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ADVANCING DECARBONIZED SUSTAINABLE DEVELOPMENT WITH RENEWABLE TECHNOLOGIES FOR CLIMATE RESILIENCE

Decarbonizing the heating sector is a critical component of the European Union's energy transition strategy aimed at achieving climate neutrality by 2050. Renewable technologies play a pivotal role in this effort, with district heating systems serving as vital platforms for integrating diverse renewable energy sources such as geothermal, bioenergy, solar thermal, and large-scale heat pumps. These technologies enhance system flexibility and support thermal-electric sector coupling by efficiently utilizing recovered energy from waste heat and various renewable heat sources, including geothermal energy, surface water, wastewater, and industrial waste heat. This article presents an analysis of large-scale heat pump installations connected to district heating networks, drawing on case studies across Europe. Key parameters and the number of installations are summarized. The findings emphasize that achieving high system efficiency and significant emissions reductions depends on the careful selection and integration of renewable technologies. Large-scale heat pumps, as part of a broader renewable technology portfolio, are essential enablers of Europe's decarbonized and climate-resilient sustainable development goals.

1. INTRODUCTION

In the face of growing climate challenges and the goal of achieving climate neutrality by 2050, the transformation of energy systems has become one of the European Union's top priorities. Reducing greenhouse gas emissions, developing renewable energy, and improving energy efficiency are key pillars of EU climate and energy policy. The heating sector, responsible for a significant share of final energy consumption and CO_2 emissions in Europe, plays a particularly important role in this process. According to the International Energy Agency (IEA), space heating in buildings accounts for around

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40% of global final energy consumption and nearly one-third of energy-related CO_2 emissions. Therefore, decarbonizing heat sources used in residential and public buildings is of crucial importance.

Heat pumps, as a highly efficient and low-emission technology, are considered one of the most important tools for transitioning from fossil-fuel-based systems to sustainable energy solutions. According to analyses by the European Environment Agency (EEA), replacing gas boilers with heat pumps can reduce CO_2 emissions by 60–80%, depending on a country's electricity mix. In countries with low-emission electricity production (e.g., Norway, Sweden), emissions reductions can approach 100%, making heat pumps virtually zero-emission over their operational lifetime.

In the context of urban and regional heating systems like district heating (DH), large-scale heat pumps (LSHPs) are a key technology that enables the integration of renewable energy sources, increases operational flexibility, and supports sector coupling strategies. Large-scale heat pumps (LSHPs) have been used in Europe since the late 1970s to reduce fossil fuel dependence. Sweden and Switzerland were among the early adopters, integrating LSHPs into district heating (DH) networks. In recent years, driven by the tightening of EU climate targets, the number of such installations has grown rapidly, and LSHPs play a growing role in enabling low-carbon DH across Europe [1].

District heating systems play a vital role in Europe's energy transition by enabling the effective integration of renewable energy sources and contributing to improved environmental outcomes. There are more than 17 000 district heating and cooling networks across Europe, which together account for about 13% of the continent's total heat market [2, 3]. Given the European Union's target of achieving climate neutrality by 2050, a deep decarbonization of the heating sector is essential. DH networks serve as a fundamental platform for incorporating renewable sources such as geothermal energy, bioenergy, solar thermal energy, energy storage (TES), and LSHPs [4].

In 2022, global district heating production exceeded 17 EJ, with Europe being a significant contributor to this volume. Despite their benefits, DH systems are still responsible for approximately 4% of global CO_2 emissions, highlighting the need to adopt more flexible and low-emission solutions. Countries such as Denmark, Sweden, and Austria already produce more than half of their district heat from renewable sources, utilizing technologies such as combined heat and power (CHP), renewable-fuelled boilers, and heat pumps [4, 5].

The growing share of variable renewable energy (VRE) technologies in the electricity grid demands greater operational flexibility in DH networks. This flexibility is achieved through thermal energy storage (TES), demand-side management, and advanced control systems, enabling dynamic balancing of supply and demand in future energy systems. In this context, large and aggregated heat pumps represent a key component, linking thermal and electrical systems and supporting sector coupling strategies. Large-scale heat pumps currently supply about 1–2% of district heating in Europe, with higher shares in countries like Norway (~13%) and Sweden (> 8%). Under EU decarbonization scenarios, LSHPs could provide up to 25% of district heating by 2050 [3, 6].

This article aims to present LSHPs installations connected to district heating (DH) networks, based on collected data from case studies across Europe. The LSHP projects are summarized in terms of heat source types, coefficient of performance (COP) values, temperature ranges, used refrigerants, and number of installations. This article also analyzes the potential and application of LSHPs as a key technology for decarbonizing DH systems in Europe.

