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# Hydrogeochemical Restrictions for Flexible Hydrogeothermal Power Generation

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## ABSTRACT

Renewable energy sources are contributing significantly to the energy market. Although weather conditions and energy demand became much more predictable over the years, there is still a need for short term control reserves to cover a sudden energy demand or overproduction. This project focused on the potential of geothermal power plants to provide a control reserve.

The gradients recorded in operation data sets of power plants in the Bavarian Molasse basin are much higher than the initial guesses, and geothermal plants providing district heating have always been run controlled by sometimes rapidly changing weather conditions. However, the inertia of the thermal water system limit the flexible operation to tertiary control reserve (provision of energy within 15 minutes). The long-term operational data suggest a generally benign behavior with just one exception: a complete shutdown and restart of the pumps has proven to increase the risk of failure and enhanced precipitations in and above the pumps. A simulation comparing the current operation and a hypothetical operation providing tertiary reserve by a variation of the flow rate and temperature spread showed no significant changes in terms of precipitates and dissolution rates in the reservoir.

These positive results cannot be transferred to the Upper Rhine Valley and the North German Basin. In both regions the hydrochemical conditions favor precipitates at lower temperatures, therefore, the injection wells are less fault tolerant and will react sensitive to temperature changes.

A flexible operation of the geothermal system makes sense with regard to a sustainable exploration of the reservoir. However, under the current subsidies for geothermal power, it makes more sense to run the power plant at full throttle; at least from a financial point of view.

## 1. INTRODUCTION

The transition from fossil fuels to renewable energy sources has taken up considerable speed. In Germany renewable energy sources contributed 37.8% in 2018 (27.4% in 2014) to the power supply (UBA 2019). Because of their dependence on the current weather conditions wind energy and solar power production are considered volatile energy sources. Sudden energy demand or overproduction have to be covered by a control reserve. The control reserve is a very flexible power source or power sink which can handle large gradients to maintain the frequency in the power grid. Geothermal power production has also been increasing over the past years. In contrast to solar and wind energy, geothermal energy is independent of weather conditions and therefore has a potential contribute to the control reserve. However, owners and operators of geothermal power plants are reluctant to adapt a flexible production for technical and economic reasons. This project addresses the hydrogeochemical part of flexible geothermal power generation.

Deep hydrogeothermal heat and power supply uses the water in the reservoir as energy source and working fluid. Initially, the fluid is in equilibrium with the rock matrix of the reservoir. The lithostratigraphic setting is mirrored in the hydrochemical composition. During production pressure changes and heat extraction lead to a disruption of hydrochemical equilibria. This causes precipitates, corrosion and formation of two-phase flow. All processes affect the technical and economic performance. Experience from the facilities in the Bavarian Molasse Basin and the North German Basin shows that the disruption of hydrochemical equilibria lead to significant down times.

## 2. METHODS

### 2.1 Hydrochemical Characteristics

The hydrochemical setting in the Molasse Basin (MB) based on data from Mayrhofer et al., 2014 is plotted as Schoeller diagram in Fig. 1. The geothermal water is dominated by calcium, magnesium, and bicarbonate (Ca-Mg-$HCO_3$-type). At some locations ion exchange affected the waters significantly (Na-Ca-$HCO_3$-type) and at other locations waters infiltrating from higher strata lead to an increase of the sodium and chloride concentrations. The concentration of total dissolved solids is usually below 2 g/L. The wells to the west of Munich show high gas concentrations up to 2 L gas per L of thermal water and a $CH_4$ to $N_2$ ratio of 12:1. Below and southeast of Munich the gas concentrations are in a range of 200 mL/L and a $CH_4$:$N_2$ ratio of 1:1 is typical. Gas concentrations are varying widely and so does the bubble point.

