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Selection of natural refrigerants for heat pumps in district heating systems

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Abstract

Heat pumps designed for district heating (DH) systems, utilizing natural refrigerants, are emerging as transformative technologies for decarbonizing urban energy networks. This study focuses on evaluating the theoretical performance of such heat pumps using different natural refrigerants and examining their integration into district heating systems. By analyzing potential heat sources, district heating temperature requirements, and capacity demands of existing or potential new DH systems, the research establishes boundary conditions that guide heat pump theoretical performance analysis of heat pump. It identifies the best-performing refrigerant options under the specified conditions.

Thermodynamic performance analyses are conducted using Engineering Equation Solver (EES) to model and simulate heat pump cycles for selected natural refrigerants. Key refrigerant properties including critical temperature and pressure, coefficient of performance (COP), volumetric heating effect (VHE), and operating pressure range are assessed to ensure compatibility with DH system requirements. The insights gained from these analyses are used to compare refrigerant performance tailored to meet specific DH requirements.

This study presents a comprehensive analysis of COP across three generations of district heating systems, examining the effects of heat source temperature and system design parameters on refrigerant performance. The results reveal that R717 consistently demonstrates dominant performance in the basic cycle, achieving the highest COP values among the evaluated refrigerants. Additionally, RE170, R600, and R600a also exhibit strong performance, particularly with the integration of an internal heat exchanger (IHEX), which enhances efficiency across all generations. Overall, this research provides valuable insights into the performance characteristics of various refrigerants, highlighting the critical role of cycle design in optimizing heat pump performance.

Keywords: District Heating; Large Scale Heat Pump; Natural Refrigerant; Hydrocarbon; CO2; Ammonia

1. Introduction

District heating systems are a cornerstone of Europe's energy infrastructure, with approximately 19,000 networks supplying heat to 80 million people representing 18% of the EU population. In 2023, these systems delivered 548.6 TWh of heat, supported by a stable installed capacity of around 309 GW [1]. However, the current energy mix remains heavily reliant on fossil fuels, with coal and natural gas accounting for 22% and 26% of the supply, respectively. Meanwhile, technologies such as heat pumps and electric boilers can be considered low-carbon only if powered by electricity generated from low-carbon sources, and they currently contribute to just 3% to the energy supply [1]. This reliance on fossil fuels poses a significant challenge to achieving Europe's climate targets. As part of the region's decarbonization plans, the number of district heating networks is expected t[*]o grow, driven by the transition to renewable energy sources, waste heat recovery, and electrification. Expanding and modernizing district heating systems offers a pivotal opportunity to reduce

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greenhouse gas emissions, enhance energy efficiency, and strengthen resilience, positioning district heating as a key solution on Europe's path toward a sustainable energy future [2].

Heat pumps represent a promising technology for decarbonizing district heating systems due to their ability to deliver efficient and sustainable heating while significantly reducing greenhouse gas emissions. These systems can utilize renewable electricity and recover ambient or waste heat from diverse sources, such as industrial processes, geothermal reservoirs, urban wastewater, and data centers, making them a versatile and low-carbon solution for modern district heating networks. Furthermore, advancements in heat pump technology, along with the growing number of projects integrating heat pumps into district heating systems in recent years, have delivered promising results. These developments demonstrate that heat pump technology can be successfully integrated into both existing systems and newly developed networks, proving its feasibility and reliability [3-5]. As Europe intensifies its decarbonization efforts, accelerating the deployment of heat pumps in district heating systems will be critical to reducing dependency on fossil fuels, including natural gas, which has become a pressing issue considering the Russia-Ukraine conflict and the resulting energy crisis [6]. By transitioning to cleaner technologies like heat pumps, Europe can not only meet its climate targets but also strengthen energy security, reduce vulnerability to external supply disruptions, and ensure a clean and resilient energy future [7].

To maximize the environmental benefits of heat pumps in district heating systems, it is essential to prioritize the use of environmentally friendly technologies. Regulatory measures, such as the F-Gas Regulation and the proposed PFAS Ban, are key drivers in this transition. The F-Gas Regulation seeks to reduce emissions from fluorinated greenhouse gases commonly used in refrigeration and air conditioning by phasing them out and replacing them with lower-impact alternatives [8]. The proposed PFAS Ban aims to address the environmental and health concerns associated with per- and polyfluoroalkyl substances (PFAS), although it is important to note that this is still in the proposal stage and no regulation has been finalized yet [9]. Since certain F-gases degrade into PFAS compounds, these regulations are closely connected and collectively encourage the development of heat pumps that operate with natural refrigerants. By promoting the adoption of environmentally friendly refrigerants, these measures ensure that heat pumps contribute not only to decarbonization but also to reducing harmful pollutants.

To support the growing demand for sustainable heating solutions, a wide range of large-scale heat pumps are now available on the market. Figure 1 below provides an overview of heat pumps with heating capacities of 5 MW and above, detailing their maximum forwards temperatures, heating capacities, and compressor types.