2. LSHPs AS A DECARBONIZATION TOOL IN DH NETWORKS

LSHPs used in DH systems vary in scale – from individual residential installations to large industrial and urban units. Effective deployment of large heat pumps requires advanced management of their responsiveness to control signals and participation in energy markets, thereby increasing the flexibility and resilience of the systems. Modern DH networks are evolving toward low-temperature fourth- and fifth-generation systems (4GDH, 5GDH). Temperature profile configurations enable the integration of decentralized renewable sources and require the implementation of advanced control and optimization methods. Thermal energy storage systems, particularly sensible heat storage, enhance the potential for load shifting, while coupling TES with large heat pumps allows decoupling of heat production from consumption, reducing peak loads and increasing network resilience.

A crucial factor in heat pump efficiency is proper alignment with operating conditions and heat sources. Large-scale systems often use stable energy sources such as groundwater, wastewater, and surface water, which allows for high efficiency throughout the year. Flexibility is measured by the ability to modulate electrical demand in response to control signals, considering parameters such as power, operation time, and recovery period.

Figure 1 presents a conceptual overview depicting a system of large-scale heat pumps LSHPs that utilize renewable thermal energy from various heat sources. This system serves as a central component of modern (DH) infrastructure, providing environmentally friendly and energy-efficient heating to entire residential neighborhoods.

Heat pumps extract thermal energy from various types of heat sources. This paper primarily focuses on the above-mentioned heat sources, including:

- geothermal energy, which provides a stable and year-round source of heat from underground;
- seawater, lake and river water, or reservoirs, which offer significant heat storage capacity and favorable temperature profiles;
- treated municipal wastewater (sewage), which contains considerable amounts of recoverable heat before discharge into the environment;

• industrial wastewater, often with elevated temperatures due to production processes, making it an efficient source of heat recovery.

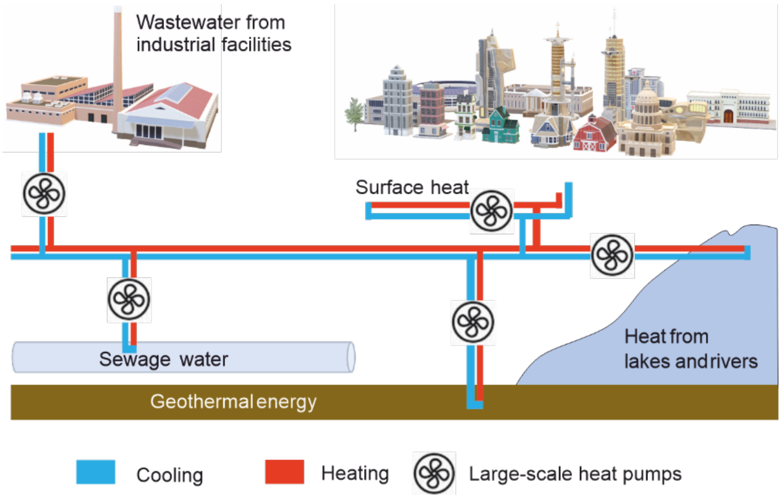

Fig. 1. Heat sources for LSHPs in sustainable district energy networks

Heat pumps raise the temperature of the extracted heat to usable levels for central heating systems (typically 55–75 °C), enabling direct supply to district heating networks that serve multiple residential or commercial buildings.

Technical and environmental benefits of heat pumps involve:

• significant reduction in CO_2 emissions compared to conventional heating systems such as gas or coal-fired boilers,

• compatibility with low-temperature heating systems, which increases overall system efficiency,

• flexibility in integrating multiple heat sources, enhancing energy security and system resilience,

• high energy efficiency, particularly in continuous operation.

Such systems are increasingly implemented in modern residential developments and sustainable urban planning initiatives, playing a key role in the energy transition and decarbonization of the heating sector.

The term high-temperature heat pump or LSHPs is frequently used in connection with industrial heat pumps, mainly for waste heat recovery in process heat supply. There are high-temperature heat pumps with heat sink temperatures ranging between 100 and 140 °C, and even more than this range for industrial purposes. The authors summarized the extent of temperature levels of the heat source and heat sink for conventional and industrial or high-temperature heat pumps, as well as the temperature range scope for various conventional utilities and industrial sectors in Fig. 2 [7–9]. LSHPs are pivotal in transforming European DH systems towards sustainability.

