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Novel reversible heat pump technologies for geothermal district heating networks

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ABSTRACT

Utilising deep geothermal energy for decarbonizing district heating networks (DHN) has a tremendous worldwide potential. In typical direct-use projects, the geothermal capacity is limited by the return temperature of the DHN, since this determines the minimal achievable reinjection temperature. At the same time, most existing geothermal DHNs experience heat demand during cold winter periods that exceeds the conventional geothermal capacity. Thus, normally, peak load boilers running with oil or gas are used to cover this peak load heat demand. Large-scale heat pumps have a high potential for decarbonising this peak load because they enable a significantly higher heat supply from the geothermal project by decreasing the reinjection temperature. However, existing geothermal DHNs indicate that such large-scale heat pump systems will have low capacity factors, which might prevent an economic business case. Simultaneously, most of the year, the geothermal capacity exceeds the actual DHN demand. Therefore, so-called reversible heat pumps, which can operate in two modes using the same equipment, may offer an attractive solution. This work presents a thermo-economic assessment of a novel reversible heat pump system, currently studied also experimentally by the authors: A reversible compression heat pump, which can also operate as an Organic Rankine Cycle for power generation. Furthermore, an absorption heat pump, which can also operate as an absorption chiller is characterized as well. By providing either power or cold during the summer months, the capacity factor of the heat pump increases significantly. The study presents detailed results for reversible concepts, their potential application cases, and economic threshold conditions.

1 INTRODUCTION

Deep geothermal energy is increasingly seen as a key option for decarbonising district heating networks. Worldwide surveys show that direct use of geothermal energy for space heating and district heating has grown steadily over the last decades and already covers several tens of gigawatts of installed capacity (Lund and Toth, 2021). In countries with favourable hydrothermal resources, such as Germany, France and the Netherlands, geothermal district heating plants are already in operation and further projects are planned, often supported by national and regional climate strategies (Sanner et al., 2025).

Despite this progress, typical deep geothermal heating projects still face two fundamental limitations. First, the useful geothermal capacity is constrained by the minimum achievable reinjection temperature, which is strongly linked to the return temperature of the district heating network. As long as return temperatures remain relatively high in existing networks, a considerable part of the theoretical geothermal potential cannot be used. Second, the heat demand in most networks is highly seasonal. Heating demand peaks during a limited number of very cold hours, while the remaining part of the year is characterised by much lower loads. These aspects are reflected in existing geothermal systems, where geothermal heat usually covers the base load of the network, and fossil fired boilers are still required to provide the remaining peak load (Kaufmann et al. 2026, Jeßberger et al. 2024).

Large-scale high-temperature heat pumps (HTHPs) have emerged as an attractive technology for increasing the share of geothermal heat and replacing fossil fuel peak load boilers. By lowering the return temperature of the network and upgrading the geothermal heat to the required supply level, they can increase the usable geothermal capacity and enable higher renewable shares in the heat supply (Jeßberger et al. 2024). However, in the specific case of peak load coverage, the annual operating hours of a large heat pump are often limited to a few hundred or at best a few thousand hours. The resulting low-capacity factor leads to high specific investment costs for the heat pump subsystem and can prevent an economically viable business case (Schlosser et al. 2020).

During large parts of the year the geothermal capacity exceeds the current heat demand, either because the network demand is low or because the existing wells are operated below their technical limits to avoid excessively high reinjection temperatures. This results also in lower revenue streams, causing potential challenges to achieve acceptable payback periods. In this situation, concepts that can use the same equipment in different operating modes throughout the year become very attractive. Figure 1 illustrates this idea. Only a relatively small share of the sorted annual heat demand corresponds to peak load that could be covered by the HTHP, while a large share of the year lies below this level. The red line in the figure marks the conventional geothermal capacity. Above this line, a heat pump would be needed to cover the district heating peak demand. Below this line, excess geothermal heat is available which could be used for power generation, cold production or seasonal storage.

