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Advancements in heat pump technology for shallow and deep geothermal sources: Three case studies from Germany

Arianna Passamonti[1,3]*, Simon Höckenkamp[2], Christopher Schifflechner[3] and Paola Bombarda[4]

Fraunhofer IEG, Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems, Karlsruhe, Germany[1]*, Fraunhofer IEG, Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG, Bochum, Germany[2], Technical University of Munich, Chair of Energy Systems, Garching b. Munich, Germany[3], Politecnico di Milano, Milan, Italy[4]

(*) Email: arianna.passamonti@tum.de, present address: Technical University of Munich, Chair of Energy Systems, Garching b. Munich, Germany

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ABSTRACT

Geothermal heat can be harnessed in various ways, depending on the temperature of the heat source. The geothermal heat pump (GHP) technology is particularly effective when utilized with medium to low-temperature heat sources, to produce the required temperature and power lifts. In the study the current state of research on the field of heat pump technology is presented, focusing especially on the integration between GHPs and geothermal sources.

Three case studies from Germany are investigated: two large-scale high-temperature heat pumps (HTHPs) at the location of Bochum, Germany, one for shallow and one for deep geothermal application, and a concept of a novel reversible Organic Rankine Cycle (ORC) and HTHP system.

The 500 kW_{th} heat pump for shallow geothermal application in Bochum consists of two units, a low-temperature stage with ammonia as refrigerant and a high-temperature stage using butane. The system extracts heat from a flooded shallow coal mine, operating between 12°C and 60°C and can inject pressurized water into the district heating grid at temperatures up to 120°C. A second heat pump test rig is connected to the same geothermal capacity, but designed for deep geothermal applications. In the respective project, a 500 kW_{th} HTHP prototype using water as refrigerant is aiming to produce heat up to 200°C, in a closed-loop or mechanical vapor recompression application. Finally, the envisaged integration and operation concept of the reversible ORC/HTHP 200 kW_{el} demonstrator is presented for a real geothermal combined heat and power project.

1 INTRODUCTION

Geothermal heat has been harvested for thousands of years, and its current application for heating purposes, with the development of geothermal-based heating networks, was triggered after the first oil crisis in the 1970s. In geographical regions like Iceland, where hot water is found near the surface, geothermal energy has played a significant role in the national energy supply. On the other hand, in Germany, geothermal heating plants have been built since the 1980s for district heating (DH) purposes, for example, in Neubrandenburg or Waren, and in the Upper Rhine Graben, where several boreholes were drilled simultaneously (Bracke et al. 2022). Commercial geothermal electricity generation began in 1913 in Italy (Larderello) (Cataldi and Arriaga 2020), was first established in Germany in Neustadt-Glewe in 2003, and accounts now for around 16 GW_{el} of worldwide capacity, primarily in areas with volcanic activity, like California, Indonesia, and New Zealand (Bracke et al. 2022).

Geothermal systems can be categorized into two types: closed and open systems. Closed systems, such as borehole heat exchangers, transfer heat purely by conduction, whereas open systems allow a significantly higher heat output per borehole due to the circulation of the reservoir brine. Open systems, exploiting typically hydrothermal resources, require at least one production well and one injection well, connected via a thermal water-bearing rock layer. The water found in the reservoir can be employed at its natural underground temperature or can be artificially heated. A hydrothermal system is considered the geothermal infrastructure in the case of deep and medium/deep geothermal exploitation, while an underground thermal energy storage system is considered in the case of shallow geothermal application.

Medium-temperature geothermal sources, ranging from 90°C to 150°C, enable electricity generation using binary cycles, namely Organic Rankine Cycles (ORC), and heat production through heat exchangers or high-temperature heat pumps (HTHPs) for applications such as paper drying and heating. Low-temperature geothermal sources, below 90°C, enable direct heat utilization through heat exchangers or heat pumps (HPs) (Nardini 2022). Furthermore, when temperatures drop below 30°C, geothermal heat pumps (GHPs) become the

most common application (World Energy Council 2013) and the most widespread type of geothermal surface application (Weber et al. 2022).

1.1 HYDROTHERMAL SYSTEMS AND UNDERGROUND THERMAL ENERGY STORAGE

Geothermal energy from hydrothermal systems is based on the use of hot thermal brines that move along natural pore, fissure, and fracture systems. Deep wells are furthermore employed for this application to achieve the high water temperatures required by the DH. Hydrothermal systems are already successfully commercialized and employed worldwide (Bracke et al. 2022).
The underground thermal energy storage (UTES) technology, categorized as aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and mine thermal energy storage (MTES), offers the possibility of storing heat and cold, which can stabilize the energy supply seasonally. To date, the feasibility of such storage facilities has been demonstrated in a few projects in Germany. In other countries, such as the Netherlands, aquifer storage for cooling and heating buildings is used in over 2000 projects, mostly at shallow depths (Bracke et al. 2022).