Overview of Large-scale Heat Pumps (≥ 5 MW) Available on the Market

Company	Model	Refrigerant	Maximum Temperature (°C)	Heating Capacity (MW)	Compressor Type
Ago Energie	AGO Caldora	R717/R718	160	10	Various Compressor
Araner Global DMCC	Large Scale Magnetic Bearing Centrifugal Heat Pump	R1234ze(E)	95	45	Centrifugal Compressor
Araner Global DMCC	Large Scale Screw Compressor Heat Pump	R717	87	23	Screw Compressor
Araner Global DMCC	Large Scale Screw Compressor Heat Pump	R1234ze(E)	80	12	Screw Compressor
Combitherm	Heat Pump	HFOs, HFCs and Natural Refrigerants	80	5	Screw Compressor
Copeland	Q95-1201	R717	95	7	Screw Compressor
EPCON	MVR Heat Pump	R718	150	30	Centrifugal Compressor
EQUANS Kältetechnik GmbH	UPGRADER95°-XL	R717	95	25	Piston Compressors/Screw Compressors/Centrifugal Compressors
Everllence	Transcritical Compression Cycle (TCC)	R744	150	50	Centrifugal Compressor
Everllence	Vapor Compression Cycle (VCC)	R744	280	100	Centrifugal Compressor
Fenagy	HCI-6000	R600a	95	6	Screw Compressor
Friotherm	Unitop 23	R134a	80	6	Centrifugal Compressor
Friotherm	Unitop 28	R134a	80	7	Centrifugal Compressor
Friotherm	Unitop 33	R134a	80	9	Centrifugal Compressor
Friotherm	Unitop 43	R134a	80	13	Centrifugal Compressor
Friotherm	Unitop 34	R134a	90	10	Centrifugal Compressor
Friotherm	Unitop 50	R134a	90	20	Centrifugal Compressor
GEA	Customized Heat Pump System	R717	95	10	Screw Compressors
Heaten	HBL 16-W/W / HBL16	HCs	200	10	Piston Compressor
Heaten	HBL 16-W/W / HBL16	HFOs	165	10	Piston Compressor
Heatlift	Hot Water Heat Pumps	R1233zd(E), R1234ze(E), R600a, R601a	210	15	Centrifugal Compressor
Heatlift	Hot Air Heat Pumps	R1233zd(E), R1234ze(E), R600a, R601a	200	15	Centrifugal Compressor
Heatlift	Steam Generation Heat Pumps	R1233zd(E), R1234ze(E), R600a, R601a	250	15	Centrifugal Compressor
Johnson Control/Sabroe	HicaHP 273S	R717	95	5	Screw Compressor
Johnson Control/Sabroe	HicaHP 273S/283L	R717	95	7	Screw Compressor
Johnson Control/Sabroe	HicaHP273L	R717	95	7	Screw Compressor
Johnson Control/Sabroe	HicaHP 273L/355S	R717	95	9	Screw Compressor
Ohmia Industry	Steam Producing Heat Pump	R717 and R718	150	10	Piston Compressors
Siemens Energy	C600	R1234ze(E)	100	40	Centrifugal Compressor
Siemens Energy	C750	R1234ze(E)	100	45	Centrifugal Compressor
Siemens Energy	High Temperature Heat Pump	R1233zd	150	50	Centrifugal Compressor
Spilling	High Temperature Heat Pump	R718	250	15	Piston Compressor
Star Refrigeration	Water Source Heat Pumps	R134a, R22 and R717	130	10	Screw Compressor
Turboden	Large Heat Pump	Various Refrigerants	200	50	Centrifugal Compressor

Figure 1. Overview of Large-scale Heat Pumps Available on the Market [10 – 11]

These large-capacity heat pumps are specifically designed to meet the needs of large-scale applications, such as district heating systems and industrial processes. The increasing development of heat pumps reflects the ongoing innovation and investment in this critical technology, which plays an integral role in achieving sustainable energy systems.

While significant progress has been made in heat pump development and the selection of natural refrigerants, a key research gap remains. Existing studies often focus on broad aspects of heat pump technology or refrigerant selection, but there is limited research that systematically evaluates the suitability of refrigerants based on specific heat sources and the characteristics of different generations of district heating systems [12-15]. This study aims to fill that gap by defining the most appropriate refrigerant options for various cases, considering the diverse boundary conditions provided by different heat sources and district heating network designs. By addressing this gap, the findings of this study can contribute to optimizing heat pump performance and further advancing the decarbonization of district heating systems across Europe.

2. Refrigerant options and properties

2.1. Refrigerant selection

In selecting refrigerants for this study, the required temperature ranges were considered, along with compliance with environmental regulations, including PFAS bans and F-Gas regulations. Additionally, existing heat pumps and the refrigerants utilized within them were evaluated, followed by a comprehensive review of relevant literature. Based on these assessments, ammonia (R717), carbon dioxide (R744), dimethyl ether (RE170), and a selection of hydrocarbons including propane (R290), butane (R600), isobutane (R600a), pentane (R601), isopentane (R601a), and propylene (R1270) were identified as the refrigerants to be analyzed in this study. The normal boiling point and critical temperature values of the selected refrigerants are presented in Figure 2.

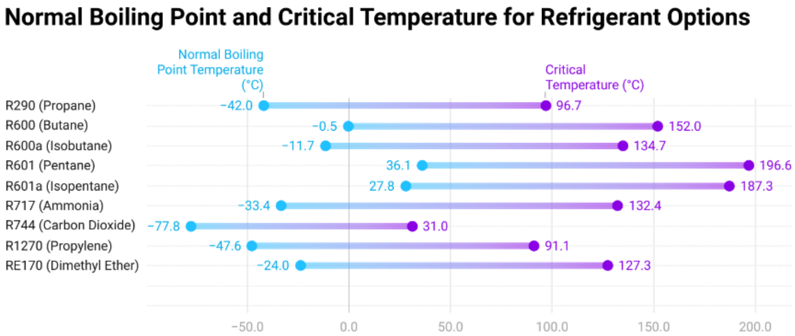


Figure 2. Normal Boiling Point and Critical Temperature of Selected Refrigerants [17]

2.2. Properties of the refrigerants

The properties of selected refrigerants were analyzed to evaluate their thermodynamic, safety, and environmental characteristics. The results presented in Figure 3 highlight significant variations in key parameters such as molar mass, boiling point, critical temperature, critical pressure, heat of vaporization, and density, which influence the suitability of these refrigerants for various applications. It is important to note that some properties, such as density and heat of vaporization, are temperature-dependent and have been calculated specifically at 0°C, whereas others, such as molar mass and critical temperature, represent general characteristics of the refrigerants.

Investigated hydrocarbons have molar masses ranging from 44.1 to 72.2 kg/kmol, which are higher than those of ammonia and carbon dioxide, while Ether has a slightly higher molar mass of 46.1 kg/kmol.