Reversible thermodynamic cycles are a promising way to exploit this surplus potential more effectively. Reversible compression systems can operate as high temperature heat pumps during the heating season and as Organic Rankine Cycles (ORC) during periods of low heat demand, thereby converting geothermal heat into electricity (Kaufmann et al., 2025; Schifflechner, 2024). Similar ideas exist for absorption based systems, where the same equipment can either upgrade geothermal heat for district heating or provide chilled water for district cooling or industrial processes (Irrgang et al., 2025) or even power generation (Novotny et al. 2021). Recent work on geothermal cooling shows that absorption chillers and hybrid compression absorption cycles can supply cold with high overall energy efficiency, even from medium temperature geothermal resources, and that they can significantly increase the utilisation of the geothermal wells over the year (Irrgang et al., 2025).

By combining these concepts, reversible heat pump technologies can address the central challenge of low capacity factors for peak load heat pumps. While there are different definitions on reversible heat pumps, this work follows the definition from a previous overview publication on rev. HTHP by Schifflechner et al. (2025) stating that in a reversible system the “circuits of the system in both modes” are not separated from each other. Such systems offer high temperature heat supply during cold periods and can switch to power or cold production during the remaining hours of the year. In this way, the same investment contributes to multiple services and the effective utilisation of the geothermal resource increases. The present work builds on recent experimental and numerical research on rev. HTHP/ORC and on advanced absorption based cycles, and provides a thermo-economic assessment of two novel reversible heat pump concepts for their application in geothermal district heating networks.

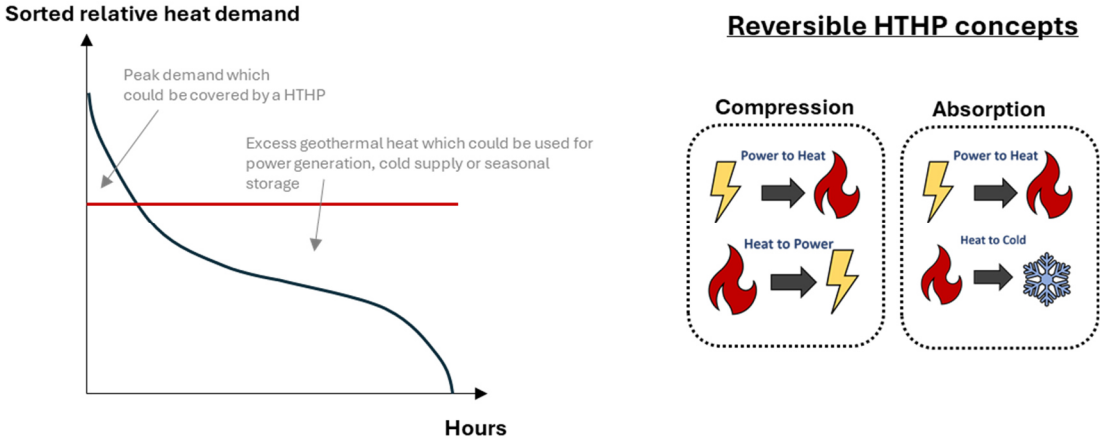


Figure 1: General characteristics of a district heating demand and two potential reversible HTHP concepts

2 REVERSIBLE COMPRESSION HTHP/ORC SYSTEMS

2.1 Technical background

Reversible compression systems combine a HTHP system with an ORC in one common circuit. The same working fluid, the same heat exchangers, and in most concepts the same rotating machine (e.g. a twin-screw) are used in both operating modes. In winter, the machine runs as a heat pump and upgrades the geothermal

brine to the supply temperature of the district heating network. In summer or in periods with low heat demand the same plant can be switched to an Organic Rankine mode and convert geothermal heat into electricity.