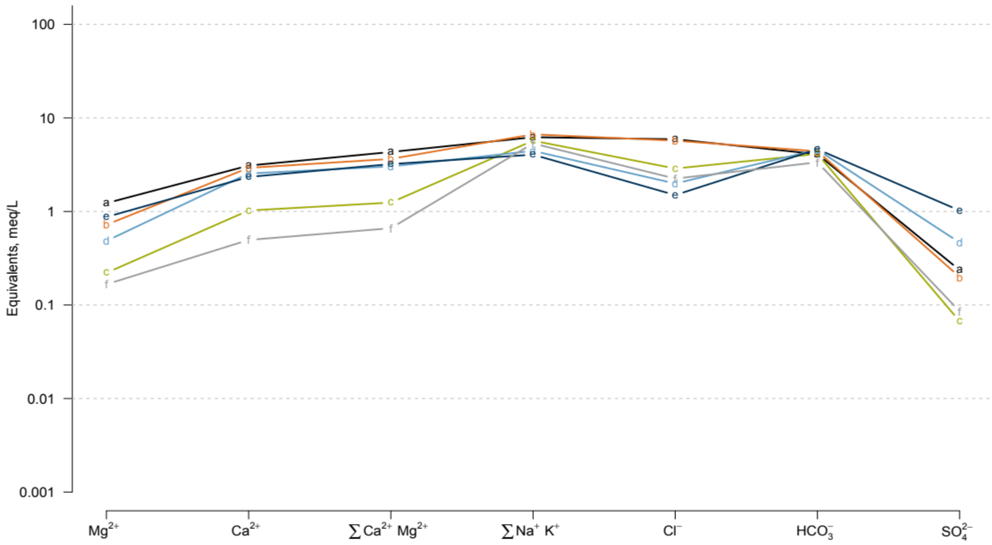


**Figure 1: Schoeller diagram for the waters in the Upper Jurassic sediments produced at the geothermal power plants in the central Molasse Basin around Munich**

## 2.2 Numerical Model

Fig. 2 shows a schematic of a geothermal power plant and the simulation checkpoints of the model. In the reservoir (sim. 99) the hot water is in equilibrium with the rock matrix. The water is produced with a pump (sim. 1) to ground level (2). At this point the samples are taken for the hydrochemical analyses. These samples are affected by degassing and require a back calculation to reservoir conditions as shown in (Baumann, 2016). The pressure in the surface level facilities is maintained at a defined level. However, local pressure drops are likely at the particle filters between sim. 3 and sim 4. After the heat exchanger, the cold water is led to the injection well. The pressure is maintained at a lower level. Contrary to initial predictions and simulations, most geothermal wells in the MB do not require active injection using pumps due to an increase in injectivity caused by the dissolution of the rock matrix (see Baumann et al. 2017). The water is flowing into the wells and the pressure levels can drop below atmospheric pressure (sim. 6). Back in the reservoir the water re-equilibrates with the rock matrix (sim. 7).