1.2 LARGE-SCALE HIGH-TEMPERATURE HEAT PUMPS AND ORGANIC RANKINE CYCLES

HPs can be used in combination with geothermal sources for heating purposes in the context of DH and industrial decarbonization, when the geothermal sources do not have sufficient temperatures and/or capacities to supply the actual local heat demand. This technology can furthermore be employed in more complex geothermal plants, which include ORCs, when the hydrothermal source is exploited at different temperature levels, for example, for combined heat and power (CHP) generation, as commonly applied in Germany (Eyerer et al. 2017).
The HP technology is state-of-the-art for supply temperatures up to 90°C (Arpagaus et al. 2018), but only a few examples are available for higher supply temperatures. Furthermore, research indicates a heightened potential for the utilization of HTHPs in DH and industrial processes (Passamonti et al. 2024). HTHPs can, in fact, be employed in the 2nd generation of district heating, which requires pressurized water with supply temperatures up to 130°C, and in industrial processes, which require pressurized water or steam at several temperature levels, with the expectation that by 2030 the technology will reach temperatures up to 200°C, covering the needed demand (Bracke et al. 2022; Wolf et al. 2014). To reach elevated temperatures while maintaining a low environmental impact, the research in the field of HTHPs moves towards the investigation of optimal working fluids (Arpagaus et al. 2018), which is also the focus of the developed HTHP reported case studies. Furthermore, common HP installations are typically developed for BTES or ATES systems; however, our research focuses on the integration of HTHPs in the context of MTES and hydrothermal systems.
Since the early 2000s, the ORC technology has experienced rapid development and is currently state-of-the-art, with more than 4.5 GW of total ORC power plant capacity installed (Wieland et al. 2023). A concept that has attracted interest during recent studies includes reversible HPs, which can also operate as ORCs (rev. ORC), with the goal of using the same equipment components. In this application, the HP condenser, evaporator, and compressor work also as the ORC evaporator, condenser, and expander, respectively. The combined implementation of a HP and an ORC in a single module allows a compact configuration, reduced CAPEX, and increased flexibility (Wieland et al. 2023).

1.3 RESEARCH FOCUS, PILOT PLANTS COMPARISON

Despite the potential for integrating HTHPs and reversible ORCs into MTES and hydrothermal sources for heat and combined heat and power, few real-world demonstrators are currently installed. In this paper, we present and compare three real-world demonstrators for HTHPs and rev. ORC. The plants are developed with various configurations, goals, and heat source types, showcasing the possible integration of geothermal sources with other renewable technologies, which contributes to flexible geothermal operation and the decarbonization of the heat and power grid.

2 OVERVIEW OF THE TECHNOLOGIES

The three configurations are presented and described, highlighting their unique elements and common aspects, each according to its main features, such as development status, specific field of application, subsurface configuration, system in which they are integrated, and components. Furthermore, their technical main characteristic parameters, like nominal operating conditions, and proven or expected performance, are reported. The technologies considered are (1) a double-stage HTHP configuration for DH application with MTES as a heat source, (2) a single-stage HTHP for industrial applications with a hydrothermal source, and (3) a rev. ORC for DH application and power production, connected to deep geothermal energy. In Table 1, the main features of each plant are reported along with their developmental status.

Table 1. Overview of the three technologies and configurations considered. Reported are the technology readiness level, the stage of development, the application, and the configuration characteristics.

(1) **Double-stage high-temperature heat pump for district heating**	
TRL	8
Development status	Test phase after installation and commissioning.
End-user	DH
Subsurface configuration	MTES
System integration	The HTHP is integrated between MTES and DH grid. Components to test the HTHP independently of the MTES and DH grid are also present.
System configuration	2 stages, connected via a 3 m^3 buffer tank.
System main components	HT stage: piston compressor, plate heat exchangers (evaporator, 3-stage condenser, superheater), and 2 expansion valves in parallel. LT stage: piston compressor, shell and plate heat exchangers (evaporator, condenser), and expansion valve.
(2) **Single-stage high-temperature heat pump for industrial applications**	
TRL, current	3
TRL, expected end of the project	5
Development status	Components development and assembly.
End-user	Industrial applications, process steam generation (e.g. pulp and paper industry).
Subsurface configuration	Potential to upgrade geothermal source temperatures above 80°C up to 200°C. During the test phase, connected to MTES (1) as a heat sink.
System integration	In the final configuration, the system can be used as HT-stage in multistage-HP systems or as HP supplied by DH or geothermal source. The compressor can be operated as a standalone steam compressor. During the test phase, sink and source conditions are simulated by a test rig.
System configuration	Water-based HTHP (screw compressor), water-based HT-test rig.
System main components	Water as working fluid, refrigerant-injected screw compressor, flooded evaporator.
(3) **Reversible Organic Rankine Cycle / high-temperature heat pump**	
TRL, current	5
TRL, expected end of the project	7
Development status	Planning phase after successful lab-scale demonstration.
End-user	DH and power grid.
Subsurface configuration	Hydrothermal reservoir.
System integration	The system is integrated between hydrothermal reservoir, DH grid, and electrical grid. It can exploit waste heat.
System configuration	HTHP with reversible compressor technology and pump for ORC operation.
System main components	Screw compressor/expander, plate evaporator and condenser, expansion valve, pump.