The normal boiling points (T_{nbp}) of hydrocarbons range from -42.0°C to 36.1°C, providing flexibility for various applications. Refrigerants with higher (T_{nbp}), such as pentane and isopentane, are particularly suitable for systems utilizing relatively high-temperature heat sources.

Hydrocarbons generally have relatively high critical temperatures (T_{cr}), such as 152.0°C for R600 and 196.6°C for R601, making them suitable for high temperature applications. However, R290 and R1270 have lower critical temperatures of 96.7°C and 91.1°C, respectively, which may limit their suitability for district heating systems with higher temperature levels when operating in sub-critical cycles. In contrast, carbon dioxide, with a critical temperature of 31.0°C, is limited to transcritical operation.

A high heat of vaporization influences the required mass flow rate to achieve a specific cooling capacity [18]. Ammonia has the highest heat of vaporization (h_{fg}) at 1262.0 kJ/kg, which significantly reduces the required mass flow rate to achieve a given cooling capacity. In comparison, hydrocarbons and ether exhibit moderate heat of vaporization values, such as 384.9 kJ/kg for R601 and 435.2 kJ/kg for RE170, which may require higher mass flow rates to deliver the same cooling effect.

The liquid densities (ρ_l) of hydrocarbons and ether, ranging from 528.7 to 644.9 kg/m³, are comparable to ammonia, with ether exhibiting slightly higher values. Higher liquid densities can reduce the required refrigerant charge in the system, potentially lowering costs and minimizing environmental impact in case of leaks [18]. Vapor densities (ρ_v), on the other hand, are generally lower for hydrocarbons due to their larger molar masses and weaker intermolecular forces. For instance, R601a has a vapor density of 1.1 kg/m³, while ether has a vapor density of 5.8 kg/m³. Lower vapor densities can result in higher volumetric flow rates, which may necessitate larger system components such as compressors and piping, increasing system size and cost.

Refrigerant Properties at 0°C

	Propane	Butane	Isobutane	Pentane	Isopentane	Ammonia	Carbon Dioxide	Propylene	Dimethyl Ether
Refrigerant No	R290	R600	R600a	R601	R601a	R717	R744	R1270	RE170
Type of Refrigerant	HC	HC	HC	HC	HC	-	-	HC	Ether
ODP	0	0	0	0	0	0	0	0	0
GWP	3	4	3	5	4	0	1	2	1
Safety Class	A3	A3	A3	A3	A3	B2L	A1	A3	A3
M (kg/kmol)	44.1	58.1	58.1	72.2	72.2	17.0	44.0	42.1	46.1
T_{nbp} (°C)	-42.0	-0.5	-11.7	36.1	27.8	-33.4	-78.5	-47.6	-24.0
T_{tr} (°C)	-187.6	-138.3	-159.4	-129.7	-160.5	-77.8	-56.6	-185.2	-141.5
T_{cr} (°C)	96.7	152.0	134.7	196.6	187.3	132.4	31.0	91.1	127.3
P_{cr} (Bar)	42.5	38.0	36.3	33.7	33.8	113.5	73.8	46.7	53.4
Heat of Vaporization (h_{fg}) (kJ/kg)	374.7	384.3	355.0	384.9	362.9	1262.0	230.9	377.8	435.2
ρ_l (kg/m^3)	528.7	600.4	580.5	644.9	639.0	638.7	927.4	544.6	699.9
ρ_v (kg/m^3)	10.4	2.8	4.3	0.8	1.1	3.5	97.7	12.4	5.8

Table: Görkem Balyaligil • Source: Engineering Equation Solver (EES) • Created with Datawrapper

Figure 3. Thermophysical Properties of the Selected Refrigerants [16 – 17]

When selecting a refrigerant, both thermodynamic properties and practical criteria must be considered to ensure optimal system performance and feasibility, as explained in the refrigerant selection section. Critical parameters such as pressure ratio, volumetric heating effect (VHE), Carnot efficiency, and discharge temperature directly influence heat pump performance, heating/cooling capacity, and application suitability. In addition, practical considerations include compliance with environmental regulations, operational safety, system compatibility, and economic viability. Balancing these thermodynamic and practical factors is essential to selecting the most suitable refrigerant for the specific application. Figure 4 presents these properties for the selected refrigerants in this study.

A high-pressure ratio negatively impacts the performance of a heat pump and may necessitate a larger size. As the pressure ratio increases, both volumetric and isentropic efficiencies are likely to decline [19]. Hydrocarbons such as propane and propylene demonstrate relatively low-pressure ratios, while pentane and isopentane exhibit higher pressure ratios, resulting in greater energy consumption. Ammonia, with a moderate pressure ratio of 9.64, offers a balanced approach to compression requirements.

The volumetric heating effect indicates the heating capacity delivered per unit of compressor swept volume, providing insights into compressor sizing [18]. Ammonia achieves the highest volumetric heating effect, enabling the use of smaller compressors for high-capacity heating applications. Propylene and propane also perform well, supporting compact and efficient system designs. In contrast, refrigerants such as butane, isobutane, diethyl ether, pentane and isopentane exhibit lower values, requiring larger compressors and limiting their suitability for systems demanding higher heating capacity. This metric is important for selecting optimal refrigerants, determining compressor sizes, and designing efficient district heating systems.

The COP and Carnot efficiency (η_{Carnot}) are key indicators of cycle efficiency, and their values are influenced by the relationship between the condensing and evaporating temperature. In this analysis, ammonia achieves the highest COP and Carnot efficiency at the boundary conditions of 80°C condensing and 0°C evaporating, outperforming other refrigerants. Dimethyl ether and pentane also show competitive values under these conditions. It is important to note that this evaluation represents one boundary analysis, and refrigerant performance varies across different temperature ranges. A broader matrix of calculations covering the temperature requirements for generations 2, 3 and 4 of district heating systems has already been conducted, and the results will be presented in the results and discussion section, highlighting how efficiency trends differ under varying temperature boundaries.