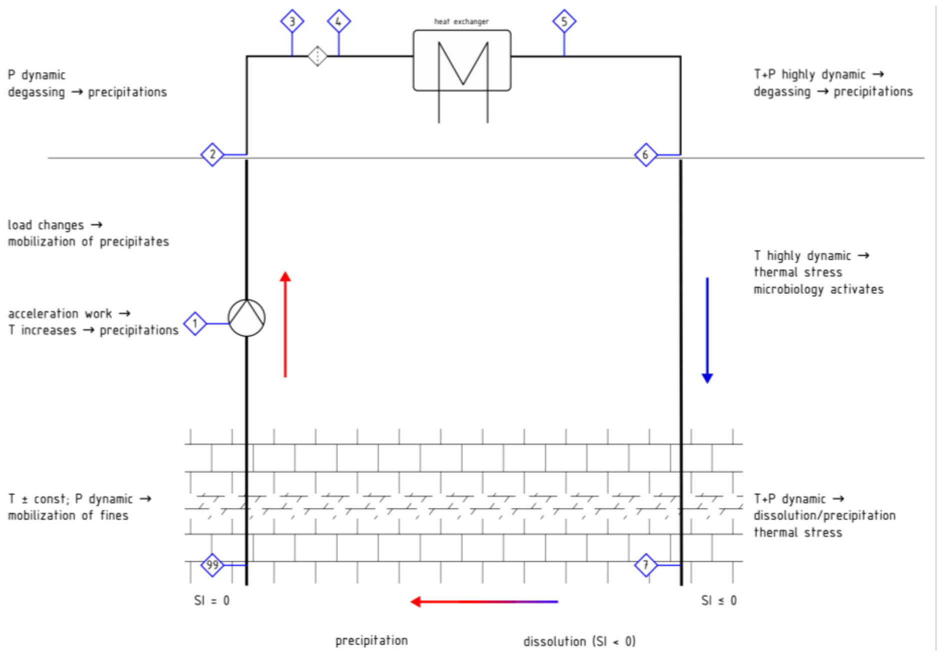


**Figure 2: Schematic of the conceptual model to predict the hydrogeochemical effects of flexible operation**

The numerical model to predict the effects of flexible geothermal power generation on the formation of scalings and the processes in the reservoir was built with PhreeqC (v. 3.4.0 with bug fixes; Parkhurst and Appelo, 1999) using the phreeqc.dat database. The model was validated for geothermal simulations in the MB (Hörbrand and Baumann, 2018). In the MB the water contains $CH_4$ and $N_2$ with combined partial pressures up to 20 bar. Any amount of $CO_2$ in the gas phase could be attributed to dissolved inorganic carbon.

### 2.3 Model of Flexible Power Generation

To simulate the hydrogeochemical effects of a participation of the geothermal power plant in the control reserve, data of the demand for the minute reserve in 2016 in the TenneT grid was used (regelleistung,net, 2019, Fig. 3). Two scenarios were simulated: First, for positive minute reserve (requirement for additional power) the pumping rate is increased from 75% to 100% within 15 minutes. The injection temperature stays constant. Negative minute reserve was simulated by a virtual disconnection the power plant from the geothermal cycle, i. e., the pumping rate stays constant and the injection temperature increases to production temperature. The pressures and temperatures at the pump were calculated based on regression functions derived from operational data. The simulation scenarios were compared to a stochastic simulation (50000 simulations with varying gas concentrations) with sensor data from the current operation of the power plant.