2.1 DOUBLE-STAGE HIGH-TEMPERATURE HEAT PUMP FOR DISTRICT HEATING

The 2-stage HTHP pilot plant was installed in 2023 in Bochum, Germany, with the goal of proving the possibility of decarbonizing the existing high-temperature DH grid using HTHPs and exploiting largely unused subsurface structures coming from the coal mining period. The system, whose nominal operating conditions are reported in Table 2, produces pressurized water at a temperature up to 120°C with a nominal thermal power production of 500 kW. Two separate stages are required due to the elevated temperature lift, namely, a low-temperature stage that runs with ammonia (R717) and a high-temperature stage that runs with butane (R600). The low-temperature stage can be bypassed when the mine water temperature is above 45°C, therefore increasing the COP of the system. Fig. 1 shows the piping and instrumentation diagram (P&ID) of the HTHP, with the two units, the intermediate buffer tank, and the hydraulic connections between the units and to the heat sink and heat source. The thermal plant is furthermore equipped with other components which allow not only to inject heat into the DH grid, but also on-site independent testing of the units by means of a 30 m^3 storage tank, 150 kW dry coolers, and a bypass heat exchanger (Passamonti et al. 2025).

Table 2. Operating conditions of the 2-stage HTHP.

Configuration	Double-stage system
Nominal produced power [kW_{th}]	500
Refrigerant	Low-T stage: R717, High-T stage: R600
Heat source type, temperature [°C]	MTES, 12–60
Heat sink type, heat transport medium	DH, pressurized water
Heat sink supply T, return T [°C]	80-120, 60-65
Nominal COP, Tlift 70K [-] (Passamonti et al. 2024)	Low-T stage: 4.23, High-T stage: 5.73 (total: 2.71)

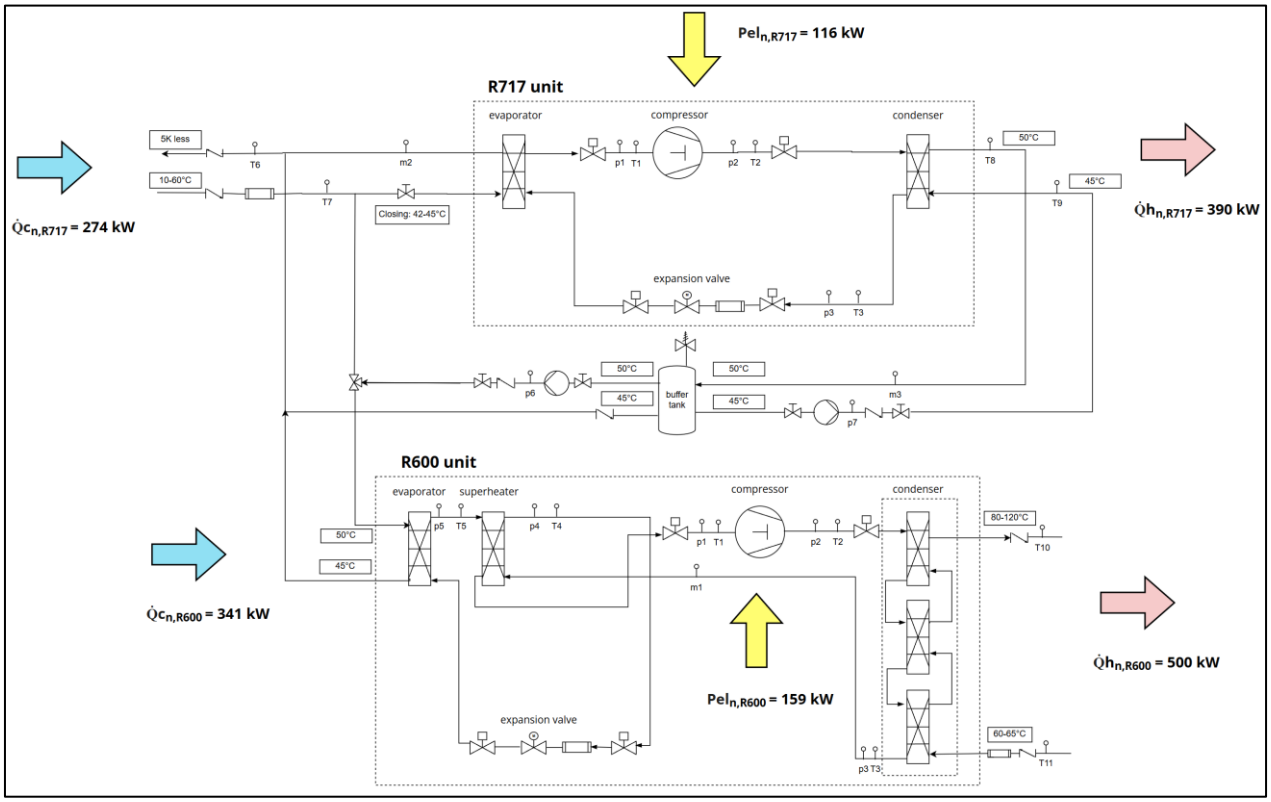


Figure 1. P&ID of the HTHP with nominal powers (Passamonti et al. 2024).