Superheating and subcooling are additional factors that influence refrigerant performance. y_1-factor measures the percentage increase in volumetric heating effect and COP per degree of subcooling at the fixed condensing temperature. y_2-factor measures the percentage increase in volumetric heating effect per degree of internal superheating at the fixed evaporation temperature. y_3-factor measures the percentage increase in COP per degree of internal superheating [19]. Additionally, the significance of the y_2 and y_3 factors lie in their role as indicators of how the internal heat exchanger (IHEX) will impact volumetric heating capacity and COP.

Propane and propylene show relatively high y_1-factor values at 3.20% and 3.51%, respectively, indicating significant gains in performance due to subcooling. This effect is especially strong because 80°C is near their critical temperature, which increases the benefits of subcooling as the temperature approaches that point. For butane, isobutane, and isopentane, the y_1-factor ranges from 1.33% to 1.52%, reflecting moderate benefits from subcooling. Ammonia demonstrates a lower y_1-factor of 0.69%, suggesting limited performance improvement with subcooling.

Hydrocarbons such as propane and propylene show positive y_2-factor values, indicating improved performance through superheating. They also exhibit positive y_3-factors, meaning their COP increases under superheating. In contrast, ammonia demonstrates negative y_2 and y_3-factors, suggesting that superheating has a negative effect on its volumetric heating effect and COP.

The hot gas temperature after isentropic compression ($T_{1c,is}$) is another important consideration for system design, as high discharge temperatures can affect compressor reliability and durability as well as lead to oil degradation. High temperatures can cause oil to degrade more quickly, reducing its effectiveness as a lubricant and coolant. This degradation can result in increased friction, overheating, and the formation of harmful deposits, which can further compromise the performance and lifespan of the compressor. Ammonia has the highest hot gas temperature 182°C, which is significantly higher than the hydrocarbons. Propylene and propane exhibit lower hot gas temperatures of 97°C and 88°C, respectively. Butane and isobutane demonstrate even lower hot gas temperatures of 80°C, which can reduce thermal stress on system components,

Cycle Performance Properties at 80°C / 0°C

	Propane	Butane	Isobutane	Pentane	Isopentane	Ammonia	Carbon Dioxide	Propylene	Dimethyl Ether
Refrigerant No	R290	R600	R600a	R601	R601a	R717	R744	R1270	RE170
P_1/P_2	6.60	9.80	8.57	14.86	13.22	9.64	N/A	6.37	8.35
Volumetric Heating Effect (VHE) (kJ/m^3)	2297	677.8	974.8	224.1	288.4	4239	N/A	2851	1954
COP_{Ideal}	1.55	2.05	1.86	2.19	2.11	2.37	N/A	1.55	2.19
η_{Carnot}	0.45	0.60	0.55	0.64	0,62	0.69	N/A	0.45	0.64
y_1 (%/°C)	3.20	1.52	1.92	1.33	1,46	0.69	N/A	3.51	1.27
y_2 (%/°C)	0.78	0.49	0.64	0.43	0,49	-0.18	N/A	0.62	0.71
y_3 (%/°C)	0.66	0.37	0.51	0.30	0,34	-0.18	N/A	0.53	0.11
$T_{1c,is}$ (°C)	88.45	80.00	80.00	80.00	80.00	182.20	N/A	97.07	97.19

Analyses are performed at 80°C condensation temperature and 0°C evaporation temperature. Since the critical temperature of carbon dioxide is 31°C, the evaluation could not be performed. Transcritical analysis is performed for carbon dioxide.

Table: Görkem Balyaligil • Source: Engineering Equation Solver (EES) • Created with Datawrapper

Figure 4. Cycle Performance Properties of the Selected Refrigerants [16 – 18]

3. Methods

The significance of this study lies in its comprehensive approach to defining boundary conditions that encompass most systems currently in operation. To ensure the evaluation was inclusive and robust, a detailed literature review was conducted to examine different generations of district heating systems. Based on this review, the forward and return temperature ranges for district heating networks, which served as the basis for the analysis, were identified. A similar methodology was applied to determine the characteristics of potential heat sources. Through the literature review, viable heat sources and their corresponding temperature values for heat pump applications were established.

To analyze heat pump performance, two distinct cycle designs were employed: a basic cycle and a cycle incorporating an internal heat exchanger (IHEX). These models were developed using the Engineering Equation Solver (EES), with thermodynamic property data sourced from REFPROP [16 - 17]. Numerical analyses were subsequently performed to evaluate system performance under varying conditions.

3.1. Boundary conditions of heat pump cycles

This section outlines the boundary conditions considered in the analysis of heat pump cycles.

3.1.1. Forward and return temperatures in district heating generations

District heating systems have evolved significantly, enhancing efficiency, sustainability, and technology to meet changing energy demands and climate goals. Figure 5 illustrates the temperature ranges of different generations. The first generation utilized steam-based systems powered by coal, which were inefficient, required high temperatures, and produced significant carbon emissions. The second generation introduced pressurized hot water systems with improved insulation, reducing heat losses but still relying on fossil fuels. The third generation advanced to low-temperature hot water systems (below 100°C) that integrated renewable energy, waste heat, and cogeneration, while using smaller, insulated pipes. The fourth generation operates at temperatures of 70°C or lower, optimizing heat distribution with renewable sources like geothermal and solar, and utilizing smart grids for flexibility and carbon reduction. Fifth-generation systems further this progress by operating at low temperatures with decentralized, bidirectional energy flows, relying on building-level heat pumps to achieve nearly zero carbon emissions through thermal energy sharing and smart technologies [20–21]. The development of district heating systems in Europe varies significantly due to regional energy policies, technological advancements, and environmental priorities. While Germany, Czechia, and Poland primarily use second- and third-generation systems, Sweden and Denmark are at the forefront of adopting third- and fourth-generation technologies, driven by advanced infrastructure, renewable energy integration, and ambitious climate goals [2].

