Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Assessing the potential of combined power and cold generation for data centers with deep geothermal

Konrad Ostermann[1]*, Ludwig Irrgang[1], Hartmut Spliethoff[1] and Christopher Schifflechner[1]

[1] Technical University of Munich, School of Engineering and Design, Chair of Energy Systems
*konrad.ostermann@tum.de

Keywords: Enhanced Geothermal System, Absorption Chiller, Organic Rankine Cycle, Compression Chiller, Data Center, Cooling, Electricity

ABSTRACT

Due to rising electricity demand and cooling requirements of data centers, combined solutions that supply both power and cooling from enhanced geothermal systems are increasingly attractive. Therefore, two geothermal supply concepts are compared. An Organic Rankine Cycle (ORC) paired with an electrically driven compression chiller (CC) and an ORC cascaded with a thermally driven absorption chiller (AC). Steady-state system modelling across a range of injection temperatures shows that the cascade ORC+AC configuration can reduce the required geothermal brine mass flow by approximately 12.5% and increase the available net electrical power by about 3.9% compared with the ORC+CC baseline. These gains stem from substituting thermally driven cooling for electrically driven cooling, thereby improving the energetic utilization of geothermal heat.

1 INTRODUCTION

Deep geothermal energy is used worldwide for both power generation and direct heat use. Currently, more than 30 countries have geothermal power plants in operation, with a combined capacity of more than 16 GW (Gutiérrez-Negrín 2024). While more than one third of this capacity is provided by flash power plants, also binary Organic Rankine Cycles (ORC) play a major role and exhibit the highest growth rate of all geothermal power plant types during the last years (Wieland et al. 2023, Gutiérrez-Negrín 2024). The ORC technology is widely used for the utilization of low- and medium-deep geothermal energy sources (Zarrouk and Moon 2014, Eyerer et al. 2020). In addition, it is also suitable in combination with both closed-loop geothermal systems (Zargartalebi et al. 2025) and Enhanced Geothermal Systems (EGS) (Kalra et al. 2012).

Enhanced Geothermal Systems extend the applicability of geothermal power by creating or enhancing fracture networks in deep, low-permeability hot rock and circulating a working fluid between injection and production wells to extract heat. Unlike conventional hydrothermal resources, EGS decouples resource availability from naturally occurring permeability and can therefore unlock very large, widely distributed heat resources if stimulation, drilling, and reservoir management are successful (Lu et al. 2018).

Over the last years, a tremendous run towards new planned geothermal power generation projects initiated. This was mainly caused by two trends: First, significant technological developments regarding the costs and performance of EGS systems, e.g. by activities of the company Fervo Energy (El-Sadi et al. 2024). Secondly, the expected rapid increase in global electricity demand for data centers, primarily resulting from current developments in the field of artificial intelligence (Castro et al. 2024). Rather stable power demand by data centers and reliable power generation potential by geothermal plants make it a promising combination (Kaniyal et al. 2012). This can be also seen in the various power purchase agreements (PPA) between geothermal project developers and companies such as Meta or Alphabet in the United States, with power plant capacities of a few hundred MW and studies suggesting up to 40 GW by 2035 and 100 GW by 2050 alone in the US (Barth and Wood 2025).

However, next to sole power generation, direct cold supply for data centers from geothermal energy with absorption chillers could be a promising approach, as for example discussed by Han et al. (2020). While obviously the power supply to operate the data center will remain the main motivation for future geothermal projects, it remains a question whether the sole geothermal power generation might be the most beneficial concept. In addition to the power demand of the IT infrastructure, a major consumer is the cooling demand of data centers, mostly in the form of compression cooling systems and dry or wet coolers (Ebrahimi et al. 2014). Geothermal cold can be rather efficiently converted into cold by absorption chillers, which is for example also done for district cooling applications in Abu Dhabi, UAE (Cariaga 2023) or Munich, Germany (Weber et al. 2022). As shown in the recent work by Irrgang et al. (2025), absorption chillers can be effectively driven by the low- to

mid-temperature heat available from geothermal brines and, when integrated in cascade with power cycles, enable improved thermodynamic utilization of the extracted thermal energy while reducing the on-site electrical demand for mechanical cooling. Such cascade arrangements allow the residual heat after power extraction to perform useful cooling work, thereby increasing the total energy yield from the same geothermal resource.