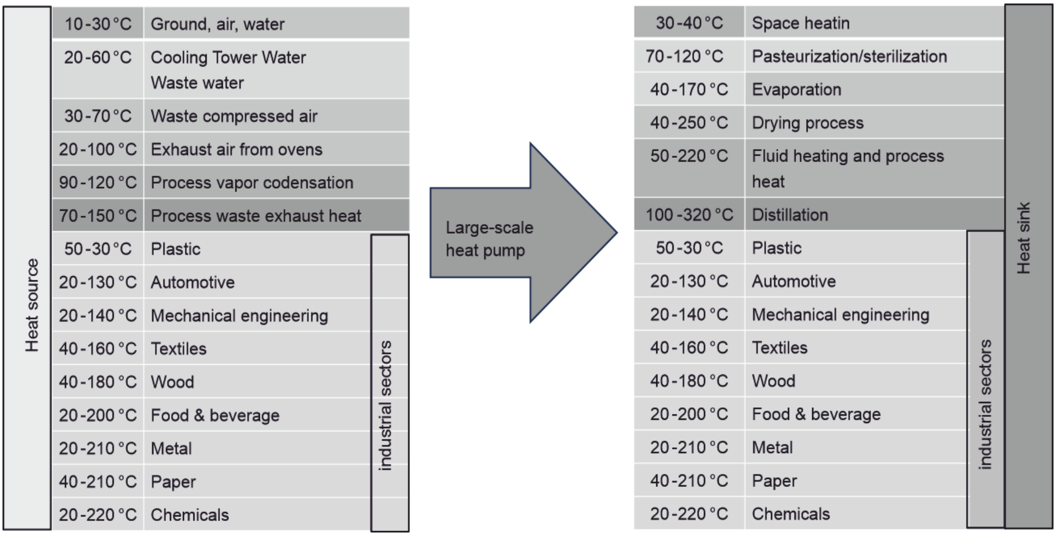

Fig. 2. Scope of heat source and heat sink temperature ranges of LSHPs for various utilities and industrial sectors

3. DEPLOYMENT OF LSHPs IN EUROPEAN NETWORKS

An analysis of heat pump installations in European cities reveals a broad diversity of technologies, capacities, and heat sources/sinks for LSHPs. France, Switzerland, Denmark, and the United Kingdom host the highest number of projects, reflecting supportive policy environments and advanced energy infrastructure development.

Heat sources include natural water bodies (lakes, seas, rivers), municipal wastewater, geothermal energy, industrial waste heat, and underground infrastructure. Source temperatures range from 4–7 °C (e.g., groundwater and river water) to over 70 °C (e.g., industrial waste heat) [10].

Water-to-water heat pumps represent the dominant technology in large-scale applications, owing to their high efficiency and ability to utilize water-based heat sources such as groundwater, surface water, or wastewater. Their COP values range from 4 to 6 [11]. Air-to-water heat pumps and water-cooled chiller-based systems are also present, especially where other sources are limited. System capacities vary widely from several hundred kilowatts to tens of megawatts, demonstrating the broad application potential in urban infrastructure [12]. Coefficient of performance (COP) values typically range from 2 to over 7.6, depending on the source and sink temperatures [10, 12].

Typical working fluids include various refrigerants such as hydrofluorocarbons, ammonia, and low-global-warming-potential alternatives, chosen according to technical performance and environmental considerations.

Figure 3 presents data from the literature [13, 14], showing the relationship between maximum supply temperature and unit capacity for large-scale heat pumps. The data, sourced from various manufacturers, indicate a trend linking temperature lift to unit size. Additionally, research reports highlight an even broader range, with some units reaching capacities above 10 MW and supply temperatures up to 275 °C.

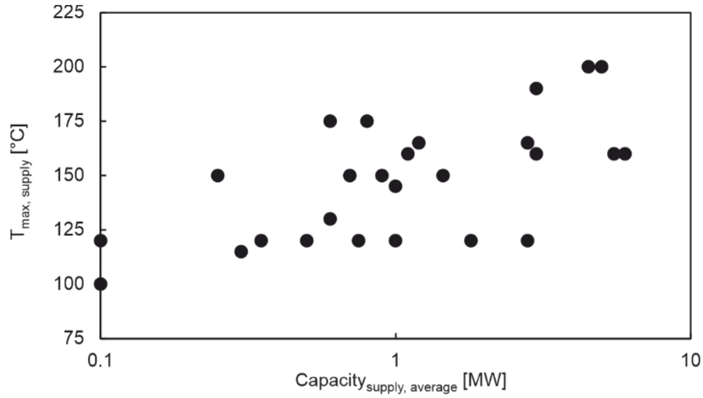

Fig. 3. Maximum supply temperature as a function of capacity

Figure 4 presents data from the literature [15] illustrating the relationship between the coefficient of performance (COP) and the mean temperature lift, which is defined as the difference between the heat pump's output and input temperatures. A bigger temperature lift usually lowers the heat pump efficiency (COP). So, COP depends on how large this temperature lift is; the smaller the lift, the more efficient the heat pump generally is.

