20	-15	-10	-5	0	5	10	15
# Compressors								
10	100%	68%	85%	100%				
9.5	96%	65%	81%	96%				
9	92%	62%	78%	92%	100%			
8.5	87%	60%	74%	87%	97%			
8	83%	57%	70%	83%	92%	86%		
7.5	79%	54%	67%	79%	87%	82%		
7	75%	51%	63%	74%	82%	77%	91%	
6.5	70%	48%	59%	69%	77%	72%	85%	
6	66%	45%	55%	65%	72%	67%	79%	92%
5.5	62%	42%	51%	60%	67%	62%	73%	85%
5	100%	68%	85%	100%	62%	57%	67%	78%
4.5	92%	62%	78%	92%	100%	52%	61%	71%
4	83%	57%	70%	83%	92%	86%	55%	64%
3.5	75%	51%	63%	74%	82%	77%	91%	57%
3	66%	45%	55%	65%	72%	67%	79%	92%
2.5			48%	56%	62%	57%	67%	78%
2				46%	51%	47%	55%	64%
1.5							43%	49%

Table 5. AHX fan speed.

The control system dynamically adjusts component speeds to their optimal levels based on the number of active compressors and ambient conditions. Tables 4 and 5 display the pre-calculated optimal pump and fan speed values, as configured by the control unit. Shaded (gray) cells represent operation with two refrigerant circuits, while unshaded cells correspond to single-circuit operation.

Each refrigerant circuit includes 20 fans and 2 water pumps, all operating at the speeds specified in the Tables 4 and 5, depending on the ambient and system

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operating conditions. These values are subject to adjustment and improvement over time, leveraging operational data to enhance overall system efficiency.

By applying the ASHP capacity and performance metrics to the heating demand profiles of the LDES, energy savings and GHG emissions reductions can be quantified under the following assumptions: the entire heating load is currently supplied by gas boilers with an efficiency of 85%, and the GHG emissions intensity of the British Columbia electricity grid is 7.6 grams of CO2 per kWh. Installing the ASHP results in a significant annual reduction of 815 metric tons of CO2 emissions and 430,000 cubic meters of natural gas consumption. Table 6 summarizes the results of the analysis.

Annual overall heating COP	Heating capacity delivered (%)	Auxiliary heating supplied by gas boilers (GJ)	Absorbed power (MWh)	Total heating delivered (GJ)	CO2 emission saving (ton)	Natural gas saving (1000m^3)	Energy saving (%)
3.5	98.4	230	1150	14,267	815	430	75%

Table 6. Energy analysis results.

Conclusion

The overall COP analysis shows that R744 air-source heat pumps outperform existing synthetic refrigerants, as long as the return temperature from buildings or districts stays below 49°C (120°F) or when the temperature difference between supply and return exceeds 30°C (54°F) for applications requiring supply temperatures below 90°C (194°F).

This article also highlights the potential of low-temperature district energy systems, where R744 heat pumps provide COP values that exceed those of existing alternatives. We quantified the energy savings and GHG emissions reduction of R744-

based air-source heat pumps as replacements for condensing boilers in the district energy system at the University of British Columbia Okanagan campus.

The article also emphasizes the crucial role of fan and pump control in ensuring efficient system operation. The electricity consumption of air heat exchanger fans can have a significant impact on overall system performance, highlighting the need for a unique approach to optimize their operation.

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