The exploitation of a flooded coal mine gallery (Fig. 2) as a high-temperature MTES was not reported previously. Its parameters are therefore of interest as an example of the utilization of an innovative geothermal heat source for high-temperature applications. The flooded mine presents the characteristics described in Table 3, with an estimated water volume of approximately 20000 m^3 and an unheated temperature of 12°C (Passamonti et al. 2024).

Table 3. Coal mine galleries (MTES) specifications (Passamonti et al. 2024).

Years of coal production [-]	1954 - 1957
Maximum mine depth [m b.g.l.]	75
Groundwater level [m b.g.l.]	23
Mine water temperature (unheated) [°C]	12
Coal extracted [t and m^3]	37043 and 27439
HT-MTES volume [m^3]	19207
Wells depth: MO1, MP1, MI1 [m b.g.l.]	64, 64, 29

The heat sink of the system is the district heating grid of Bochum south, which operates with a supply temperature between 80°C and 120°C, that varies according to the ambient air temperature as explained in Fig 2.a.. Due to the seasonal operation of the plant, the HTHP operates in different conditions throughout the winter. In particular, at the beginning of the heating season, the MTES is at its highest temperature, and the required DH supply temperature is on average around 80°C; therefore, the heat pump presents the lowest necessary temperature lift. On the contrary, at the end of the heating season, when the MTES is fully discharged, the HTHP needs to provide the highest temperature lift (70°C), as shown in Fig. 2.b.. The considerations are made on average monthly values; therefore, the HTHP is dimensioned to be able to supply the temperature lift of the worst-case scenario (110 K).

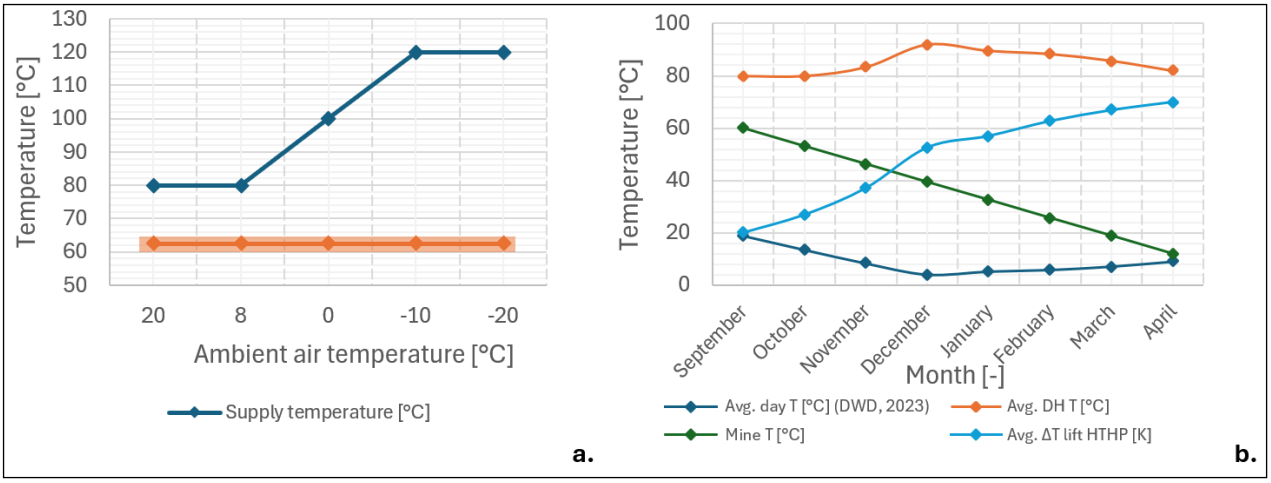


Figure 2. a. Variation of nominal DH supply temperature with ambient air temperature (blue) and nominal DH return temperature (orange), which presents ±2.5K variation. b. Heating season temperature variation of average measured day temperature, average DH temperature based on the day temperature, MTES temperature, assuming a constant heat extraction, and average temperature lift of the HTHP based on the temperature difference between heat sink and heat source, after (Passamonti et al. 2024).

