PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

DeepStor - Heat Cycling in the Deep and Medium-Deep Subsurface

Eva Schill[1], Roland Knauthe[2], Xheni Garipi[1], Florian Bauer[1]

[1]Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Technische Universität Darmstadt, Schnittspahnstrasse 10, 64287 Darmstadt, Germany

eva.schill@kit.edu

Keywords: Numerical modelling, high-temperature heat storage, up-scaling

ABSTRACT

More than 40% of CO_2 emissions in Germany are generated in the heating sector. This contrasts with the expansion potential of deep hydrothermal geothermal energy, which accounts for around 25 % of the country's total heating requirements. One of the regions in Germany that can provide resources for this is the Upper Rhine Graben. There, fracture-bound deep geothermal systems are often associated with medium-depth hydrocarbon reservoirs. Examples are Soultz-sous-Forêts, Landau, but also the former Leopoldshafen oil field, below which a temperature of 170°C at 3,000 m depth has been proven. Heat networks in Germany typically show a low heat demand in summer and a high demand in winter. The base load supply in summer typically accounts for only a few to around 15 percent of the peak load in winter. Since the conversion of excess heat into electrical energy is associated with low efficiency levels, the storage of excess heat in medium-depth reservoirs is proposed here to optimize the overall system.

The DeepStor research infrastructure at the KIT-Campus North represents an analog for such storage systems in the Upper Rhine Graben. With a planned production from the fractured geothermal system at depth of more than 3,000 m, heat can be extracted in sufficient quantity and temperature to cover the base and medium load. The surplus heat can be stored in the peripheral areas of the former Leopoldshafen oil field (with 70 % water saturation at the end of hydrocarbon production) and recovered in winter.

A 3-D subsurface model for DeepStor and the city of Karlsruhe was created on the basis of 2-D and 3-D seismic data and information from more than 20 boreholes in former oil fields. Using temperature and hydraulic data from the corresponding boreholes, thermo-hydraulic simulations were carried out to 1) estimate the state of the deep geothermal system and 2) optimize the planned campus supply. In summary, our results show that the share of renewable geothermal heat energy can be increased from 25 % to about 65 % by storing the excess heat without heat losses to the atmosphere. Assuming that technical problems such as scaling can be solved, we are currently in the process of scaling up the storage system to the city of Karlsruhe with peak and base loads of around 250 and 30 MW.

1. INTRODUCTION

The climatic conditions in Central Europe require the provision of considerable amounts of thermal energy for heating purposes in the winter months, which leads to a seasonal imbalance between heat supply and demand when supply is constant, as is the case with base load-capable geothermal plants. This discrepancy requires buffer systems with a large capacity.

The Upper Rhine Graben with its generally high temperature gradients, which can locally reach up to 100°C km^{-1}, offers one of the most favorable geothermal conditions in Central Europe (e.g., Baillieux et al., 2013; Vidal and Genter, 2018). Nowadays, a number of 16 geothermal wells are in operation for production and reinjection of thermal brine from Tertiary Fms. (2), Muschelkalk Fms. (2), Muschelkalk Fms. to the Variscian basement rock (2), Buntsandstein Fms. to the Variscian basement rock (6), and only Variscian basement rock (4, Frey et al., 2022). The causal close connection between hydrocarbon and geothermal reservoirs is shown by the spatial proximity of temperature anomalies below hydrocarbon reservoirs and the coexistence of geothermal fluids and hydrocarbons in fractured Mesozoic reservoirs (e.g., Böcker, 2017). The long history of hydrocarbon and geothermal exploration has led to the Upper Rhine Graben being a continental rift system that has been intensively studied by geoscientists. The numerous depleted oil fields in the Upper Rhine Graben are proven reservoirs that are well characterized in terms of their depth, geometry and reservoir properties. Moreover, seismicity and environmental impact have shown to be minimal during hydrocarbon production and have been minimized during reservoir engineering and operation in the deep geothermal systems (e.g., Schill et al., 2017; Genter et al., 2012).

Nowadays, there are numerous storage applications in near-surface underground systems, ranging from gravel pits to aquifer thermal energy storage (ATES). State of the art is borehole thermal energy storage, in which the heat pump cycle is reversed to store excess heat. Worldwide, > 2,800 ATES systems are in operation, mainly in the Netherlands, providing more than 2.5 TWh a^{-1} for heating and cooling purposes (Fleuchhaus et al., 2018). The operating temperatures of ATES are generally < 50 °C and cover low-temperature heat applications. There are only a few plants worldwide that operate at higher temperatures. Holstenkamp et al. (2017) describe the conditions and experiences of the two German plants in Berlin and Neubrandenburg. High-temperature heat storage for industrial applications or district heating supply, for which temperatures of up to >110 °C are required, are typically not taken into account (Fraunhofer ISI, 2017).

Assuming a doublet system with seasonal injection and production cycles, a numerical potential study for the injection of 140 °C water into a typical 70°C reservoir shows an annual storage capacity of up to 12 GWh per well and significant recovery efficiencies increasing up to 82 % after ten years of operation (Stricker et al., 2020). Around 90 % of the reservoirs investigated in the Upper Rhine Graben can be converted into such high-temperature ATES (HT-ATES). In summary, this indicates a total storage capacity in depleted oil reservoirs of about 10 TWh a^{-1}, which represents a considerable part of the thermal energy demand in this area.