The basic idea is illustrated in Figure 2. The left part of the figure shows the situation in heating mode. Geothermal brine from the production well is cooled in the evaporator of the heat pump before being reinjected into the reservoir. The working fluid evaporates at a temperature a few degrees below the brine outlet temperature and is then compressed to a higher pressure level. In the condenser, the compressed working fluid releases heat to the district heating network and condenses at the required supply temperature. By lowering the reinjection temperature, the reversible system increases the thermal output of the geothermal wells during peak load periods. The right part of Figure 2 shows the same system in the ORC mode. The district heating network is bypassed in this mode, and the focus is on converting surplus geothermal heat into electricity. The working fluid is now evaporated at a higher pressure, using the geothermal brine as the heat source. The fluid expands through the machine, which now runs as an expander and drives a generator instead of a motor. Afterwards, it is condensed against ambient air in an air-cooled condenser.

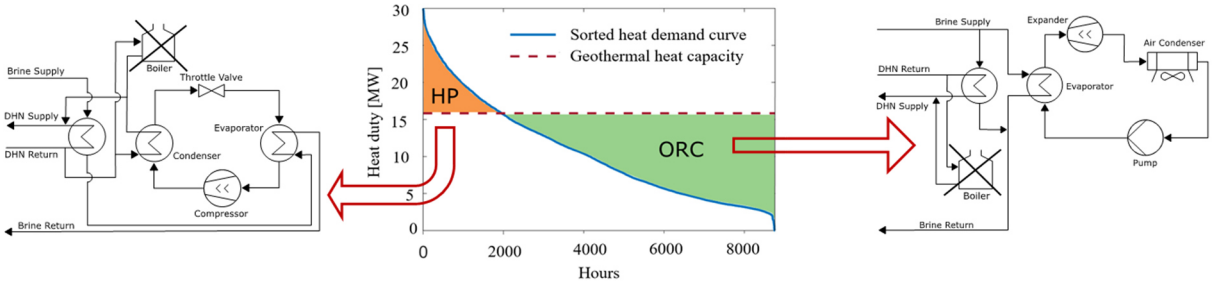


Figure 2: Operational strategy of a rev. HTHP/ORC system

2.2 Experimental activities and upscaling

Several reversible test rigs at laboratory scale have been developed and demonstrated in recent years, mainly for building applications, industrial waste heat, and thermal storage. Dumont et al. (2015) experimentally investigated a small unit coupled to a passive house and reported stable operation in both modes, as well as the importance of control strategies to handle the different pressure levels and fluid inventories. Other test rigs have been developed with the main scope on industrial waste heat recovery (Ravindran et al., 2024) or Carnot battery applications (Weitzer et al., 2025). While these test rigs provide valuable insights into the general feasibility of reversible operation and achievable plant performance, they have not been optimized for geothermal applications. Kaufmann et al. (2023) presented a first design of a rev. HTHP system for a geothermal combined heat and power plant (CHP) building up on a preliminary thermo-economic study (Kaufmann et al., 2022). The rig uses a 20 kW_{mech} twin screw machine that is able to operate both as compressor and as expander. On the heat source side, a plate heat exchanger represents the geothermal evaporator with a 200 kW_{th} heat source, which can supply up to 140°C. On the sink side, a second plate heat exchanger represents the district heating condenser. Figure 3 shows selected experimental results from the test rig for both operating modes, while an in-depth characterization can be found in Kaufmann et al. (2025). The left part of the figure illustrates the measured performance in heat pump operation. For different operating points, the figure shows the coefficient of performance (COP) and the corresponding temperature lift. It can be seen that the heat pump achieves typical COP values for the given lifts. The right part of the figure presents the measured net power output and electrical efficiency in ORC as a function of the mimicked geothermal inlet temperature and part load. Even at moderate brine temperatures, the reversible unit can produce a noticeable amount of electricity with efficiencies in the expected range for small Organic Rankine systems test rigs at these conditions (cf. Eyerer et al., 2022).