Compared with a sole focus on electricity production, combined power-and-cooling concepts can therefore improve the overall energy utilization of a geothermal installation and, in many cases, reduce the required brine mass flow or increase net electrical availability for the same resource conditions (Irrgang et al. 2025; Chidire et al. 2025). These potential advantages depend on the matching of temperature levels between the ORC, the absorption chiller, and the geothermal reinjection constraints, and they are sensitive to assumptions on parasitic electrical loads, chiller performance and ORC working fluid characteristics.

The motivation of this work is to quantify these trade-offs for a large reference data center by directly comparing two practical supply concepts. (A) an ORC supplying electricity combined with an electrically driven compression chiller (CC) for cooling, and (B) an ORC cascade with a thermally driven absorption chiller (AC) that uses the ORC outlet heat. Therefore, determining, across a representative range of injection temperatures, the geothermal brine mass flow required to meet both the electrical and sensible cooling load, to compare the resulting net electrical power available on-site after meeting cooling demand, and to identify key sensitivities that govern whether the cascade (ORC+AC) configuration yields a material advantage over the conventional ORC+CC baseline.

2 POWER AND COOLING DEMAND OF DATA CENTERS

The energy demand of data centers continues to increase, driven by rising computational requirements and, consequently, higher power densities. Data centers are typically classified into enterprise, colocation, and hyperscale facilities (Bangalore et al. 2022). Among these, hyperscale data centers show the most significant growth in both number and capacity, largely due to the expansion of AI and high-performance computing (HPC) workloads (Shehabi et al. 2024). Modern hyperscale facilities commonly reach electrical capacities between 20 MW and 50 MW, while the largest campuses under development may exceed 100 MW per site (Rollinson et al. 2025).

To compare different data center types, the power density (expressed in kW per rack) is often used. Current facilities exhibit densities ranging from 1 to 100 kW/rack, with most operating in the range of 1 to 29 kW/rack. AI-optimized sites increasingly exceed 30 kW/rack, necessitating advanced cooling solutions (Donnellan et al. 2024).

Almost all electrical power consumed in data centers is ultimately converted into heat. Consequently, cooling systems account for up to 38 % of total electrical demand (Abbas et al. 2021), making them a critical factor in overall efficiency. The Power Usage Effectiveness (PUE) is the most common metric for evaluating data center efficiency and is defined as the ratio of total facility power to IT equipment power. State-of-the-art hyperscale data centers achieve PUE values as low as 1.1 under favorable operating conditions (Setyo et al. 2025).

Three main cooling technologies are currently deployed in data centers:

1. Air cooling, used in roughly 70–80 % of installations,
2. Liquid (water) cooling, used in about 15–20 %, and
3. Immersion cooling, currently below 5 %, but rapidly emerging for AI-intensive applications (Azarifar et al. 2024).
   Hybrid systems combining air and liquid cooling are increasingly common.

The choice of cooling technology strongly depends on rack power density. Traditional air-cooled systems are typically effective up to 20 kW/rack, while liquid and immersion cooling can handle much higher thermal loads. These technologies also differ in their required coolant temperatures: air-cooled systems generally operate with chilled-water supply temperatures of around 6 °C, liquid-cooled systems at about 20 °C, and immersion systems can tolerate temperatures up to 40 °C.

To provide the necessary cooling capacity, data centers employ various thermal management technologies. Achieving PUE values close to 1.1 typically requires free-cooling systems, which use ambient air or water when outdoor temperatures are sufficiently low. For peak-load coverage and baseline cooling, compression chillers (vapor-compression refrigeration systems) are still widely applied. Hence, most hyperscale data centers rely on

hybrid cooling architectures, combining free-cooling and mechanical refrigeration to balance energy efficiency, reliability, and operational flexibility.