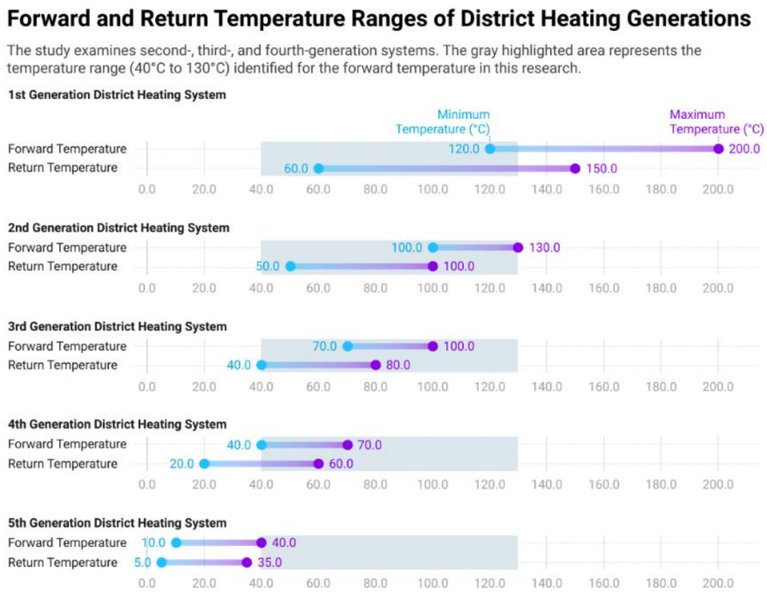


Figure 5. Forward and Return Temperature Ranges of District Heating Generations [20 - 21]

3.1.2. Heat sources and temperature levels

In this study, a wide range of heat sources has been considered for integration into district heating systems, reflecting both conventional and emerging technologies. The selected heat sources include sea water, lake water, river water, sewage water, data centers, electrolysers, carbon capture systems, district cooling systems, industrial waste heat, and geothermal energy. These heat sources have diverse temperature ranges presented in Figure 6, ranging from low-temperature sources such as natural water bodies and sewage water to higher-temperature sources like industrial waste heat, geothermal energy, and emerging technologies such as electrolysers and carbon capture systems. The heat source temperature range used in this study covers all the possible heat sources for a DH heat pump. By incorporating these sources, the study aims to address the growing need for decarbonized heating solutions while optimizing the utilization of locally available energy.

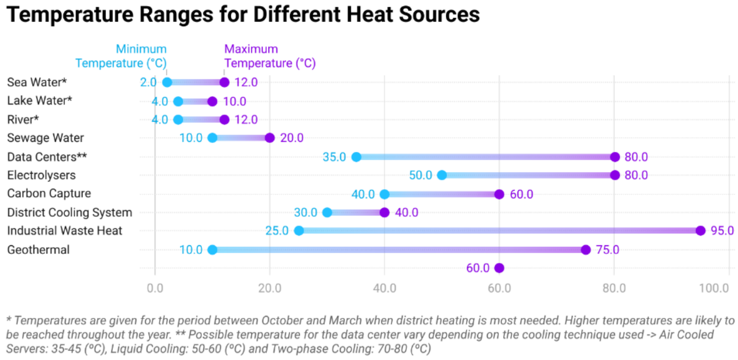
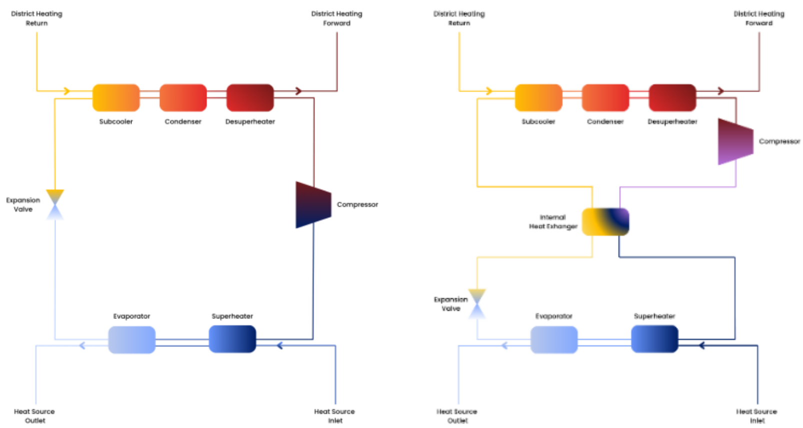


Figure 6. Temperature Ranges for Different Heat Sources [22]

3.2. Thermodynamic cycles

This paper aims to compare the performance of heat pumps operating with different working fluids, while keeping the cycle layouts consistent. To achieve this, the focus is placed on simple cycle configurations, as illustrated in Figure 7a and Figure 7b.

Figure 7a shows the layout and temperature-heat diagram of a standard cycle, consisting of the minimum required components. In this cycle, the working fluid absorbs heat from the heat source during evaporation and is then superheated before entering the compressor. The compressor increases the pressure and temperature of the working fluid, enabling heat rejection at higher temperatures. The heat rejection process includes desuperheating, condensation, and subcooling. After releasing heat, the working fluid is expanded through a throttling process, returning it to the low-pressure side of the cycle. Figure 7b illustrates a cycle incorporating an internal heat exchanger (IHEX). The IHEX exploits the potential for additional subcooling by using the relatively warm liquid refrigerant from the high-pressure side to further superheat the low-pressure/temperature refrigerant. This enables further superheating of the refrigerant before entering the compressor. The scope of this analysis is to single-stage cycles without devices for expansion work recovery.



Figures 7a and 7b. Basic Cycle and Basic Cycle with IHEX Design

3.3. Heat pump modelling assumptions

For modeling and analysis, several assumptions were made to ensure consistent and comparable results across the cycle, which are detailed in Table 1.