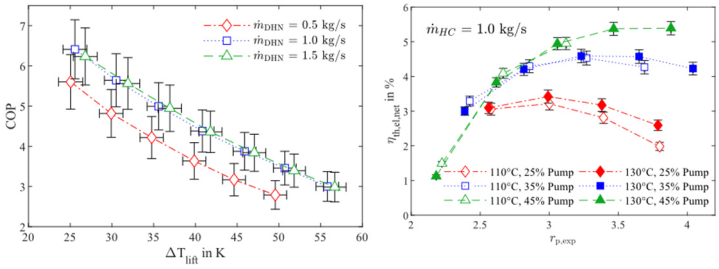


Figure 3: Experimental results in both operational modes (adapted from Kaufmann et al. 2025)

The test rig at the Technical University of Munich (TUM) therefore fills an important gap between generic reversible prototypes and geothermal applications. It confirms that a reversible compression system can be operated at deep geothermal temperature levels and that a single machine can deliver both high-temperature heat and electrical power. Based on the laboratory experience, a scale-up roadmap, shown also in Figure 4, has been developed in the currently ongoing European research project FlexGeo. Starting from the existing test facility at TUM and a smaller one at the University of Liege with three parallel scroll machines (Neven et al., 2024), currently a 1 MWth /200 kWel demonstrator is built by the German company Orcan Energy and initial operation is expected for 2027.



Figure 4: Scale-up roadmap for the rev. ORC technology in the framework of the FlexGeo project

2.3 Thermo-economic assessment

The following section discusses the potential thermo-economic performance of a rev. HTHP system for a real geothermal site in the South of Munich, Germany, which is also discussed in more detail in a recent study by some of the authors (cf. Kaufmann et al., 2026). The general modelling framework, shown in Figure 5, is used for a complete annual real district heating operational profile and detailed, component-based, simulation of the reversible system in both modes is carried out. A main focus was on the realistic off-design modelling of all components, mainly the reversible twin-screw machine and the heat exchangers. In the next steps, cost functions for all key components are used, and a thermo-economic optimization is carried out.

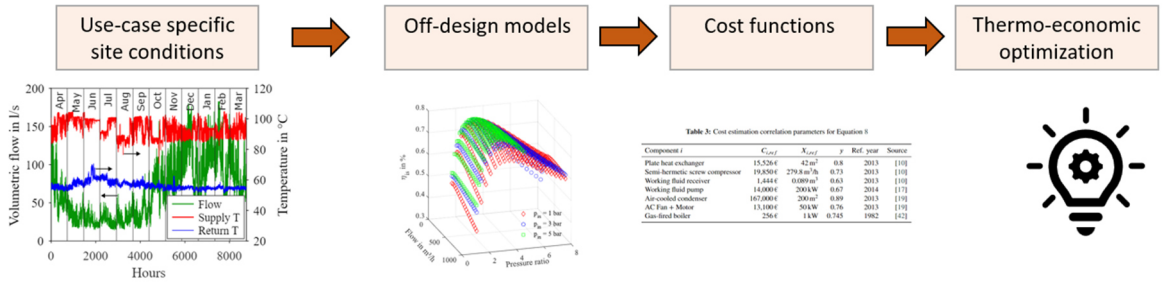


Figure 5: Thermo-economic modelling framework

The key findings can be summarized in Figure 6, which displays a favorability map between the currently used peak load cover by gas boilers, a conventional large-scale heat pump for peak coverage and a reversible heat pump (presented by the green area). It gets clear that with the currently rather low gas and high electricity prices in Germany, the application of the heat pump in general might be economically challenging. However, further cost reductions and expected changes in the electricity and gas prices combined with a decarbonization pressure for district heating operators might change that. More interestingly is also the general comparison between the conventional and reversible heat pump. We see that the favourability between both modes is mainly determined by the electricity price. A further central aspect highlighted also in the study is the role of the air-cooled condenser. Its size and cost strongly influence the economic performance of the reversible plant. A condenser designed for high electrical output can represent a significant share of the total investment, which may offset the advantages of reversibility. The sensitivity analysis by Kaufmann et al. shows that a more moderate sizing leads to a better balance between investment cost and net power output. This finding emphasises that the design of the condenser is one of the main levers for improving the economic viability of reversible compression systems in geothermal applications.