One particularly efficient and modern data center that serves as the use case for the following investigations is Sandia National Laboratories' Building 725E in New Mexico, which was completed in 2018. The facility was designed to support up to 14 MW of IT load at full buildout and employs a hybrid air–water cooling architecture. Cooling capacity is provided through three distinct chilled-water circuits: a chilled water loop (CW) connected to a free-cooling system and a compression chiller (CW supply ~14.4 °C), a medium-temperature water loop (MTW) that supplies the air-handling units for the data hall (MTW supply ~15.6 °C), and a process water loop (PW) that serves the direct liquid-cooling systems (PW supply ~24.4 °C). The loops are hydraulically decoupled via plate-frame heat exchangers, providing flexibility and resilience. This allows the facility to maximize free-cooling operation and capture as much IT heat as possible into the liquid loops before resorting to evaporative or chiller-based rejection. Building 725E has been reported as a LEED Gold facility and has achieved a year-round average PUE of close to 1.10 under operational conditions, making it an illustrative example of current best practices for energy- and water-aware HPC/data center design.

3 METHODOLOGY

Supplying the reference data center with geothermal energy requires meeting both the electrical and cooling demands. The IT electrical load amounts to 14 MW and is converted entirely into heat, resulting in an equivalent sensible cooling requirement for the data hall. To assess how geothermal energy can simultaneously cover both demands, two alternative supply concepts are analyzed in this chapter.

3.1 Scenario description

3.1.1 Scenario A: ORC + CC

In the reference configuration, the geothermal brine first transfers heat to the Organic Rankine Cycle (ORC) through a surface heat exchanger. The ORC converts the available thermal energy into electricity, which supplies both the data center's IT load, as well as the auxiliary systems (pumps, dry coolers). The cooling demand for the data center is produced entirely by the electrically driven compression chiller (CC). The CC provides the required chilled-water temperatures and consumes a portion of the ORC's electrical output. A schematic of this layout is shown in Figure 1 as Scenario A.

3.1.2 Scenario B: ORC + AC

The alternative configuration uses the geothermal source not only to drive an ORC for electricity production but also to operate an absorption chiller (AC) in cascade with the ORC. In this arrangement, the geothermal brine first supplies heat to the ORC. After passing the ORC heat exchanger, the cooled brine is routed to the absorption chiller via an intermediate heat exchanger, where the remaining thermal energy drives the desorption process. The AC provides the required cold for the data center, while the ORC provides the electrical load for the IT equipment and for ancillary systems (including the dry cooler used to reject heat from the AC). This cascade arrangement is sketched in Figure 1 as Scenario B.

The fundamental difference between the two concepts lies in the method by which cooling is generated. The CC in Scenario A consumes additional electrical energy, whereas the AC in Scenario B utilizes low-temperature thermal energy to produce cooling. The expected objective of Scenario B is to increase the total energetic utilization of the geothermal resource and achieve a net increase in available electrical power to the data center compared to Scenario A.

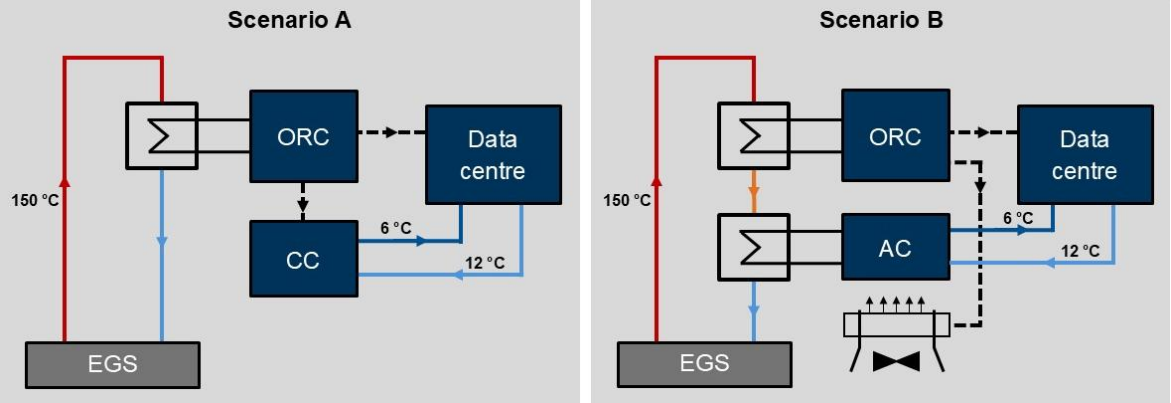


Figure 1: System design for two scenarios for supplying electricity and cooling to a data center using geothermal energy