2.2 SINGLE-STAGE HIGH-TEMPERATURE HEAT PUMP FOR INDUSTRIAL APPLICATIONS

Within the framework of the SteamScrew project, an infrastructure is being established to enable the development and testing of a HTHP using water as the working fluid. Key specifications of the system are summarized in Table 4. The intended target applications are industrial processes with significant heat demand, particularly those driven by steam at temperatures below 200°C, which can be served by HPs with satisfactory COPs. Furthermore, the project aims to theoretically scale up the HTHP to industrial dimensions, targeting the multi-megawatt power range.

Table 4. Operating conditions of the 1-stage HTHP.

Configuration	Single-stage system
Nominal produced power [kW_{th}]	500
Refrigerant	R718
Heat source type, temperature [°C]	Deep geothermal, lower-temperature heat pump stages, waste heat (process industry), 80-120
Heat sink type, heat transport medium	Industry, steam
Heat sink supply T [°C]	Up to 200
Nominal COP, T lift 80K [-]	3 (expected)

A major focus of the project is the water-injected screw compressor, which serves as a key component and the primary driving element of the HTHP. Water injection into the working chamber prevents excessive superheating of the fluid during compression, allowing for a single-stage compression to relatively high pressure ratios without thermal overstress. Simulations indicated favorable compressor behavior and suggested that the mass flow can be increased by water injection (Höckenkamp et al. 2024). The compressor can also be employed in mechanical vapor recompression (MVR) processes, where steam at moderate to elevated pressures (e.g., approximately 10 bar, with potential for higher pressures in future applications) and temperatures below 200°C is required.
A versatile test rig is being designed to meet multiple requirements (Fig. 3). Its primary purpose is to provide the infrastructure for vapor compressor testing, and it is integrated within a mobile HTHP skid to allow field testing. The rig is pressurized and water-based, enabling simulations of high-temperature applications such as a DH network, geothermal sources, waste heat, or the intermediate cycle above a lower-stage HP within a cascade. The system is designed to recover heat from the sink side and return it to the source side of the test subject. Waste heat from operation can be utilized in various ways, including a dry cooler as a backup, a MTES, or heat can be further utilized in the 2-stage HTHP for the DH network described in Section 2.1.

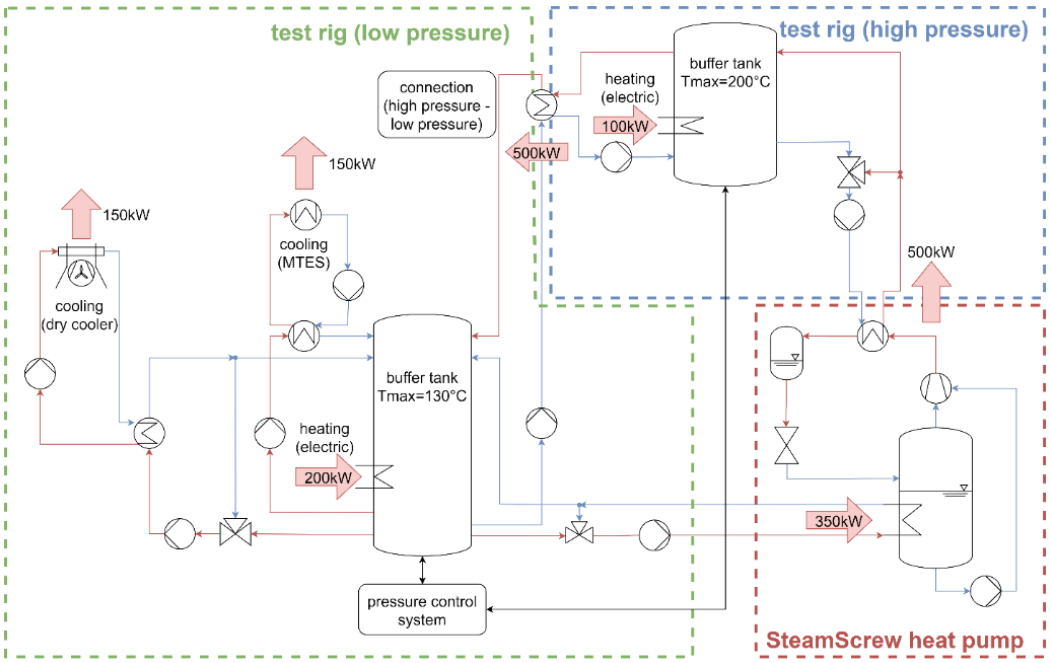


Figure 3. Schematic setup of HTHP and associated test rig (shown heating powers are exemplary).

Several studies indicate that water (R718) is a very suitable refrigerant for high-temperature applications (Arpagaus et al. 2018). It is environmentally friendly, safe, and exhibits highly favorable thermodynamic properties, such as a high evaporation enthalpy. A typical drawback is its low density, which generally requires larger machinery and higher investment costs. However, this limitation becomes less significant at elevated temperatures, with the practical lower limit often around 80°C (Chamoun et al. 2014; Di Wu and Hu 2023). Another challenge arises at temperatures below 100°C, where the refrigerant operates under vacuum conditions, which increases the requirements for system tightness and complicates the mechanical design.
The combination of HTHPs with MVR enables high-COP steam generation applications. By compressing the steam after evaporation, the energy required for water evaporation can be supplied at a lower temperature level. This reduces the required temperature and, consequently, the pressure lift of the lower-stage HTHP, resulting in higher COPs. Additionally, the steam quality can be adjusted and optimized through water injection during or after compression, resulting in a higher mass flow.