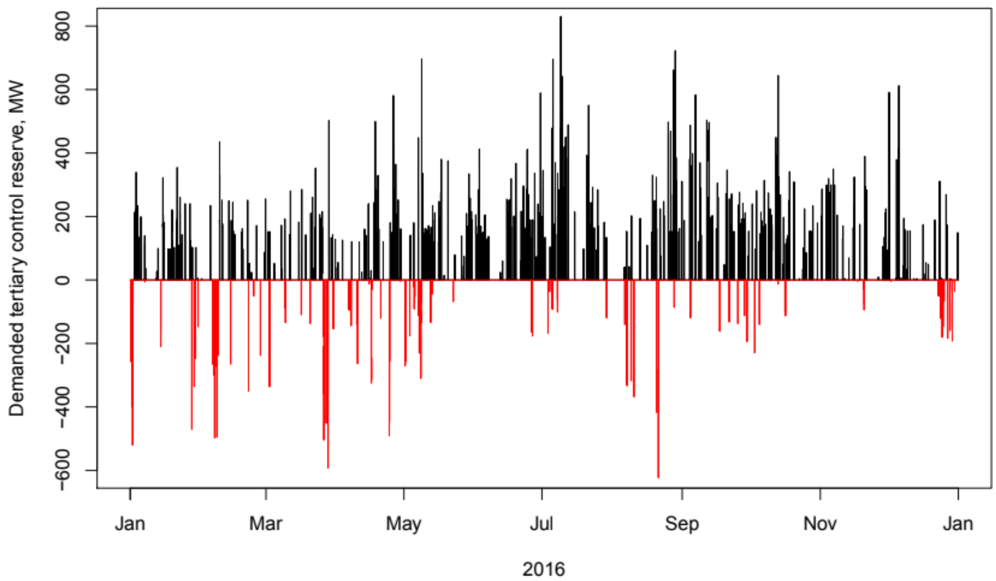


**Figure 3: Demand for tertiary control reserve in 2016 for the TenneT grid.**

## 3 RESULTS

Fig. 4 shows the measured temperatures along the geothermal cycle (well head = 100%). Temperatures at the motor of the submersible pump show the highest variation reflecting the varying load scenarios. Pressure (Fig. 6) decreases from 38 +5/-10 bar at the pump to 12 ± 0.2 bar at the well head and before the heat exchanger, 8 ± 0.1 bar after the heat exchanger and 0.2 ± 0.1 bar at the well head of the injection well. Temperature and pressure are reflected in the saturation index for calcite which is supersaturated at the motor (temperature above reservoir temperature), slightly supersaturated in the production pipes and up to the heat exchanger (partial degassing) and undersaturated after the heat exchanger until the well head of the injection well. Here, due to heavy degassing, even the cold water is supersaturated. However, due to kinetic limitation most crystallization nuclei are transported back into the reservoir. In the reservoir the water in the vicinity of the bore hole is colder than the reservoir and therefore undersaturated. The dissolution of the rock matrix as predicted by the model has been experimentally verified in (Baumann et al., 2017, Ueckert and Baumann, 2019).

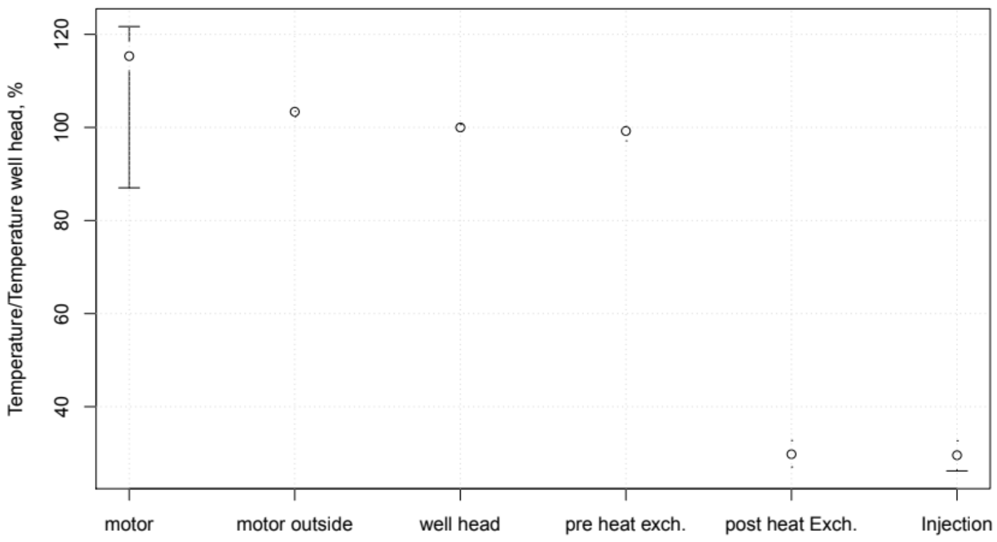


**Figure 4: Measured temperature development along the thermal water cycle (well head = 100%).**

The saturation indexes for calcite, barite and quartz are plotted in Fig. 5 as a function of the temperature for the simulated thermal water. At reservoir temperature the water is in equilibrium with the matrix (here calcite). Even a small reduction of the temperature brings the saturation index to slight undersaturation, while degassing at 5 bar leads to supersaturation. This is in line with experimental data, which show that precipitations in a shell and tube heat exchanger occur in the first centimeters only. At injection temperatures between 40 and 60 °C the water is strongly undersaturated with regard to calcite, even after degassing. Both, quartz and barite show increasing saturation index with decreasing temperature. While barite stays undersaturated even at ambient temperature, quartz should precipitate at least after the heat exchanger. Experimental data, however, does not show such precipitates in surface level facilities, which makes sense, because the rate constants for quartz precipitation are much slower than for calcite.