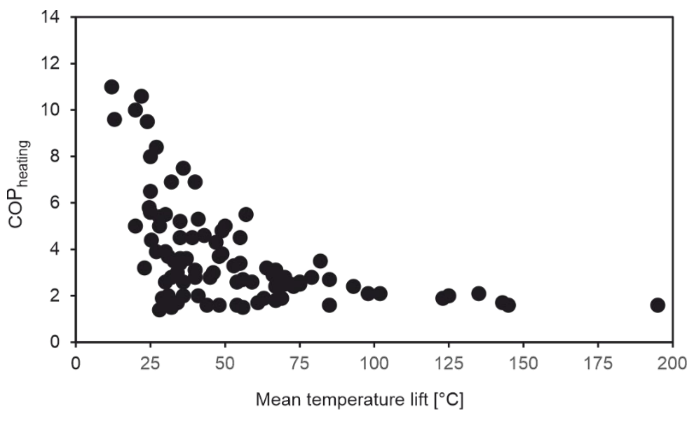

Fig. 4. COP as a function of the mean temperature lift

Tables 1–4 provide a comprehensive overview of large-scale heat pump (HP) installations implemented across various European cities using different renewable heat sources, informed by case study data collected across various EU countries [16, 17]. These tables summarize key design parameters, including the year of commissioning, HP technology type, heating and/or cooling capacity, heat source and sink with their respective temperatures, coefficient of performance (COP), and working fluid used. The data illustrate the diversity of technical configurations and environmental integrations of heat pumps within district heating and cooling systems [16].

3.1. HEAT PUMP INSTALLATIONS POWERED BY SEWAGE WATER

Table 1 provides an overview of heat pump installations powered by sewage water across various European locations. The table includes information about the location, country, year of operation start, heat pump (HP) technology used, heating/cooling capacity in megawatts (MW), the heat source and its temperature, the heat sink and its temperature, coefficient of performance (COP), and the working fluid employed.

Table 1

Heat pump installations powered by sewage water [16, 17]

Location	Start from	HP technology	Heating /cooling capacity [MW]	Heat source[a]	Heat sink[a]	COP	Working fluid
Stockholm (Hammarby), Sweden	1997	NA	80	sewage water	NA	NA	NA
Oslo (Skoyen West), Norway	2005	NA	18.4	sewage water	NA	NA	NA
Helsinki (Katri Vala), Finland	2006	NA	90	sewage water	NA	NA	NA
Amiens, France	2019	water –water HP	15	sewage water	water	NA	NA
Zurich, Switzerland	2014	wastewater –water	0.41	wastewater 7 °C	heating 50 °C	NA	R134a
Amiens, France	2019	water –water HP	15	sewage water	water	NA	NA
Bergheim I, Germany	2014	water-cooled chiller	0.293	sump water 10 °C	water	4.4	R134a
Bergheim II, Germany	NA	water- -cooled chiller	0.865	sump water 26 °C	water 80–90 °C	3.1	R744

[a]The temperatures of the heat source and the heat sink were provided, if available. NA – not available.

The installations vary significantly in scale, ranging from small systems like the 0.293 MW water-cooled chiller in Bergheim I, Germany, to large urban installations such as the 90 MW system in Helsinki, Finland. Most systems utilize sewage or wastewater as the primary heat source, although specific temperature data for the heat source is often unavailable. Technologies predominantly include water-to-water heat pumps and water-cooled chillers. Heat sink temperatures vary from moderate values around 50 °C to higher temperatures reaching up to 93 °C in some German installations. COP values, where provided, range from 3.1 to 4.4, reflecting the efficient operation of these systems. Working fluids vary, with common refrigerants such as R134a and CO_2 (R744) used depending on the installation. The data illustrates the growing role of sewage water as a renewable heat source for district heating and cooling systems, highlighting its potential for sustainable urban energy solutions.