2.3 REVERSIBLE ORGANIC RANKINE CYCLE / HIGH-TEMPERATURE HEAT PUMP

The rev. ORC technology can be employed in combination with a deep hydrothermal source or a combined heat and power (CHP) project to limit greenhouse gas emissions by replacing fossil fuel peak load boilers and to increase the flexibility of the geothermal plant. The rev. ORC technology employs several key components in both operational modes and is capable of switching between ORC and HTHP mode depending on the actual needs. While the technology has been studied by academia for more than one decade, its demonstration on a higher TRL level is lacking (Schifflechner et al. 2025).
Fig. 4 illustrates the plant layout of the conceptual system, showing: a. the HTHP mode, operated through the compressor, for thermal power production, and b. the ORC operation, with electricity production through the expander. The operational mode depends on the actual heat demand of the district heating system. As shown in the detailed thermo-economic study by Kaufmann et al. 2026 for an actual geothermal project in the south of Munich, Germany, the reversibility can exhibit favorable economic results compared to a conventional HTHP. Furthermore, in Table 5 are reported the operating parameters and target powers of the pilot plant, which is the first commercial application of a rev. ORC, and is planned during the FlexGeo project (Horizon Innovation Actions).

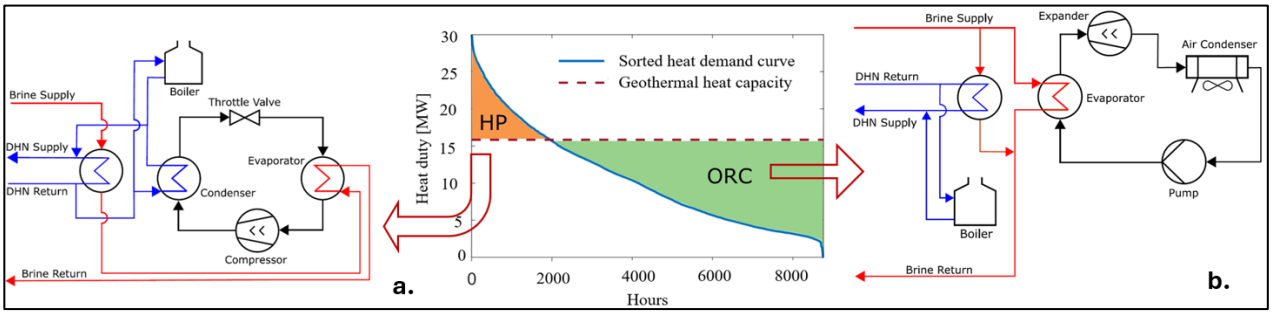


Figure 4. Plant layout for a reversible HTHP integrated into a geothermal CHP plant with, a. HTHP mode, and b. ORC mode. The HTHP is used for peak demand, while the ORC is in operation during the base-load heat production (Kaufmann et al. 2026).

Table 5. Operating conditions of the ORC/HTHP.

Configuration	ORC and single-stage HTHP
Nominal produced power [MW_{th}, kW_{el}]	1, 200
Refrigerant	R1233zd(E)
Heat source type, temperature [°C]	Deep geothermal/hydrothermal or waste heat (for the HP), ORC mode: 90-160, HP mode: 50-65
Heat sink type, heat transport medium	Industry or DH, steam or pressurized water
Heat sink supply T, return T [°C]	70-120, 50-65
COP, T lift 57 K [-]	3 (from lab values)

The possibility of implementing a real-world application of a rev. ORC is proven by the successful construction and investigation of lab-scale test rigs, such as the one developed in Munich. The test rig is supplied by a 200 kW hot water heating circuit as a heat source and utilizes a fully reversible 20 kW twin-screw machine as both a compressor and an expander. A closed-loop intermediate cooling circuit enables the simulation of a DH network with varying temperature levels and mass flows during HTHP operation. The HTHP is capable of handling thermal loads of up to 110 kW with heat sink outlet temperatures of up to 120°C. For investigated temperature lifts between 25 K and 57 K, COPs ranging from 6.4 to 3.0 have been observed (Kaufmann et al. 2025). The test rig can be divided into three subsystems: the heating circuit, the cooling circuit, and the combined working fluid and oil cycle. Fig. 5.a. shows the installed test rig used to prove the feasibility of the technology and obtain data for the large-scale implementation, exemplarily depicted in Fig. 5.b..

