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Unlocking the flexibility potential of geothermal with reversible Organic Rankine Cycles

Christopher Schifflechner[a,*], Florian Kaufmann[a], Kai Zosseder[b], Hartmut Spliethoff[a]

[a]Chair of Energy Systems, Technical University of Munich, Garching, Germany

[b]Chair of Hydrogeology, Technical University of Munich, Munich, Germany

*c.schifflechner@tum.de

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ABSTRACT

A general advantage of geothermal power generation is its reliability and base-load capability. However, the future energy system requires reliable energy sources that can also respond quickly to changes in demand. Reversible Organic Rankine Cycles (ORCs), which can also operate as high-temperature heat pumps (HTHPs), enable geothermal systems to operate more flexibly. Combined with a district heating system and/or heat storage system (e.g. HT-UTES), reversible ORCs can react to the needs of the electricity grid and either produce electricity from the geothermal brine or consume power within the HTHP mode. Through the implementation of a storage system, the high-temperature heat produced during the HTHP operation can be used to increase the geothermal power output at a later time. This work provides an overview of the application and flexibility potential of reversible ORCs for geothermal systems and presents a potential system layout for such a system.

1. INTRODUCTION AND MOTIVATION

The increasing capacities of fluctuating renewable energy sources such as wind or PV result in a growing demand for reliable and efficient storage systems which can provide the required flexibility to the electric grid. While in the past, one highlighted key advantage of geothermal heat and power generation was its reliability and base-load capability, research and industry are now focusing more and more on the flexibility potential of geothermal energy (Millstein et al. 2021). E.g. the recent study by Ricks et al. (2024) investigated the role of flexible Enhanced geothermal systems (EGS) in a decarbonized electricity system. The authors found for the western United States that a load-following generation combined with in-reservoir energy storage substantially increases the geothermal penetration and reduces bulk electricity supply costs compared to systems with inflexible EGSs. The recently published “Flexible Geothermal Economics Modeling” tool FGEM by Aljubran and Horne (2024) investigates several promising potential dispatch strategies, such as wellhead throttling and energy storage. Ricks et al. (2022) highlight the value of in-reservoir storage for flexible geothermal power, which can provide storage durations above 100 hours. Also the combination of geothermal energy with district heating systems and heat pumps can be a promising approach to provide flexibility with geothermal energy (Liu et al. 2024) .

Next to the previously mentioned possibilities to increase the flexibility of geothermal systems, also the concept of the so-called reversible Organic Rankine cycle (ORC) / high-temperature heat pump (HTHP) has experienced significantly increased interest from both academia and industry during the last years. This technology makes use of the similar process components in ORCs and HTHPs (Dumont et al. 2014). Therefore, one single plant can either operate in the ORC mode to generate electricity or in the HTHP mode to supply heat. Within this paper, the highly promising flexibility potential of a reversible ORC system will be outlined. First, the general working principle of the reversible ORC is explained in more detail. Afterwards, the flexibility potential of the proposed system is outlined, and our work will conclude with an outlook regarding potential future activities and next steps towards innovative, flexible geothermal energy systems.

2. THE REVERSIBLE ORC / HTHP TECHNOLOGY

Reversible ORC systems have gained significant attention in academia and industry within the last ten years. Such systems are generally capable of operating either as an ORC or as a HTHP by mostly using the same components (cf. Fig. 1). While an ORC uses low-temperature heat from various sources (e.g. geothermal, waste heat or solar) to generate electricity, a HTHP upgrades otherwise unused heat to a useful temperature level while consuming electricity. Multiple applications have been proposed for reversible ORC systems, such as within net-zero-energy-buildings or industrial settings (Kosmadakis and Neofytou 2022). Another promising application field is the use of geothermal combined heat and power plants, as recently analyzed by Kaufmann et al. (2022). Here, the primary task of the geothermal well is heat supply to a district heating network (DHN) within the context of a combined heat and power plant (CHP), which is a quite common application scenario for deep geothermal energy in European countries, such as Germany (Eyerer et al. 2020). In the case of such a “heat-driven operational mode”, which is shown in Fig. 2, excess heat in times of low heat demand is used to generate electricity with the ORC, while during the winter time, the unit operates as a HTHP in order to provide additional heat to the DHN and therefore reducing the need of fossil fuel for the peak demand heat supply. As shown by Kaufmann et al. (2022) such a system can improve the economic performance of a geothermal CHP system. Thus, in general, reversible ORC systems can be quite favorable for geothermal CHP systems in order to provide additional heat during the winter periods by decreasing the fossil fuel demand for the peak supply, which results in both economic and environmental benefits. Also in case of an expanding district heating system over the lifetime of the geothermal project (cf. Fry et al. 2022) the reversible ORC provides high flexibility for the plant operator regarding the future operational strategy.