3.2. HEAT PUMP INSTALLATIONS USING GEOTHERMAL HEAT SOURCE

Table 2 presents an overview of LSHP installations using geothermal sources across Europe, including sites in France (Créteil), Denmark, Germany, Austria, and Switzerland.

Table 2

Heat pump installations employing geothermal heat sources [16, 17]

Location	Start from	HP technology	Heating /cooling capacity [MW]	Heat source	Heat sink	COP	Working fluid
Blagnac, France	2012	water–water HP	2.4	geothermal, 59 °C	water, 70 °C	4	NA
Neuilly-sur--Marne, France	2014	water –water HP	7.645 /5.590	geothermal, 57 °C	water, 70 °C	5.7	NA
Créteil, France	2014	water–water HP	3.785 + 4.870	geothermal, 76 °C	water, 89 °C	4.65	NA
Fresnes, France	2013	water–water HP	3.625	geothermal, 50 °C	water, 62.7 °C	7.3	NA
Le Plessis--Robinson, France	2013	water–water HP	7.2	geothermal, 39 °C	water, 80 °C	4.8	R134a
Gl. Rye, Denmark	2015	two stage std. unit SMC112/116 HPO 26/28	2.048/1.584	groundwater, 2 and 35 °C	groundwa-ter, 9, 75 °C	4	R717
London, UK	2013	J&E Hall WHP 602	1.12/1.1	borehole	water, 45 °C	NA	R134a
Meyrin, Switzerland	2018	water-cooled chiller	5	groundwater	NA	NA	R1234ze
Enfield, London, UK	2019	Kensa	2.5	borehole	water, 45 °C	NA	R410a

NA – not available.

It summarizes location, country, commissioning year, heat pump type, heating and cooling capacity, source and sink characteristics, COP, and refrigerants. Most are water-to-water systems, favored for their high efficiency and geothermal compatibility. Capacities range from 1 MW to over 7 MW, serving both small urban and large DH systems. Heat source temperatures range from 2 °C to 76 °C, while sink temperatures fall between 35 °C and 89 °C. COPs range from 4.0 to 7.3. Common refrigerants include R134a, R410a, R717 (ammonia), and R1234ze, though some data are not available. The table highlights the technical and geographic diversity of geothermal LSHPs and their role in low-carbon district heating

3.3. HEAT PUMP INSTALLATIONS USING WATER HEAT SOURCES

Table 3 summarizes water-source heat pump installations across Europe, detailing location, country, start year, heat pump type, capacity (MW), heat source and sink temperatures, COP, and working fluid. Systems use various water sources: lake water (Lake Léman, Lausanne), seawater (Drammen, Cherbourg), and river water (Kingston Heights, Courbevoie). Source temperatures range from 4 °C (The Thames) to ~11 °C (seawater), with some entries marked NA. Sink temperatures vary from 45 to 90 °C. Technologies include water-to-water heat pumps and water-cooled chillers. Capacities range from 2.2 MW (Cherbourg) to 15 MW (Courbevoie), reflecting diverse scales. COPs, where reported, range from 3.0 to 4.8. Refrigerants used include ammonia (NH_3/R717), R134a, and R410a, chosen for performance and environmental impact. Overall, the table demonstrates the adaptability and efficiency of water-source heat pumps in DH, using natural water bodies as renewable, low-carbon heat sources.

Table 3

Heat pump installations employing water heat sources [16, 17]

Location	Start from	HP technology	Heating/cooling capacity [MW]	Heat source	Heat sink	COP	Working fluid
Lausanne, Switzerland	1985	water–water	4.5	the lake Leman, 6–7 °C	NA, 50–65 °C	4.8	NH_3
Drammen, Norway	2011	water--cooled chiller	3×4.5	seawater, 8–9 °C	water, 75 °C	NA	R717
Cherbourg, France	2013	water–water HP	2.2	seawater, 11 °C	water, 63 °C	3	R134a
Kingston Heights, UK	2016	Ecodan x 41 units	2.3	theThames, 4–25 °C	water, 45 °C	NA	R410a
Courbevoie, France	2019	water–water HP	15	river water, NA	water, 90 °C	NA	NA

3.4. HEAT PUMP INSTALLATIONS USING INDUSTRIAL HEAT SOURCES

Table 4 provides an overview of diverse large-scale heat pump (HP) installations in European cities that utilize a variety of unconventional or hybrid heat sources.