Heat Pump Modelling Assumptions	Basic Cycle	Basic Cycle with IHEX
Subcooling	5 K	
Superheating	5 K	
Isentropic Efficiency	80 %	
Motor Efficiency	100 %	
Pinch Point Temperature Difference	3 K	
Internal Heat Exchanger (IHEX) Efficiency	-	60%

Table 1. Heat Pump Modelling Assumptions

4. **Results and Discussion**

A comprehensive analysis of COP was conducted for three different generations of district heating systems, considering varying heat source temperature ranges and system design parameters. The heat source temperatures were analyzed within the range of 10°C to 80°C, with the following constraints applied based on the generation of the district heating system. For second-generation district heating systems, the analysis assumed a minimum temperature difference of 40°C between the district heating forward temperature and return temperature, utilizing the entire specified heat source temperature range. Similarly, for third-generation systems**,** the analysis was conducted with a minimum temperature difference of 30°C, also covering the full range of heat source temperatures. The analysis for fourth-generation district heating systems was limited to heat source temperatures of up to 50°C, with the temperature difference between the district heating forward temperature and the heat source temperature set at a minimum of 20°C. This restriction was imposed to align with the operational characteristics of fourth-generation systems, which are designed to operate at lower temperature levels to improve efficiency and integrate renewable energy sources effectively.

4.1.1. Basic Cycle Analysis

The figure 8 presents the COP results for the basic cycle shown in Figure 7a, under the boundary conditions of three district heating generations, as defined in Figure 5. For each heat source and forward temperature, the three refrigerants with the highest COP values are highlighted.

A colorbar on the right side of the figure displays the COP values, providing a visual representation of refrigerant efficiency under specified conditions. The analysis ranks refrigerants based on their COP, with the refrigerant exhibiting the highest COP positioned first, the second highest in the middle, and the third highest placed below.

R717, RE170, R600, and R600a demonstrate superior performance in second-generation systems where the forward temperature exceeds 100°C. Among these refrigerants, RE170 and R717 typically rank as the top two performers in terms of COP, while the third position alternates between R600 and R600a.

For third-generation systems, R717 and RE170 consistently achieved high COP values across all temperature levels. R600 also maintained competitive COP values throughout much of the range but was surpassed by R1270 as the top-performing refrigerant at 90°C. At 80°C, R600a emerged alongside R717 and RE170 as one of the leading refrigerants, indicating its suitability for moderate-temperature applications. However, at 70°C, R600a’s COP decreased, while R717, RE170, and R600 continued to demonstrate superior COP values.

In low-temperature applications characteristic of fourth-generation systems, R717 and RE170 maintained their positions as top-performing refrigerants across all temperature levels. At 60°C and 50°C, R600 joined R717 and RE170 as one of the most efficient refrigerants. At 40°C, R744 emerged as the refrigerant with highest COP alongside R717 and RE170, showcasing its suitability for operation with low return temperature from DH.

It is important to note that results for R601 and R601a could not be included in this evaluation due to limitations in their thermodynamic properties. Specifically, when the analysis was conducted with 5°C superheat, the refrigerants remained in the two-phase region after compression, which prevented the analysis from being performed. These refrigerants require a minimum of 10°C superheat or higher for proper analysis.

Additionally, it is worth mentioning that the normal boiling points of R601 and R601a are higher than 25°C. Therefore, it is important to consider the normal boiling temperature when evaluating these refrigerants. The availability of these refrigerants should be checked in relation to the heat source temperature to ensure optimal system perfrmance.

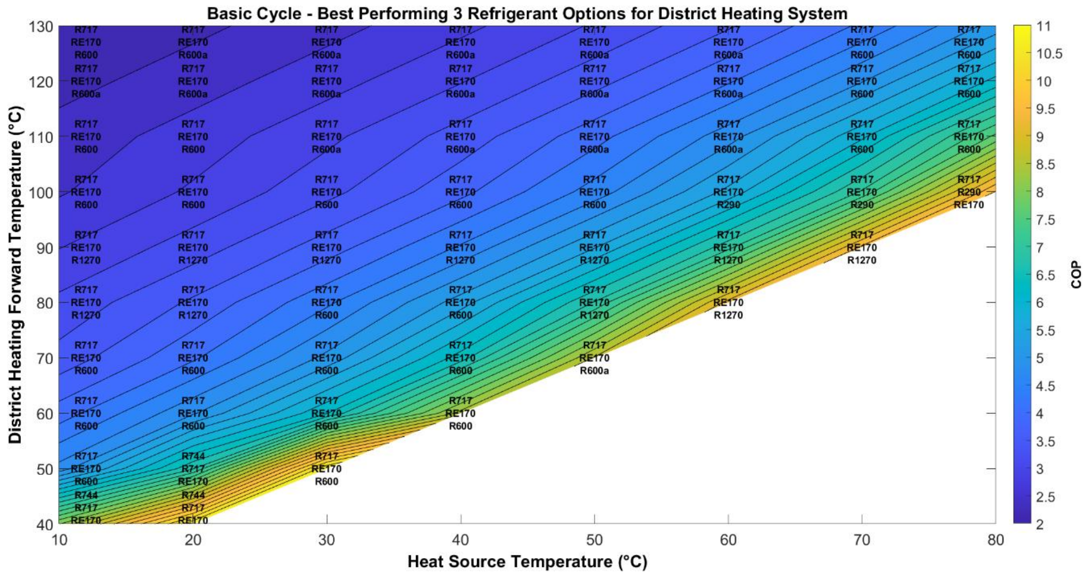


Figure 8. Basic Cycle – Best Performing Refrigerant Options for District Heating's Large Scale Heat Pumps

While this ranking provides a clear overview of each refrigerant's performance, Figure 9 further illustrates the relative performance differences. This figure offers valuable insights for selecting the most effective refrigerant options across various applications, enabling a comprehensive comparison of efficiencies. Notably, R717 is highlighted as a benchmark refrigerant in third-generation district heating systems due to its superior COP values compared to the selected refrigerants.