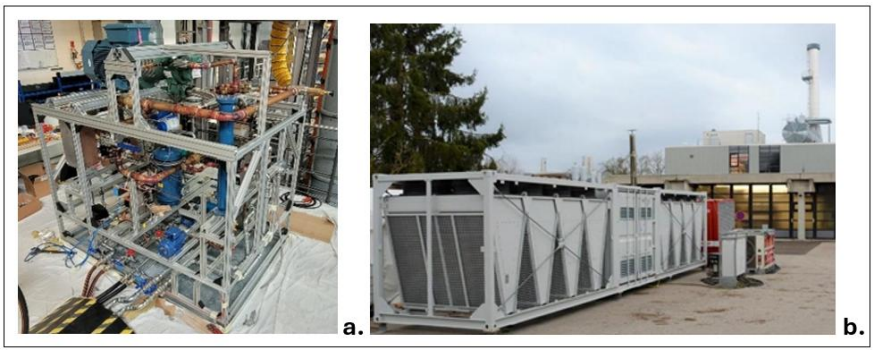


Figure 5. a. Rev. ORC test rig installed in the laboratories of the Technical University of Munich (Kaufmann et al. 2025). b. example of the large-scale rev. ORC installation.

3 COMPARATIVE ANALYSIS

The technologies described represent innovative large-scale solutions for the exploitation of geothermal sources. They tackle the lack of real-world facilities for HTHPs and rev. ORC systems to enable heat production with hundreds of thermal kW at elevated temperatures, and in one case, also producing electrical power.

While the technologies are HTHP configurations that exploit geothermal sources and share common technological aspects, each also has many unique features. In the Venn diagram depicted in Fig. 6 are shown the elements in common among all demonstrators, at the center, the ones shared among two of them, along with the unique characteristics of each one, in the external sections.

The technologies, being developed with unique focal points, draw attention to different techno-economic aspects. In particular, the double-stage HTHP focuses on exploiting the seasonality of the heat source, which

substantially varies in temperature (50 K during the heating season), as well as the DH temperature variation (40 K, up to 120°C). Furthermore, importance was given to the utilization of natural refrigerants and the first-time installation of an R600 unit. The goal of the demonstrator is to inject heat into the DH, integrate the HTHP into the MTES system, and enable independent testing of the system components. The double-stage system also lays the groundwork for on-site testing in Bochum and for the development of further technologies, such as the one-stage R718 configuration described. The single-stage HTHP focuses on the technology required to utilize R718 as a refrigerant, with a particular emphasis on developing an efficient screw compressor. In fact, water as a medium for HTHPs shows high potential and environmental advantages, but it also presents challenges regarding the implementation of compression technology.
The rev. ORC has the goal of increasing the working hours and therefore the capacity factor of a HTHP, which would mostly produce heat in the cold months, reducing the CAPEX of the system. This is achieved through power production during periods of low heat demand, when excess geothermal heat or waste heat is often present. The focus is therefore the reversibility of the system operation and its flexibility, according to the heat demand.