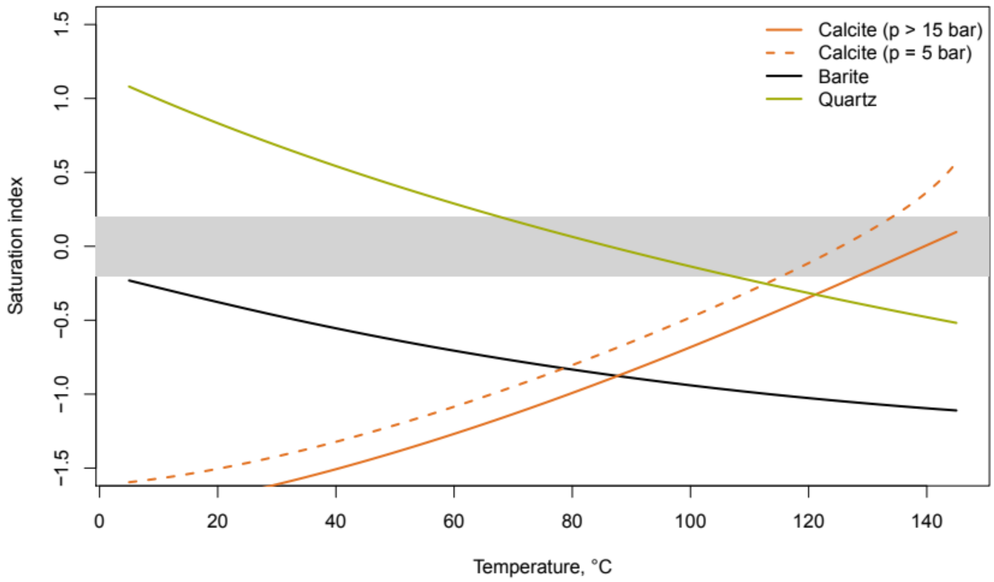


**Figure 5: Saturation index for calcite, barite and quartz as a function of temperature for the simulated water in the Upper Jurassic reservoir in the Molasse basin.**

Following long standing best practice in well design and operation, engineers are reluctant to expose the geothermal system to strong gradients. It was, however, unclear what the actual gradients are and how a flexible operation would affect the gradients. Fig. shows the gradients of the motor frequency for one geothermal power plant. In the first year of installment, the gradients easily reached close to ±6 Hz/h (Fig. 6). Obviously there were a large number of test runs and unintentional shutdowns, so later operation shows less variance. The data, together with field data on precipitates, shows that the technical capabilities were underestimated. A similar result was obtained for the injection temperatures. Here, the variation of the geothermal power plants was comparable to geothermal district heating systems. Since the latter were operating for a much longer time, is can be assumed that the reservoir does not suffer significantly from higher injection temperatures.