Basic Cycle - Performance Comparison of Refrigerants: COP Difference Relative to R717 for 3rd Generation District Heating System

COP Percentage Difference

−40.00 5.00

Heat Source Temperature (°C)	District Heating Forward and Return Temperature (°C)	R290	R600	R600a	R717	R1270	RE170
10	100-70	−24%	−22%	−28%	2.65	−19%	−10%
10	90-60	−18%	−15%	−20%	2.83	−14%	−5%
10	80-50	−17%	−15%	−19%	3.27	−14%	−6%
20	100-70	−23%	−21%	−27%	2.98	−19%	−10%
20	90-60	−20%	−17%	−22%	3.33	−17%	−8%
20	80-50	−17%	−14%	−18%	3.78	−14%	−6%
30	100-70	−22%	−20%	−26%	3.39	−17%	−10%
30	90-60	−19%	−16%	−21%	3.86	−16%	−8%
30	80-50	−16%	−13%	−17%	4.47	−13%	−6%
40	100-70	−20%	−19%	−24%	3.92	−16%	−9%
40	90-60	−18%	−15%	−19%	4.56	−15%	−7%
40	80-50	−15%	−12%	−15%	5.45	−12%	−6%
50	100-70	−18%	−17%	−22%	4.64	−13%	−9%
50	90-60	−16%	−14%	−18%	5.56	−13%	−7%
50	80-50	−13%	−11%	−14%	6.93	−11%	−6%
60	100-70	−15%	−16%	−20%	5.66	−10%	−8%
60	90-60	−13%	−13%	−16%	7.07	−11%	−7%
60	80-50	−11%	−10%	−12%	9.40	−9%	−5%
70	100-70	−10%	−14%	−18%	7.21	−4%	−8%
70	90-60	−10%	−11%	−14%	9.62	−6%	−6%
80	100-70	−3%	−13%	−15%	9.83	7%	−7%

Figure 9. Basic Cycle Performance Comparison of Refrigerants

In a basic cycle for 3rd generation district heating, R717 (ammonia) consistently outperforms every alternative refrigerant, with COP penalties for others ranging from −3% to −28%. R600a suffers the largest losses, followed by R290 and R600, while R1270 and RE170 trail by smaller but still consistent margins. The performance gap is most pronounced at low source temperatures with high temperature lifts and narrows as source temperature increases, with R290 notably closing to just −3% at 80°C. Overall, ammonia stands well ahead of the field in the basic cycle, though the relatively modest difference of R1270 and RE170 may make them worth considering where safety or regulatory constraints rule out ammonia.

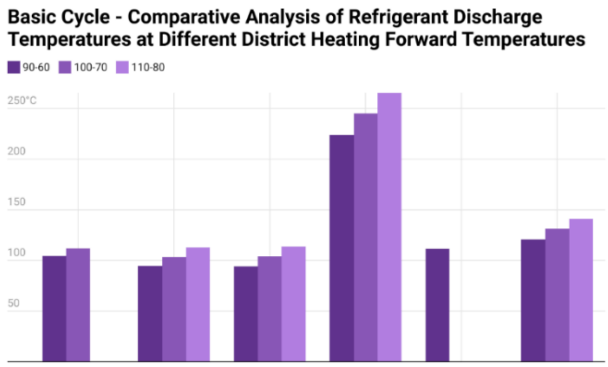


Figure 10 Basic Cycle Compressor Discharge Temperature Comparison of Refrigerants

While refrigerant selection is largely based on thermodynamic performance, compressor discharge temperature must also be considered due to its impact on system reliability. Designing compressors for high temperatures requires careful consideration of tolerances, as the critical point of the working medium and compressor operating constraints at high temperatures and pressures can pose significant limitations. Additionally, lubrication at high temperatures is a critical issue, as most used compressor oils have a safety limit of 180°C to avoid oil degradation [23].

Among the refrigerants evaluated, R717 demonstrates superior COP but generates significantly high discharge temperatures that exceed the oil degradation threshold, potentially hindering its practical application in high-temperature systems. However, in high-temperature heat pumps, this challenge can be mitigated by using specialized oils designed to withstand the elevated discharge temperatures of ammonia. Conversely, refrigerants such as R290, R600, R600a, and RE170 exhibit much lower discharge temperatures.

4.1.2. Basic Cycle with IHEX Analysis

The Figure 11 presents the COP results for the basic cycle with IHEX shown in Figure 7b, under the boundary conditions of three district heating generations, as defined in Figure 5.

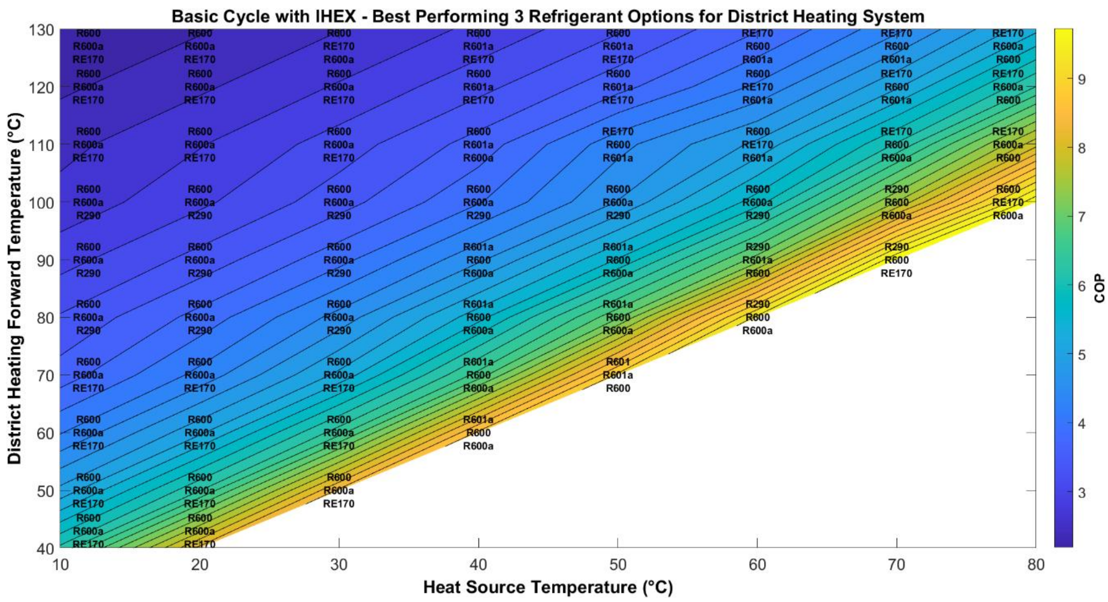


Figure 11: Basic Cycle – Best Performing Refrigerant Options for District Heating's Large Scale Heat Pumps