Table 4

Heat pump installations employing industrial heat sources [16, 17]

Location	Start from	HP technology	Heating /cooling capacity [MW]	Heat source	Heat sink	COP	Working fluid
Salzburg, Austria	2006	NA	7.5	flue gas from a biomass power plant, 50 °C	NA	NA	NA
Marstal, Denmark	2012	NA	1.5	TES, NA	NA	NA	NA
Skjern, Denmark	2014/2015	high-pressure heat pump 4 × HPAC 157	5.400/4.671	drying air, 25, 37 °C	district heating water, 47, 63 °C	6.8	R717
Bunhill, London, UK	2019	GEA	1	London underground, 24 °C	water, 75 °C		NH_3
Ghent Belgium	2019	water–water HP	0.4	cooling of CHP engine, 70 °C	water 105 °C	3	R245fa
Basel, Switzerland	2018	air-water heat pump	0.81/ 0.111	air, NA	heating, 65 °C	NA	R134a
Thônex, Switzerland	2012	water- -cooled chiller	0.338	waste heat recovery, water (geothermal probe), 14–16 °C	heating, 63 °C	NA	R134a
Brive, France	2019	water–water HP	5.5	return water of the network 60 °C	water, 85 °C	NA	R1234ze
Dijon, France	2015	water–water HP	0.419/0.255	chiller condensation, 10–15 °C	water, 90 °C	2.6	R134a
Le Mans, France	2019	water–water HP	3.7	incineration flue gas, 48 °C	water, NA	4	NA
Paris La Défense, France	2014	water–water HP	12 / 7.0	cooling towers 12 °C	water, 90 °C	4.5	R134a
Nordhavn, Copenhagen, Denmark	2018	NA	0.8	salt containing groundwater, 10.5–4.5 °C	NA	NA	R717

NA – not available.

The table lists key information such as location, country, year of operation start, HP technology, heating/cooling capacity (in MW), type and temperature of heat source, type and temperature of heat sink, coefficient of performance (COP), and working fluid used.

Several papers highlight various projects demonstrating the broad versatility of LSHPs in capturing and upgrading heat from non-traditional sources:

- flue gases from biomass and waste incineration (e.g., Salzburg, Le Mans),
- underground infrastructure (e.g., the London underground in Bunhill),
- thermal energy storage (TES) (e.g., Marstal),
- drying processes or cooling of CHP engines (e.g., Skjern, Ghent),
- cooling towers and return water from heating networks (e.g., Paris La Défense, Brive),
- geothermal probes and saltwater groundwater (e.g., Thônex, Nordhavn),
- outdoor air (e.g., Basel).

Heat pump technologies vary from water-water systems and water-cooled chillers to high-pressure industrial units. Reported capacities span a wide range from small-scale systems (e.g., 0.338 MW in Thônex) to large installations (e.g., 12 MW in Paris La Défense). COP values, where provided, vary between 2.6 and 6.8, indicating differing performance levels based on source conditions and system design.

Common working fluids include ammonia (R717), R134a, R1234 ze, and R245fa, chosen for their thermodynamic and environmental characteristics.

Overall, Table 4 highlights the adaptability of heat pumps to a wide spectrum of heat sources, both renewable and residual, reinforcing their role in urban heat decarbonization and energy efficiency improvements.

4. DISCUSSION

This discussion is based on the analysis of data presented in the previously provided tables, which primarily focus on the mentioned heat sources. It highlights the potential of high-temperature heat pumps for heat recovery and heat upgrading in industrial processes.

Figure 5 illustrates the installed heating capacity [MW_{th}] and the number of (LSHPs) installations in Europe. Apart from the industrial processes, they can also be used for heating, cooling, and air-conditioning in industrial, commercial, and multi-family residential buildings, and are increasingly often used in DH networks. By replacing fossil-fuel-based systems, large-scale heat pumps contribute significantly to the reduction of CO_2 emissions, supporting the decarbonization of the heating sector. Starting with a few 100 kW power, they can reach capacities of several megawatts, which is sufficient to provide heating and cooling purposes for the European countries, e.g., in Helsinki, Stockholm, or Oslo [18].