3.2 Modelling approach and boundary conditions

The geothermal resource is represented as an Enhanced Geothermal System (EGS) with a production temperature of 150 °C and a wellhead pressure of 20 bar. A fixed ambient temperature of 16 °C is assumed. For each scenario, the geothermal mass flow rate and the reinjection temperature are solved iteratively such that both the electrical and cooling demands of the data center are met while respecting resource limitations.

The following ORC and absorption chiller models are based on Chidire et al. (2025). The ORC is modelled as a single-stage cycle using R1233zd(E). Net electrical output is computed as turbine power minus pump and auxiliary loads, including the power required for downhole pumping (specific pump power of 1,786 W kg^{-1} s^{-1} following Frick et al. 2010). Recent experimental investigations have shown that several modern low-GWP working fluids, specifically R1224yd(Z), R1233zd(E) and R1336mzz(Z), are viable replacements for the high-GWP refrigerant R245fa in ORC applications, offering comparable or improved thermodynamic performance while substantially reducing global-warming potential. These studies additionally assess lubricant interaction and broader environmental impacts and support the selection of R1233zd(E) as a suitable low-GWP option for geothermal ORC systems. Heat rejection from ORC and AC is handled by dry coolers; their electrical parasitics are included in the auxiliary loads.

The electrically driven compression chiller is represented with a conservative reference COP of approximately 5 and a linear dependence on ambient temperature, capturing performance degradation at higher dry-cooler temperatures. The absorption chiller is modelled as a single-effect, single-lift LiBr–H_2O system sized to deliver chilled water at 6 °C supply and 12 °C return (Ziegler 2002). Generator and absorber pinch-point constraints are included following literature correlations by Chidire et al 2025. All parameters that are used for modelling are summarized in Table 1.

Table 1: Parameters used to model the EGS, ORC, CC and AC

Parameter	Quantity	Unit
Production temperature EGS	150	°C
Wellhead pressure	20	bar
Electricity demand for downhole pump	1,786	W kg^{-1} s^{-1}
Ambient temperature	16	°C
ORC turbine efficiency	75	%
ORC pump efficiency	80	%
Electricity demand for air-cooled condenser	150	W kg^{-1} s^{-1}
ORC superheating	3	K
Min. ORC pinch point temperature difference	5	K

ORC working fluid	R1233zd(E)	-
Cooling demand temperature	6 / 12	°C
COP_{CC}	5	-
AC working fluid	LiBr-H_2O	-
Electricity demands AC dry cooling	0.023	kW_{el}/kW_{th}

4 RESULTS

To enable a transparent comparison between the two supply concepts, the geothermal brine mass flow required to cover both the electrical and the cooling demands of the reference data center is determined. After the mass-flow sizing is established as a function of reinjection temperature, the energetic benefit is assessed by comparing the produced net electric power for a defined mass flow.

4.1 Geothermal brine mass flow

The required brine mass flows for Scenarios A (ORC + CC) and B (ORC + AC) are sized such that the reference demand (14 MW electric and 14 MW sensible cooling) is met. The investigated reinjection temperature range is 60–95 °C. This span is chosen to represent typical operational reinjection temperatures for medium-deep EGS plants and to cover the region where ORC extractable heat and AC generator requirements exhibit significant changes.

To determine the mass flow required for each injection temperature, the following procedure is used for Scenario A. Based on a fixed outside temperature, the electric power required by the CC to deliver the cooling is calculated. Using this electric power for cooling together with the fixed electrical load of the data center, the total electrical demand is known, and the ORC mass flow can be sized accordingly. The ORC receives a constant brine inlet temperature of 150 °C and is iteratively cooled to various outlet temperatures. The ORC outlet temperature corresponds to the injection temperature of the EGS. For each injection temperature, an appropriate mass flow of geothermal brine is determined.