For second-generation systems with forward temperatures above 100°C, the addition of the IHEX significantly improved COP of refrigerants across the temperature range. Refrigerants such as RE170, R600, and R600a showed enhanced COP due to the increased superheating and subcooling provided by the IHEX. For low heat source temperatures, R600, R600a, and RE170 exhibit high COP values. However, as the heat source temperature increases, R601a takes the place of R600a, becoming one of the best-performing refrigerants alongside R600 and RE170, achieving even higher COP values.

With forward temperatures between 70°C and 100°C, the use of an internal heat exchanger enhances the performance of several refrigerants, particularly R600, R600a, R290, and R601a. These refrigerants benefit significantly from the IHEX. However, the data reveals that R717, which performed well in the basic cycle for third-generation systems, show limited presence or reduced efficiency in the IHEX cycle at these temperature ranges.

In fourth-generation systems, a similar trend to that observed in second-generation systems is evident, as the addition of the IHEX continues to enhance refrigerant performance across the temperature range, improving efficiency and COP values for refrigerants like RE170, R600, R600a and R601a.

Overall, the inclusion of an internal heat exchanger enhances the thermodynamic properties of certain refrigerants, allowing them to operate efficiently across a broader temperature range. The IHEX cycle demonstrates improved flexibility and efficiency, making it a valuable modification for optimizing heat pump performance across various district heating generations.

The Figure 12 presents the relative performance of selected refrigerants compared to R717 in third-generation district heating systems using a Basic Cycle. In a basic cycle with IHEX for 3rd generation district heating, R717 is generally outperformed by several alternatives. R600 consistently delivers the highest COP advantage at low-to-mid source temperatures, followed closely by R600a and RE170, while R601 and R601a also surpass R717 where they are operationally feasible (above ~40–50°C source temperatures). R290 and R1270 are the only refrigerants that underperform R717 across most conditions, though R290 notably flips to a significant 7% advantage at 80°C. Overall, the differences remain modest, but the pattern clearly shows R717 sitting in the middle of the pack rather than at the top in this particular cycle configuration

Basic Cycle with IHEX - Performance Comparison of Refrigerants: COP Difference Relative to R717 for 3rd Generation District Heating System

COP Percentage Difference
−3.00 13.00

Heat Source Temperature (°C)	District Heating Forward and Return Temperature (°C)	R290	R600	R600a	R601	R601a	R717	R1270	RE170
10	100-70	-3%	4%	1%	N/A	N/A	2.65	-3%	3%
10	90-60	-1%	4%	2%	N/A	N/A	2.83	-2%	3%
10	80-50	0%	4%	3%	N/A	N/A	3.27	-1%	3%
20	100-70	-3%	3%	1%	N/A	N/A	2.98	-3%	2%
20	90-60	-2%	3%	2%	N/A	N/A	3.33	-2%	3%
20	80-50	-1%	4%	2%	N/A	N/A	3.78	-1%	3%
30	100-70	-3%	3%	1%	N/A	N/A	3.39	-3%	2%
30	90-60	-2%	3%	1%	N/A	N/A	3.86	-3%	2%
30	80-50	-1%	3%	1%	N/A	N/A	4.47	-2%	2%
40	100-70	-3%	2%	0%	N/A	4%	3.92	-3%	2%
40	90-60	-2%	2%	1%	N/A	3%	4.56	-3%	2%
40	80-50	-1%	2%	1%	N/A	3%	5.45	-2%	2%
50	100-70	-2%	2%	0%	4%	3%	4.64	-2%	1%
50	90-60	-2%	1%	0%	3%	2%	5.56	-2%	1%
50	80-50	-1%	1%	0%	2%	2%	6.93	-2%	1%
60	100-70	-1%	1%	-1%	3%	2%	5.66	0%	1%
60	90-60	-1%	1%	-1%	2%	1%	7.07	-1%	0%
60	80-50	-1%	0%	-1%	1%	0%	9.40	0%	0%
70	100-70	1%	0%	-1%	1%	1%	7.21	4%	0%
70	90-60	1%	-1%	-1%	0%	0%	9.62	2%	0%
80	100-70	7%	-1%	-2%	0%	-1%	9.83	13%	0%

Table: Görkem Balyaligil • Created with Datawrapper

Figure 12: Basic Cycle with IHEX Performance Comparison of Refrigerants

5. Conclusions

This comprehensive analysis of COP across three generations of district heating systems highlights the significant impact of heat source temperature and system design parameters on refrigerant performance. The study reveals that R717, RE170, R600, and R600a consistently demonstrate superior COP values in second-generation systems, while R601a emerges as a strong contender in higher temperature applications. Notably, the addition of an internal heat exchanger (IHEX) positively affects all generations, enhancing refrigerant performance by improving superheating and subcooling, which leads to higher COP values.

The findings indicate that while R717 remains a benchmark refrigerant, alternatives such as R600a and R600 exhibit competitive COP values, especially at lower heat source temperatures. The analysis also underscores the importance of considering compressor discharge temperatures in the selection of refrigerants, as high discharge temperatures can pose challenges for system reliability. Overall, the integration of IHEX technology proves to be a valuable strategy for optimizing heat pump performance across various district heating generations, allowing for improved efficiency and flexibility in refrigerant selection.

The results indicate that changes in cycle design can significantly affect refrigerant performance. Therefore, future work could focus on developing refrigerant-specific cycle designs and conducting performance analyses to further optimize COP and heat pump performance.

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