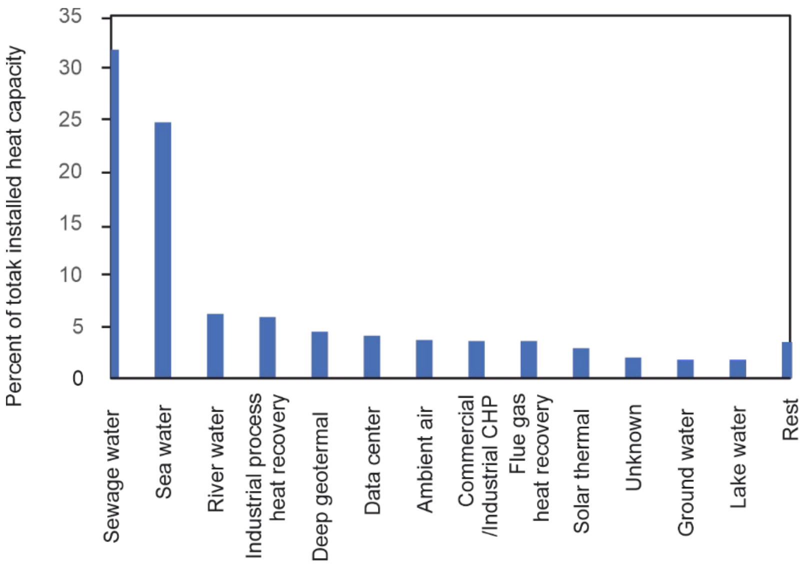

Fig. 5. Total heating capacity [MWth] of LSHP installations in Europe

Techno-economic analyses indicate that LSHPs could meet a substantial portion of urban heat demand by mid-century, particularly in regions such as the Baltic Sea area. However, their competitiveness is highly sensitive to energy prices and tax policies, necessitating flexible approaches to investment planning and market development [18].

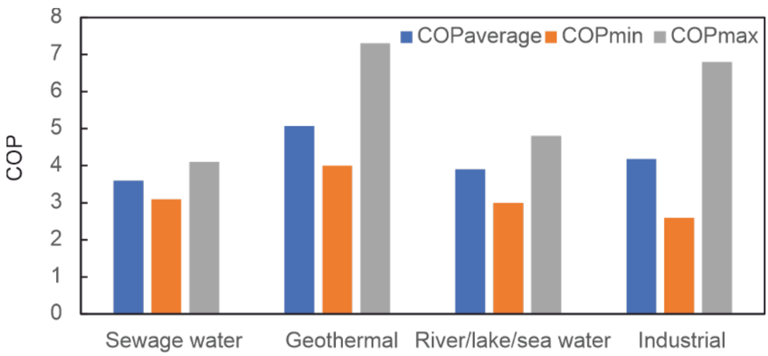

Fig. 6. COP values for different heat sources

In the case of geothermal sources, higher source temperatures result in more favourable operating conditions for heat pumps as illustrated in Fig. 6 [18]. For example, the installation in Fresnes (France), operating with a source temperature of 50 °C, achieves an impressive COP of 7.3, the highest among the examples presented. Other geothermal systems, such as those in Créteil and Le Plessis-Robinson, also achieve COP values above 4 with source temperatures ranging from 39 °C to 76 °C, confirming the efficiency of geothermal energy as a stable and high-potential heat source.

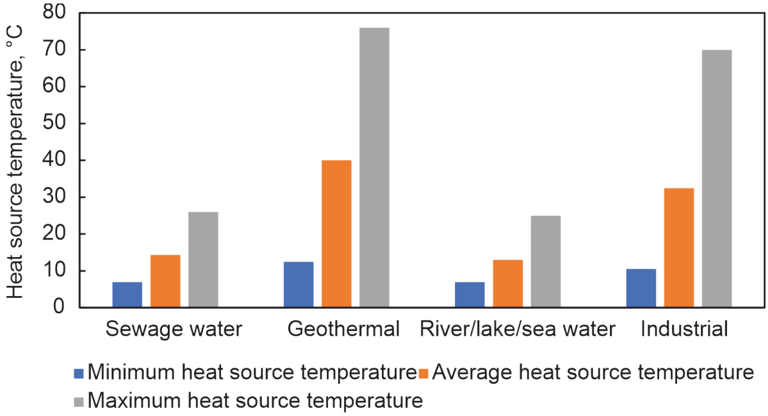

Fig. 7. Average temperature of different heat sources

Sewage and sump water sources are generally low in temperature but stable, as presented in Fig. 7 [17]. In Bergheim, Germany, one system using 10 °C water and refrigerant R134a achieves a COP of 4.4 (as shown in Table 1). Another system using 26 °C water and R744 shows a lower COP of 3.1, likely due to a high sink temperature (up to 93 °C), which increases system load (also noted in Table 2).