Regarding its technological readiness, reversible ORCs are currently only investigated at a lab scale and no potential commercial product is close to market introduction. For example, Dumont et al. (2015) investigated a reversible ORC, which uses scroll machines. More recently, Steger et al. (2021) and Weitzer et al. (2023) carried out experiments with a twin-screw machine. The dual use of the screw-compressor as both compressor and expander is a major achievement for improving the economic viability of reversible ORC plants. Furthermore, the twin-screw machine is characterized by a high robustness and up-scale potential for larger capacities. Nevertheless, these test rigs are not optimally designed for the integration in geothermal systems. Currently, the Technical University of Munich (TUM) is constructing a novel 20 kWel test rig of a reversible ORC optimized for geothermal applications. The current status of the test rig is shown in Figure 3 and a detailed description can be found in Kaufmann et al. (2023). The test rig is supplied by a 200 kW hot water heating circuit as a heat source and uses a fully reversible 20 kW twin-screw machine. A closed loop intermediate cooling circuit allows simulating a DHN with varying temperature levels and mass flows during HTHP operation.

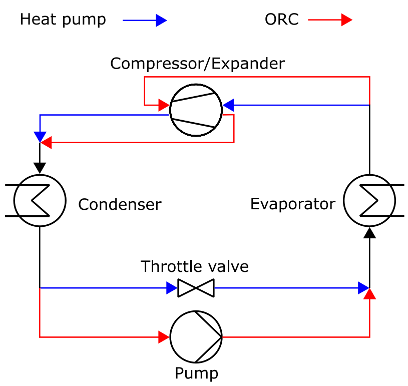

Figure 1: Simplified sketch of a reversible ORC

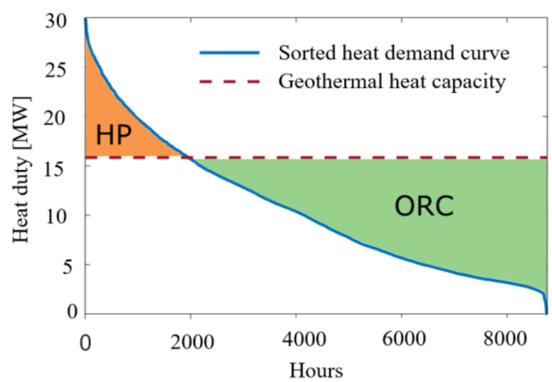

Figure 2: Potential heat driven operation mode of a reversible ORC

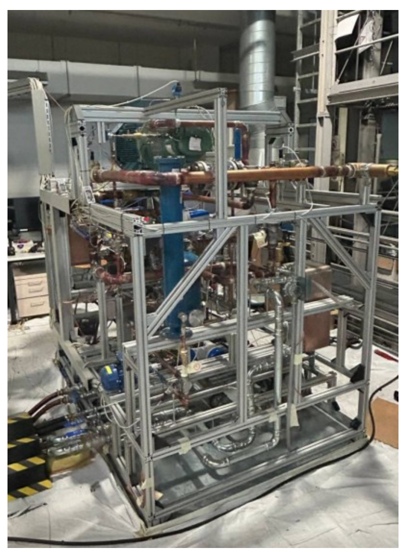

Figure 3: Picture of the reversible ORC test rig at TUM

3. THE FLEXIBILITY POTENTIAL OF REVERSIBLE ORC SYSTEMS

Thus, while the previous section has mainly focused on the general description of the reversible ORC technology and its application scenario in the context of a "heat driven" operational strategy, the technology has also a tremendous potential to provide flexibility services for the grid, especially if it is coupled with a thermal storage system. While the heat storage can either take place on the surface (cf. Guelpa and Verda 2019), especially Underground Thermal Energy Storage (UTES) systems are a promising approach for cost-efficient large-scale heat storage systems (Chicco et al. 2022). High-temperature UTES (HT-UTES) can significantly contribute in balancing the mismatch that arises between periods of excess energy supply and phases of high energy demand. E.g. Tzoufka et al. (2023) present a detailed numerical model of a HT-Aquifer Thermal Energy Storage (ATES) system in the greater area of Munich, Germany. As outlined by Abdur Rehman et al. (2021), UTES systems have in general a high sector coupling potential. Therefore, the combination of a reversible ORC and HT-UTES systems can benefit from the sector coupling potential of both technologies and result in a novel flexible geothermal energy system design.