Overall, the results from Kaufmann et al. indicate that reversible operation can improve the utilisation of geothermal resources and provide a meaningful additional value stream. The actual economic position of such

systems depends strongly on local energy prices and on careful selection of component sizes, particularly the condenser.

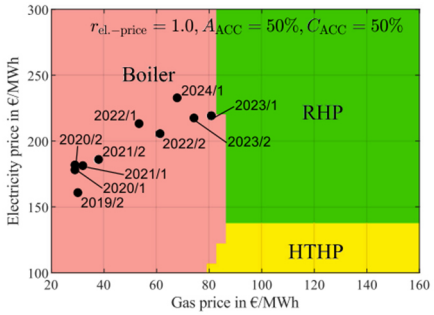


Figure 6: Thermo-economic results for a case study in Southern Germany, adapted from Kaufmann et al. 2026

3 REVERSIBLE ABSORPTION SYSTEMS

Absorption systems have long been used in cooling and in industrial processes, particularly when a constant thermal source is available and electricity consumption needs to be kept low. In geothermal applications, absorption systems can utilize available geothermal heat either for upgrading heat or supplying cold. In tropical regions, geothermal cold supply could be also one of the main products of a project due to the high constant cooling demand, as discussed for example by Maragna et al. (2024) and Chidire et al. (2025). Figure 7 illustrates the basic motivation for a potential reversible absorption system in geothermal district heating and cooling networks or even in the context of a trigeneration system, also generating power (Schifflechner et al., 2023). In heating dominated climates like Central Europe, the heat demand shows a strong seasonal variation, while the cooling demand rises in the summer months. At the same time, the geothermal plant continues to supply warm brine at almost constant temperature. Without technologies that can use geothermal heat in summer, a large share of the available resource remains unused. A reversible absorption concept can use this surplus heat and convert it into cold for industrial processes or district cooling, as for example done in Munich (Weber et al., 2025). In winter, the same system can increase the temperature lift of the geothermal plant and reduce the reinjection temperature, thereby increasing the annual utilization of the wells. This combined use of cooling and heating is one of the central motivations for the reversible absorption concept.

Figures 8 and 9 present the general working principles of the absorption chiller, the absorption heat pump and the absorption heat transformer as well as the potential integration of a geothermally supplied geothermal absorption chiller in a district cooling network. These three cycles use the same basic components, including the absorber, the generator, the solution heat exchanger and the evaporator. The refrigerant–absorbent pair is usually water–lithium. The difference between the three cycles lies in the temperature levels at which heat is supplied and recovered. In summer the system operates as a chiller and produces cold for industrial users or for district cooling. Irrgang et al. (2025) show that both single effect chillers and hybrid compression absorption systems can make efficient use of medium temperature geothermal heat and can provide cooling at very low electricity demand. In winter the same system can operate as a heat pump or as a heat transformer and upgrade part of the geothermal heat to the temperature level required by the district heating network. In this way, the reversible absorption system enables a seasonal trigeneration concept with heat, cold, and in some configurations even an upgraded heat stream at intermediate temperature.