LSHPs using natural surface water like lakes or rivers typically operate with low temperature sources ranging from 6 °C to 11 °C, as in Fig. 7. In Lausanne, a system using Lake Léman water at 6–7 °C and ammonia achieves a COP of 4.8. In Cherbourg (as shown in Table 3), a system using 11 °C water reaches a COP of 3, showing how design and technology affect efficiency. Industrial LSHPs often use high source temperatures, like in Ghent (70 °C), which enables sink temperatures up to 105 °C but with a modest COP of 3, as in Fig. 7. In contrast, Skjern (Table 4) achieves a COP of 6.8 using drying air at 25–37 °C, showing that medium-temperature sources can perform very efficiently with the right technology.

Figures 6 and 7 show the minimum, maximum, and average values of the COP coefficients and heat source temperatures in the analysed case studies. COP values in the presented tables range from 2.6 to 7.3, and system performance is strongly influenced by the heat source temperature, its stability, and the applied technology. Generally, higher source temperatures enable better COP and higher sink temperatures. However, even low-temperature sources such as lake water or sewage can be effectively utilized thanks to modern heat pump designs. The presented tables highlight the flexibility and potential of LSHPs in Europe's energy transition and the decarbonization of heating systems. Tables 1–4 presenting LSHPs installations using various heat sources show a diversity of refrigerants that are crucial for the efficiency and environmental friendliness of the systems. Figure 8 [18] shows the number of heat pump installations using various refrigerants in the analysed case studies. Overall, the selection of the refrigerants is closely linked to the operating conditions of the heat pump, its efficiency, and environmental protection requirements.

The most commonly used refrigerants include R134a, R410a, R717 (ammonia), R1234ze, and R245fa. The choice of working fluid depends on the specifics of the installation, the temperatures of the heat source and sink, and environmental requirements. For example, R717 (ammonia) is preferred in high-efficiency systems with low environmental impact and is often used in installations using water as the heat source. R134a and R410a are popular due to their good thermodynamic properties and wide application in urban and industrial systems. In some cases, especially in newer and more environmentally friendly solutions, R1234ze is used, characterized by a low global warming potential.

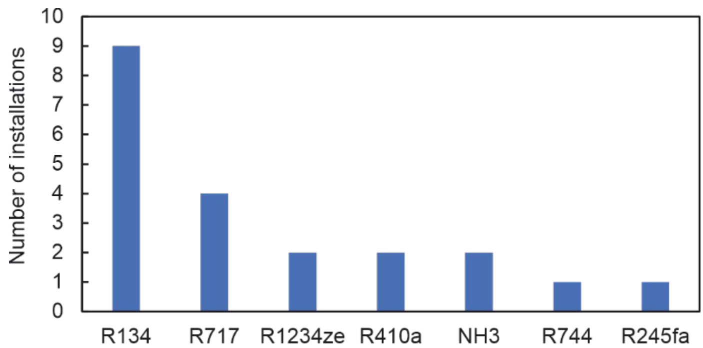

Fig. 8. The number of installations and refrigerants used in LSHP systems

Technologies such as water-to-water heat pumps and chillers offer scalable capacities; however, deployment is limited by high upfront costs, sensitivity to electricity prices, and insufficient policy support. Regulatory frameworks and financial incentives are essential, particularly in countries with low shares of renewable heating.

5. CONCLUSION

Achieving sustainable development and climate neutrality requires a profound transformation of the energy sector, with particular emphasis on reducing greenhouse gas emissions. In this context, decarbonization of heat supply systems plays a crucial role, as heating remains one of the largest sources of energy-related CO_2 emissions. Large-scale heat pumps (LSHPs), when integrated into district heating (DH) networks, represent a key technology that can effectively utilize renewable heat sources, improve energy efficiency, and contribute to the transition toward a low-carbon economy. Their deployment supports not only environmental objectives but also energy security and resilience of urban infrastructure.

The development and integration of large-scale heat pumps (LSHPs) into district heating (DH) systems are essential for meeting Europe's long-term climate and energy goals. Their wider adoption should be supported through coherent public policies, continued technological innovation, and greater engagement from investors and DH network operators.

- LSHPs contribute significantly to the transition toward low-carbon heating, utilizing renewable sources such as groundwater, lakes, rivers, and seawater in various European countries.
- These systems offer high efficiency and scalability, with coefficients of performance (COPs) ranging from 2.0–3.0 up to 7.3–7.6, and heating capacities between 1 MW and over 15 MW, suitable for both small and large-scale networks.
- Key technologies include water-to-water heat pumps and chillers, operating with refrigerants like hydrofluorocarbons, ammonia, and low-global-warming-potential alternatives.
- Challenges to broader deployment include high upfront investment costs, limited availability of suitable heat sources, sensitivity to electricity prices, and insufficient long-term policy support.

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