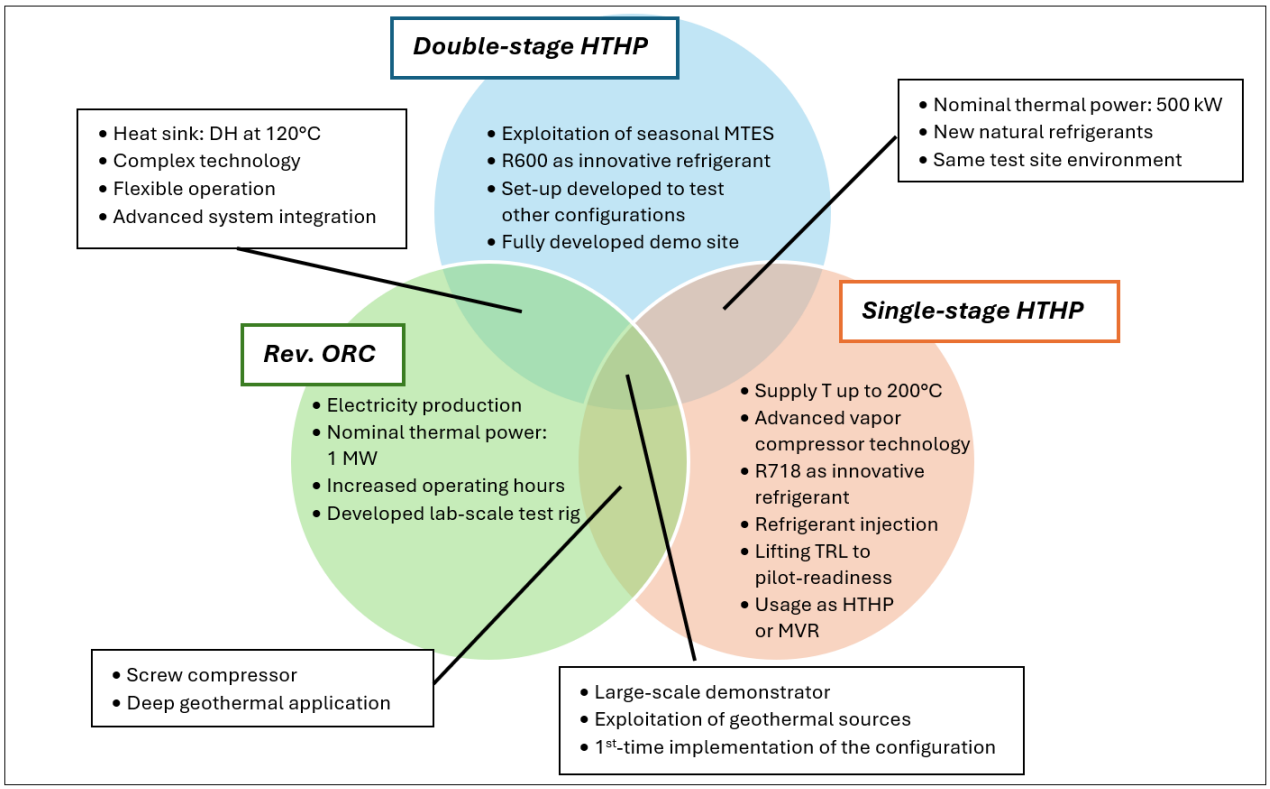


Figure 6. Distinctive features and shared characteristics among the three considered demonstrators.

4 DISCUSSION

The construction of large-scale demonstrators represents a vital step for the further development and market readiness of novel technologies. To achieve this goal, the three described technologies have been developed to contribute to the rollout of HTHPs in both DH and industrial decarbonization contexts.
The combination of HTHPs and geothermal energy has significant potential to upgrade the temperature of the heat source, in the case of shallow geothermal, but also if the medium/deep geothermal source does not present the needed temperatures for direct utilization. Furthermore, excess heat from deep geothermal reservoirs or industry can be integrated into the HTHP or rev. ORC systems to increase the overall plant efficiency. The utilization of different technologies optimized for specific geothermal heat sources enables coverage of broad geographical areas, including those with or without deep geothermal reservoirs. Furthermore, testing technologies for both industry and DH applications allows a widespread exploitation of the technology in various fields under different heat sink operating conditions.
The focal points of the described pilot configurations differ, namely, the 2-stage HTHP focuses on the variation of temperatures between the heat source and the heat sink and operates with innovative refrigerants for HTHP applications, such as R600. The 1-stage HTHP focuses on producing steam at temperatures of up to 200°C using water as the refrigerant and an advanced screw compressor. The rev. ORC focuses on not only producing heat up to 120°C but also electricity, while maintaining a high COP.

The initial comparison carried out revealed the same operating framework conditions for pairs of technologies, such as the supply temperatures for the 2-stage HTHP and the rev. ORC and the nominal thermal power between the 1- and 2-stage configurations, as illustrated in Fig. 6. This is a relevant starting point for more in-depth studies on single components, such as a comparative analysis of the screw compressor of the single-stage configuration and the rev. ORC. The next steps for the comparative analysis of the technologies will focus on the performance. In fact, while the COPs of the three systems are comparable in value, the measurement conditions and temperature lifts differ. For the double-stage system, the COPs are experimental values of the units in factory settings. For the 1-stage system, they are the planned values, and for the rev. ORC system,are considered the experimental values, which correspond to those of the laboratory prototype.

5 CONCLUSIONS AND OUTLOOK

To further develop geothermal surface technologies, the construction of real-world demonstrators to prove the feasibility of concepts and the integration into the geothermal sources is highly needed. In the context of the promising technology of HTHPs, research aims to answer the challenging question of which refrigerants and configurations are most suitable in terms of environmental and performance goals to meet the required heat sink and heat source needs. A further challenge is the low employment of HTHPs during seasons with little to no heat demand. To tackle these issues, three innovative demonstrators have been presented and compared. The pilot configurations include an installed 500 kW double-stage HTHP with R717 and R600 as refrigerants, connected to MTES and DH grid, which produces pressurized water up to 120°C; an under-development 500 kW single-stage HTHP with R718 as refrigerant and a newly-developed screw compressor; and a 1 MW_{th}, 200 kW_{el} rev. ORC system, representing the first large-scale installation for a rev. ORC. In terms of nominal performance, the double-stage HTHP presents an overall COP of 2.71 (T lift 70 K), the single-stage HTHP a COP of 3 (T lift 80 K), and the rev. ORC a COP of 3 (T lift 57 K). Further investigation is planned to compare the technologies under the same operating conditions.
Advantages and unique features of each technology have been presented, along with common characteristics of paired technologies, which allows for the next studies to focus on specific selected components.
The demonstrators, developed for both shallow, medium/deep, and deep geothermal heat sources, each present unique technological features, and their development represents an important milestone for the introduction of low-environmental impact heat and power production in the surface application of geothermal energy.

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