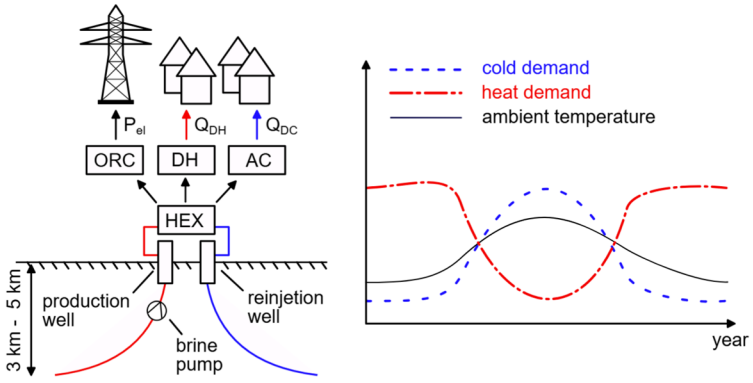


Figure 7: Potential geothermal trigeneration concept and annual heat and cold demand for Central Europe

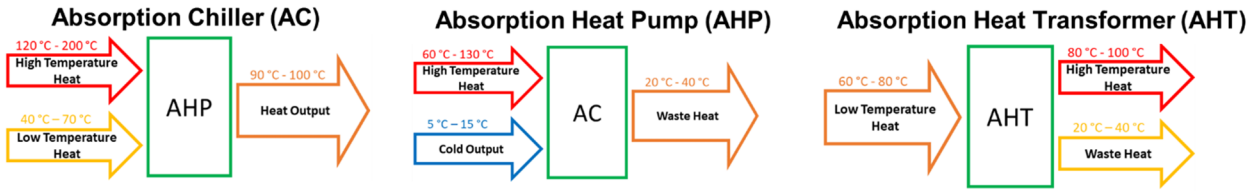


Figure 8: General working principle of an absorption chiller, heat pump and transformer

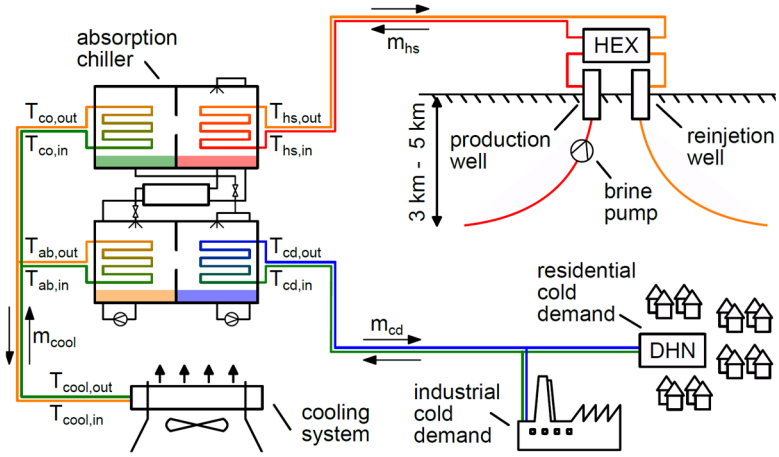


Figure 9: General working principle a district cooling network supplied by a geothermal absorption chiller

Thus, while there is a high promising application potential of reversible absorption systems, especially capable of operation as heat transformer, in geothermal systems, the technology is not commercialized yet. Therefore, experimental work on such advanced absorption systems for geothermal heating and cooling is being carried out at TUM. The aim of the test rig, shown in Figure 10, is to evaluate the behaviour of single-effect absorption chillers and absorption heat pump & transformer configurations under boundary conditions that resemble those of deep geothermal plants. The design follows directly from the need to operate the same absorption system in cooling mode during summer and in heat-upgrading mode during winter, as described in the previous section.

The plant is designed for a cooling capacity of around 100 kW at representative geothermal conditions. The working pair is water and lithium bromide, which is suitable for geothermal applications because it is non-toxic and operates at the required temperature and pressure levels. The system includes an intermediate heating circuit that allows realistic geothermal inlet conditions to be recreated in the laboratory and enables controlled investigation of how the absorption cycle interacts with varying brine temperatures.

Several design features of the test rig reflect its intended use in geothermal systems. The absorber and desorber are arranged such that relatively low solution temperatures can be maintained, which supports cold production down to approximately 5°C. Parallel cooling of the desorber and absorber is included to reduce solution temperatures on the high-pressure side and to increase the amount of recoverable heat. The plant operates at vacuum pressures typical for water–lithium bromide systems, and the hydraulic layout facilitates flexible switching between operating modes.