The subsequent figure shows two possible operational strategies for one potential future system concept. Considering a deep geothermal system for combined heat and power generation with an additional medium- or high-temperature UTES, the reversible ORC units enable an optimal flexible operation of the whole system. During times with low, zero or negative electricity prices, the UTES system is charged by potential excess heat from the brine directly (if the DHS demand is lower than the geothermal capacity) and the HTHP operation, which cools down the brine further and increases the thermal input to the storage system. During periods with high electricity prices, the concept can maximize its power output by discharging the UTES system in order to supply the district heating demand. Thus, the reversible ORC is highly attractive for providing flexibility if combined with a UTES system.

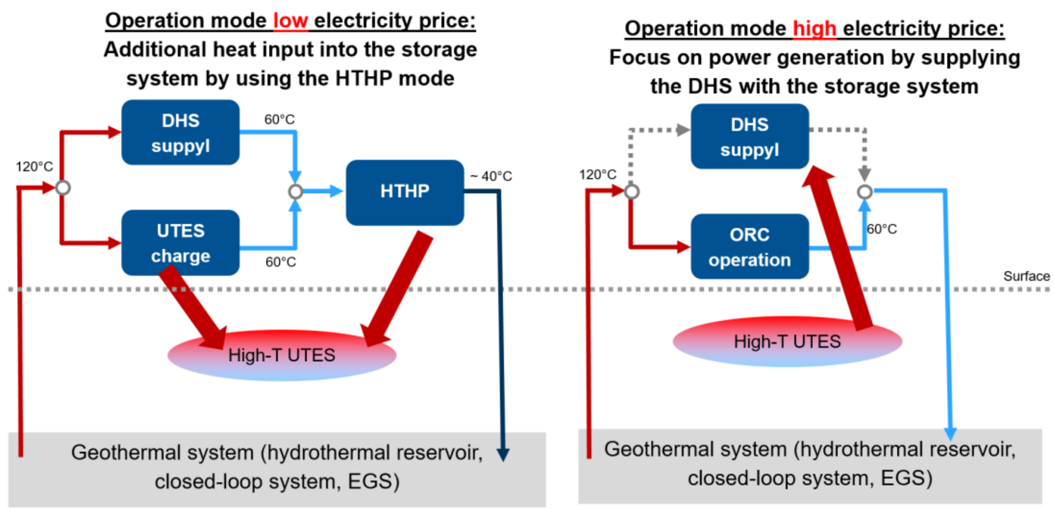

Figure 4: Two exemplary operation modes of the proposed novel flexible geothermal energy system