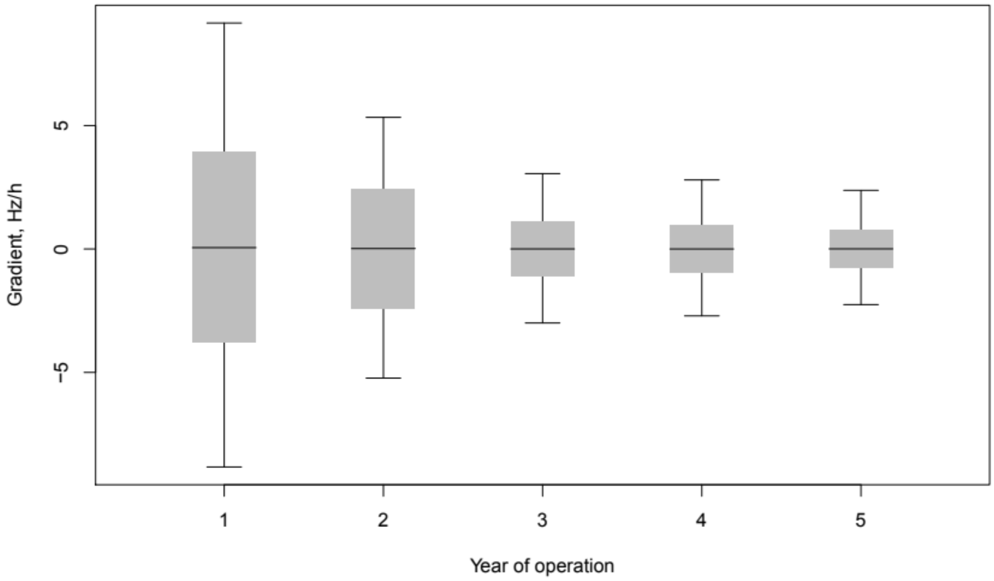


**Figure 6: Gradients of the pump frequency of a submersible pump at a geothermal power plant in the Molasse basin.**

Simulation results with the calibrated numerical model (Baumann et al. 2017, Ueckert and Baumann, 2019) predict a net dissolution of calcite in the vicinity of the bore hole of 2 m³/year at current operation conditions. Participitation in the control reserve as outlined above leads to a slight increase to 2.2 m³/year. At this point, the MB proves to be benign because the solubility of calcite is increasing with decreasing temperature. Things will be entirely different for saline reservoirs, where massive precipitations were observed after the heat exchanger and in the injection wells.

## 4 CONCLUSION

Based on hydrogeochemical predictions and supported by operational data from geothermal district heating plants, the geothermal plants exploring the Upper Jurassic reservoir in the Molasse Basin can be operated with higher flexibility than initially considered. Flexible operation is limited by the dynamic range of the motor of the submersible pumps and the allowed difference between production and injection temperatures. Flexible operation increases the stress to motors, pumps, and pipes. More importantly thermal stress to the injection well has to be considered, if hot and cold water are injected during flexible operation. The hydrogeochemical bottlenecks in the Molasse Basin are high temperatures at the motor and degassing in pumps, filters and surface level facilities. These processes cause a disruption of the lime-carbonic-acid-equilibrium and precipitations in the thermal water cycle. Precipitations are also expected at the well head of the injection well where pressure levels below ambient pressure have been recorded. Data indicates that high gradients promote degassing in the pump and increasing precipitation rates in the production pipes. With regard to the reactions in the reservoir simulations indicate that there is no significant difference between flexible and constant operation. Here, the Upper Jurassic reservoir in the Molasse Basin stands for a benign behavior of the injection wells. Preliminary simulations for the North German Basin indicate, that a flexible operation is likely causing additional problems at the injection wells.

Although most of the facilities in the Molasse Basin are small scale facilities (4.2 MW net on average), they could possible add to a stabilization of the power grid in regional and local pools. The dilemma with the provision of negative control reserve could be circumvented with surface level storage systems. Even if this is not possible, the injected heat helps to prolongate the time for thermal breakthrough. While the technical feasibility seems to be given, the current economic conditions are in favor of a 24/7 operation at maximum load and with as little downtime as possible. This, however, might change rapidly with upcoming regulations.

## ACKNOWLEDGEMENTS

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## REFERENCES

Baumann, T.: Validation of Hydrochemical Analyses and Gas Concentrations of Deep Geothermal Aquifers. *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering Bd. SGP-TR-209, Stanford University (2016)

Baumann, T., Bartels, J., Lafogler, M., and Wenderoth, F.: Assessment of Heat Mining and Hydrogeochemical Reactions With Data from a Former Geothermal Injection Well in the Malm Aquifer, Bavarian Molasse Basin, Germany. *Geothermics* **66** (2017), S. 50–60

Hörbrand, T., Baumann, T., and Moog, H. C.: Validation of Hydrogeochemical Databases for Problems in Deep Geothermal Energy. *Geotherm. Energy* **6** (2018)

Mayrhofer, C., Niessner, R., and Baumann, T.: Hydrochemistry and Hydrogen Sulfide Generating Processes in the Malm Aquifer, Bavarian Molasse Basin, Germany. *Hydrogeol J.* **22** (2014), 151–162

Parkhurst, D. L. and Appelo, C. A. J.: Description of input and examples for PHREEQC version 3 -- A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations, U.S. Geological Survey, Techniques and Methods 6-A43 (2013)

regelleistung.net: Kalenderjahresdateien – Eingesetzte MRL 2013-2017. 2018. – URL https://www.regelleistung.net/ext/download/MRL_Jahresdatei_Abruf

UBA (2019): https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen.

Ueckert, M. and Baumann, T. Hydrochemical Aspects of High Temperature Aquifer Storage in Carbonaceous Aquifers - Evaluation of a Field Study, *Geotherm. Energy* **7** (2019) https://doi.org/10.1186/s40517-019-0120-0