The experimental programme associated with this facility includes full characterisation of the absorption chiller mode, investigation of part-load behaviour and evaluation of conditions relevant for heat-upgrading operation. The collected data will be used to validate numerical models that describe the thermodynamic performance of the absorption cycle and its integration into geothermal plants. Commissioning of the facility is planned for early 2026 , after which systematic operation in both cooling and heat-upgrading modes will begin.

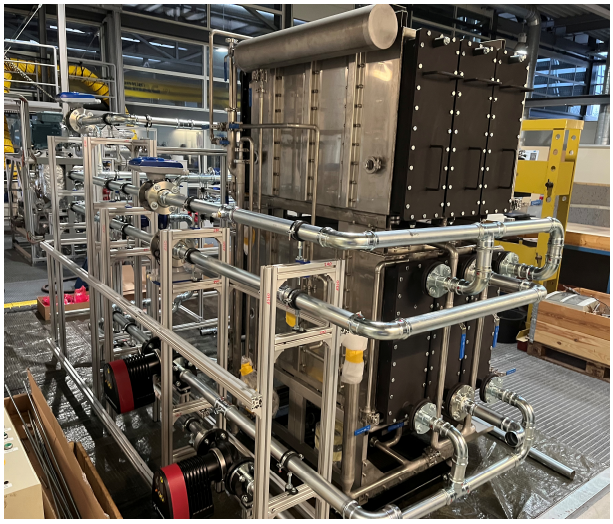


Figure 10: View on TUM's currently built reversible absorption test rig optimized for geothermal applications

4 SUMMARY & OUTLOOK

Deep geothermal systems provide a valuable and stable renewable heat source, yet their utilisation is strongly characterized by the seasonal mismatch between heat demand and constant geothermal supply in many regions of the world. This work presents two reversible heat pump concepts that aim to adapt to these seasonal characteristics by offering additional operating modes outside the heating season. Both concepts build on the same underlying motivation: increasing the annual utilisation of the surface equipment and reducing the dependence on fossil-fired peak load boilers, which still play a significant role in many existing district heating networks.

The first concept, a reversible compression-based system, can operate as a HTHP in winter and as an ORC in summer. The experimental and numerical activities shown in this work demonstrate that such systems are technically feasible and that a single machine can deliver both functions across a broad range of geothermal operating conditions. The recent thermo-economic case study provides the first detailed assessment for a real geothermal plant and shows that reversible operation can substantially increase annual operating hours and create an additional value stream through electricity generation. The analysis also demonstrates that the economic balance depends strongly on the price relation between gas and electricity as well as on the design of the air-cooled condenser. A more moderate condenser sizing can improve the cost–performance ratio considerably and demonstrates that the economic viability of the reversible system is largely determined by a few key design choices.

The second concept presented is the reversible absorption system, which offers a complementary form of flexibility. In summer, the system can convert geothermal heat into cold with very low electricity consumption, and in winter it can upgrade part of the geothermal heat to the temperature level required by the district heating network. As the cooling demand in cities and industry continues to grow, such systems will become increasingly relevant. The ongoing experimental work at TUM will provide the first consistent data for geothermal boundary conditions and will allow the performance of the absorption chiller, heat pump and heat transformer modes to be characterised under realistic conditions.

Taken together, the results underline the potential of reversible heat pump technologies to increase the flexibility and productivity of geothermal heating systems. Both concepts help to address the low-capacity factors of peak load heat pumps and offer additional operational value during the many hours in which geothermal heat would otherwise remain unused. Future work will include a more detailed comparison between compression-based and absorption-based reversible systems for different geothermal conditions, district heating return temperatures and network structures. In addition, ongoing demonstration projects such as in the framework of the FlexGeo project will provide essential practical experience and will help to clarify the cost and performance boundaries for commercial deployment.

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