The mass flows for Scenario B are determined using the mass flows computed for Scenario A. First, for each investigated injection temperature, the temperature that must be present at the AC inlet is determined, which equals the ORC outlet temperature. An iterative procedure determines the minimum AC inlet temperature that still meets the required cooling load after cooling to the injection temperature. In the first iteration, it is assumed that the AC is supplied with the same mass flow rate as in Scenario A, which yields the ORC outlet temperature and the electrical power required to operate the AC. The required mass flow is computed in the same way as for Scenario A, and this electrical power, together with the defined electrical load of the data center, must be covered by the ORC. Finally, it is checked whether the resulting mass flow in Scenario B allows the AC to meet the cooling demand. If not, a second iteration is performed, and the mass flow is adjusted.

The mass flows determined for the investigated injection temperatures are shown in Figure 2. It can be observed that the mass flows for Scenario A are always greater than those for Scenario B, with the mass flow of Scenario A remaining constant at approximately 560 kg s^{-1} up to an injection temperature of 80 °C, increasing to around 610 kg s^{-1} at the highest injection temperatures. Scenario B starts at approximately 490 kg s^{-1} and rises more rapidly, reaching about 605 kg s^{-1} at an injection temperature of 95 °C.

The calculated geothermal brine mass flows are within the normal production range for commercial plants (Olasolo et al. 2016). The initially constant mass flow in Scenario A is explained by the chosen working fluid for the ORC. At low ORC outlet temperatures, the cycle efficiency drops, and little additional power can be extracted. Consequently, the ORC's electrical output and thus the required mass flow stagnates when the ORC's inlet temperature falls below approximately 80 °C. The earlier increase in mass flow in Scenario B is explained by the fact that an absorption chiller requires a higher ORC outlet temperature compared to Scenario A, enabling cooling production. As a result, the available extractable heat and the matching between the heat source and sink change for a given injection temperature, causing the required brine mass flow to rise at lower injection temperatures compared to Scenario A.

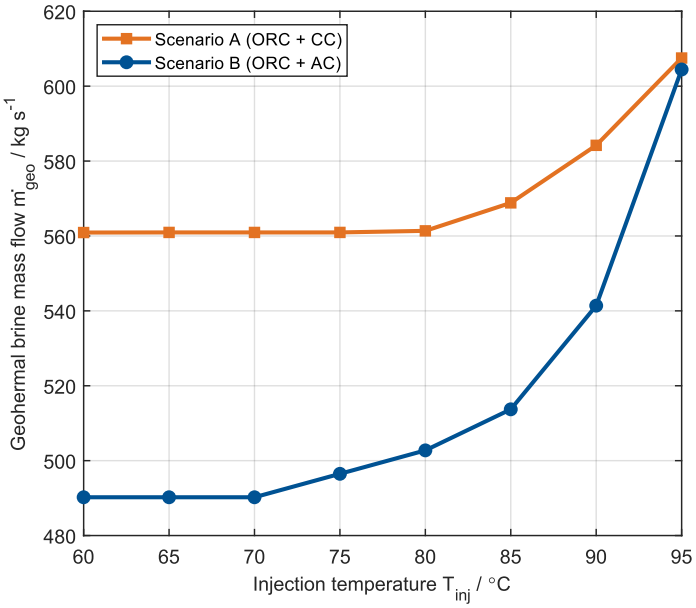


Figure 2: Geothermal brine mass flow plotted over different brine injection temperatures for Scenarios A and B

4.2 Net electric power

After the geothermal brine mass flows for both scenarios have been calculated for the range of injection temperatures, the mass flows can be used to determine the net electric power outputs of both scenarios as a function of injection temperature. Therefore, a suitable reference mass flow is selected from Figure 2 and used for the comparison.