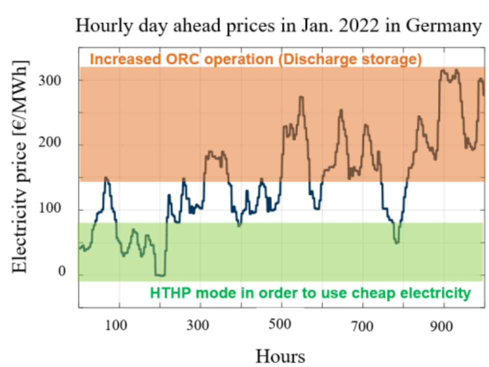

Figure 5: Exemplary spot market prices on the German electricity market

While existing either sole ORC and HTHP systems can only operate between their maximum capacity and minimal load (often between 20 % and 30 % of the installed capacity), reversible systems can generate power within the ORC mode and consume power within the HTHP mode. Furthermore, smart district heating systems with rather high supply temperatures have a certain flexibility potential, but without major electrical prosumers, the flexibility potential is limited. Finally, also large-scale reversible ORC systems might be a possible innovation pathway in the long run. However, they have a significantly longer development time until market entry and the pivotal drawback is that they might not be able to switch from the HTHP to the ORC mode during wintertime, if the HTHP is required to provide the required heating demand. Integrating a UTES system and, above all, the focus on modular ORC systems makes it possible to switch all (or even in extreme winter periods) at least some modules all year round. Thus, the modular reversible ORC approach system combined with UTES and advanced control strategies is by far surpassing the flexibility potential of the state-of-the-art geothermal systems and potential other innovation pathways. Thus, as visualized in Fig.5, the combination of reversible ORC modules with heat storage systems such as UTES and the implementation of smart control can significantly increase the flexibility potential of geothermal energy compared to the state-of-the-art and other potential innovation pathways.

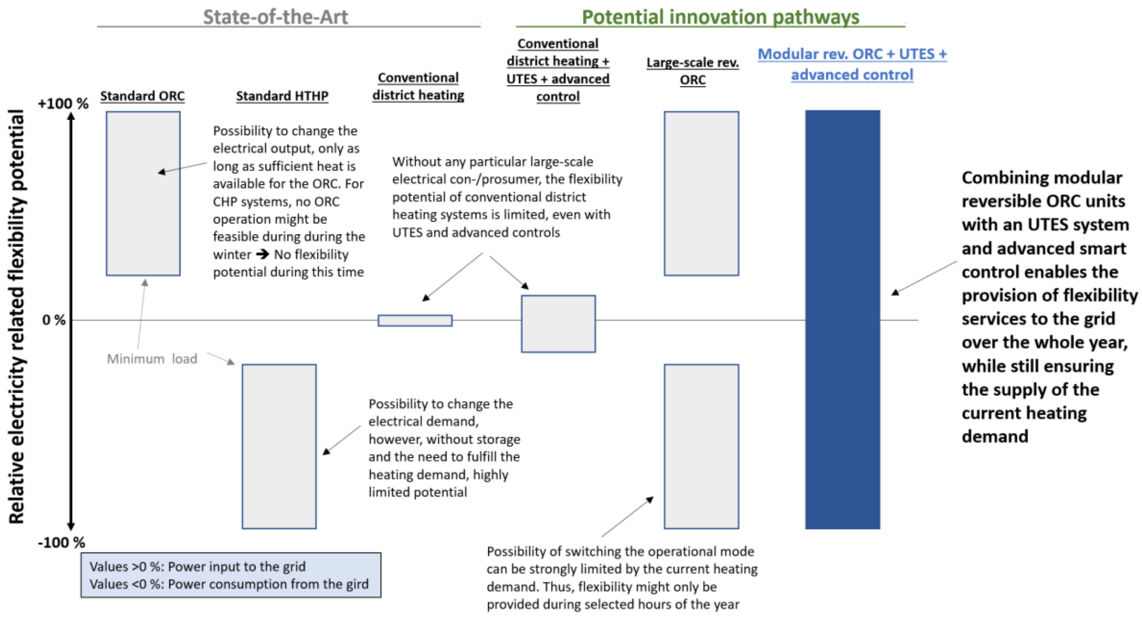

Figure 6: Relative flexibility potential of different geothermal energy system concepts

4. CONCLUSION AND OUTLOOK

In conclusion, reversible ORC systems have a tremendous potential to unlock a new level of flexibility potential for geothermal energy. Since one unit can operate in both modes (ORC and HTHP), it can provide flexibility services in a range that is twice as high as its own installed electrical capacity by switching from one operational mode to the other within a very short time frame of, e.g. less than five minutes. Thus, combining the reversible ORC with thermal energy storage systems such as ATES or flexible DHN can allow future geothermal energy systems to have a flexibility potential far beyond the current state-of-the-art. In the next months, the previously described test rig at TUM will provide the first experimental results for a novel reversible ORC layout optimized for geothermal application. The test rig will be experimentally characterized by a broad measurement campaign investigating different temperature levels and heat source mass flow rates. The obtained efficiencies and COP values will allow conclusions on the quality and flexibility of the proposed design. This allows deducting measures to improve the general design and part-load efficiency. In addition, optimised control strategies for reversible ORCs will be derived. Finally, the gathered insights and lessons learned from the 20 kW test rig will be the starting point for future scale-up activities with the goal of developing and demonstrating a large-scale reversible ORC within the next few years.

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