For EGS plants, it is crucial to select an optimal injection temperature, as this affects the production temperature of the EGS. For the selection of the mass flow rate, an injection temperature of 80 °C is chosen, which is consistent with commercial EGS plants operating under similar conditions (Li et al 2023, Giroud et al. 2012). From the chosen injection temperature, Scenario A requires a mass flow of 560 kg s^{-1}. The mass flow of Scenario A is selected, so that for a comparison of the net electric power outputs, both scenarios meet the data center demands at 80 °C injection temperature

The net electrical power output is calculated analogously to the mass-flow sizing. For Scenario A, the ORC gross power is obtained iteratively from the fixed production temperature (brine inlet 150 °C) and the prescribed mass flow for each investigated injection temperature. Net power is then computed by subtracting all auxiliary electrical loads and the electrical consumption of the compression chiller from the gross ORC output.

For Scenario B, the required absorption chiller inlet temperature is first determined for each injection temperature such that the demanded cooling capacity can be delivered. The AC inlet temperature is equal to the ORC outlet temperature. Using the ORC outlet temperature, the ORC gross power is calculated. From that gross power, the auxiliary loads and the electrical demand of the dry cooler (used to cool the AC) are subtracted to obtain the net electric power.

Figure 3 shows the net electric power outputs of both scenarios plotted against injection temperature. Over the entire investigated injection temperature range (60–95 °C), Scenario B provides a larger net electric power than Scenario A. This is consistent with the mass-flow results shown in Figure 2. Scenario B achieves a net electric power greater than the required 14.0 MW up to an injection temperature of 93 °C. This is reasonable because the system is sized for the demand of Scenario A. From Figure 2, Scenario B requires a mass flow of 560 kg/s, corresponding to an injection temperature of 92.5 °C, to provide 14.0 MW. This is consistent with the results shown in Figure 3, where the net electric power output at an injection temperature of 93 °C drops to 14.0 MW.

Analogous to Figure 2, the net electric power output of Scenario A is nearly constant at an injection temperature of 80 °C. This behavior has the same origin as explained in Section 4.1. Below a certain ORC outlet temperature, the ORC cycle efficiency of the chosen working fluid decreases and gross electrical output stagnates. Therefore, the net output does not increase with decreasing injection temperature. The assumed mass flow of Scenario A

(560 kg s^{-1}) at 80 °C yields a net electric power of 14.0 MW, which validates the internal consistency of the two models.

Quantitatively, at a reinjection temperature of 80 °C, Scenario B yields an additional net electrical output of 2,140 kW compared with Scenario A for the same production temperature and brine mass flow. For this operating point, the CC requires 2,680 kW of electrical input, whereas the AC-based solution requires only the electrical parasitics associated with the AC system. For the current operating point, these parasitics comprise the dry-cooler power (~350 kW) and AC auxiliary power (~190 kW). Hence, the net electrical saving achieved by substituting the CC with the AC is 2,140 kW (2,680 kW − 350 kW − 190 kW), which is numerically identical to the additional net electrical output computed for Scenario B. This implies that, at this operating point, the ORC in Scenario A and the ORC in Scenario B deliver the same electrical power.

Consequently, at this operating point, the ORC in Scenario B can supply the original IT and plant electrical loads, and, due to the reduced electrical cooling requirement, produces an excess of electrical power equal to the CC electricity avoided. The remaining on-site electrical demand under Scenario B comprises only the AC parasitics (≈540 kW) instead of the full CC requirement (2,680 kW). This balance is sensitive to the assumed values for CC electricity, dry-cooler consumption and AC auxiliary loads; a perturbation in any of these parameters will change the magnitude of the surplus and the fraction of CC electricity that can be offset by the ORC.

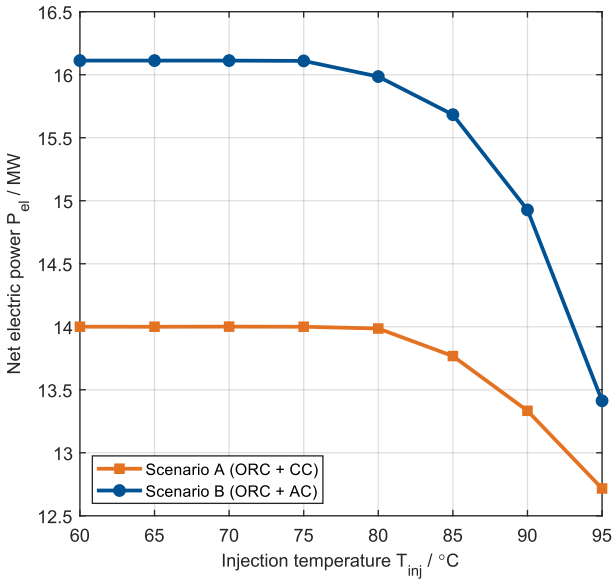


Figure 3: Net electric power output plotted over different brine injection temperatures for Scenarios A and B

5 SUMMARY & OUTLOOK

This study examined alternative system concepts for meeting a data center's electrical and cooling demands using geothermal heat, comparing a conventional configuration using an organic Rankine cycle with an external compression chiller to a cascade arrangement incorporating an ORC followed by an absorption chiller. The modelling focused on how injection temperature and plant boundary conditions affect the required geothermal brine mass flow and the net electrical power available after satisfying cooling demands.

The results show that replacing the CC with an AC can reduce the geothermal brine mass flow for the same cooling and electrical demand under the investigated conditions, and that this advantage is most pronounced at larger temperature differences between production and injection. For the reference case with a production temperature of 150 °C and an ambient temperature of 16 °C, the scenario using an AC required noticeably lower brine flows at lower injection temperatures. For example, flows on the order of 490 kg s^{-1} were found for Scenario B, compared with 560 kg s^{-1} for Scenario A at the lower end of the injection-temperature range, resulting in a mass flow savings of around 12.5%. As the injection temperature increases and the ORC outlet temperature rises, the benefit of reduced brine flow diminishes because the ORC's extractable thermal head and cycle efficiency change non-linearly.

When the analysis is extended to net electrical output, the AC-based configuration consistently provides higher net electrical power across the examined injection-temperature range. Using the reference mass flow (560 kg

s^{-1}) at an injection temperature of 80 °C, the AC configuration yields an additional net electrical output of about 2,140 kW compared with the CC configuration, corresponding to a 3.89% increase in net power. Since, at this operating point, the ORC gross output is essentially the same for both scenarios, the cascade (AC-based) configuration can therefore provide the electrical power required for the compression chiller as an extra, minus the parasitic electrical consumption of the AC system for the dry cooler (~350 kW) and the auxiliaries (~190 kW). This demonstrates that the cascade solution materially improves the plant electrical balance and thereby increases the utilization efficiency of an EGS installation supplying both power and cooling.

The study also highlights sensitivities that deserve further attention. The magnitude of the AC benefit depends on assumptions about parasitic electrical loads (dry cooler and other auxiliaries), the chosen ORC working fluid and its temperature-dependent efficiency, and site-specific thermal losses that determine the effective production temperature. Preliminary checks with varying production and ambient temperatures produced similar qualitative trends, but a formal sensitivity and uncertainty analysis would quantify the robustness of the conclusions and identify the parameter ranges where an AC provides the greatest advantage.

In summary, the modelling indicates a clear technical potential for using absorption chillers instead of compression chillers in geothermal-driven cooling of data centers. The AC approach can reduce the required brine mass flows and increase the net electrical output under typical operating conditions, thereby improving the overall performance of the EGS plant.

Future work should investigate the influence of changing ambient temperatures on these results. Preliminary tests showed similar technical potential. However, ambient temperature has a significant impact on ORC performance and alters the electrical power required to operate the absorption chiller. It is therefore important to determine the minimum and maximum ambient temperature limits within which the cascade configuration remains beneficial.

Furthermore, the present study used a simplified (conservative) modelling approach for the compression chiller. The CC performance was represented by an assumed COP of 5 with a linear dependency of the ambient temperature, which is comparatively high. More detailed and accurate compression-chiller modelling in subsequent studies could change the quantitative outcomes and may further strengthen the advantages found for Scenario B. Additionally, future work could investigate alternative ORC working fluids and incorporate an economic assessment to evaluate the cost-effectiveness of the proposed configurations.

Acknowledgements

Funding from the Bavarian State Ministry of Education, Science and the Arts, Germany in the framework of the project Geothermal-Alliance Bavaria is gratefully acknowledged.

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