In this study, we numerically investigate the heat extraction from a deep fractured reservoir at the DeepStor site in combination with the seasonal storage of heat at the edge of the depleted Leopoldshafen oil field (Figure 1). The motivation for this study is our concept to mitigate the induced seismicity during operation of the deep fractured reservoir through stable and moderate flow rates (Schill et al., 2017; Genter 2012). In order to keep the flow rates in the deep fractured reservoir stable, although the heat demand in summer is significantly lower, we propose heat storage in a porous reservoir with comparatively low potential for induced seismicity. This concept has the positive side effect of automatically reducing the flow rates required to cover the heat demand in winter in the deep, fractured reservoir with a higher potential for induced seismicity.

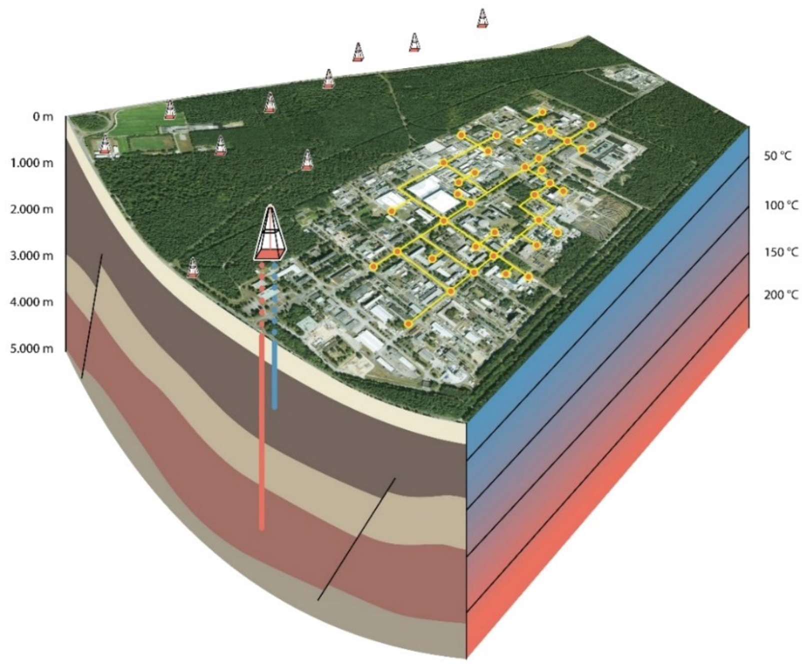

Figure 1: Sketch of the geological and thermal situation in the subsurface of DeepStor including the locations of the former oilfield Leopoldshafen and the corresponding surface installation such as the district heating network.

2. GEOTHERMAL SETTING AT THE DEEPSTOR SITE

The DeepStor site is located in the central segment of NNE trending, essentially non-volcanic Upper Rhine Graben, which developed from about 47 Ma onwards between Germany, France and Switzerland. Tectonically, it is located in the hanging wall of the Main Eastern Boundary Fault. In the central graben, the Cenozoic sediments reach a thickness of up to 3,500 m (Geyer et al., 2011) and are subdivided into Pliocene to Holocene fluviatile siliclastics that unconformably overlie late Eocene (Lutetian) to early Miocene (Burdigalian) syn-rift sequences. These sequences were deposited in a generally low-energy environment under alternating marine, brackish, fluviatile and lacustrine conditions and contain deposits of carbonates, sands, silts, clays, marls and locally intercalated evaporites.

The DeepStor site is adjacent to the eastern edge of the depleted Leopoldshafen oil field in the footwall of the Leopoldshafen fault. This NNE-striking normal fault (Wirth 1962) is part of the Main Eastern Boundary Fault and exhibits a syndepositional normal faulting from the Oligocene to the early Miocene, with the synrift layers dipping shallowly to the NE (Schad 1964). A total of around 188,000 tons of oil were extracted from a few meters thick, fine-grained, mica-rich calcareous sandstone deposits, which are embedded in hundreds of meters thick, mostly marly Meletta and Bunte Niederrödener layers (Wirth 1962; Böcker 2015). The Meletta layers are part of the Froidefontaine Formation and were deposited under marine conditions during a regressive phase. They show coarsening upward trends in the late Rupelian (ca. 29 Ma), followed by a transgression phase in which the finer upward trends in the upper part of the Meletta strata merge into the marly, still marine to brackish Cyrena strata. These strata show a further phase of regression and further development into the fluvio-lacustrine Niederröderner Formation (Schad 1962; 1964; Grimm et al. 2011; Pirkenseer et al. 2011; 2013).

The Leopoldshafen field was explored by around 20 boreholes to a depth of approximately 3,000 m. The corrected temperature data (Sauer et al., 1981), which yield about 100 °C at a depth of 2,000 m, include measurements in the Meletta and Bunte Niederrödener sandstone layers. Maximum temperatures of 170 °C at a depth of about 3,000 m are reported from the Leopoldshafen-20 borehole.

3. 3-D GEOLOGICAL MODEL

The basis of the of the numerical modeling of optimized heat cycling between the deep fractured reservoir and the porous reservoir at intermediate depth through the surface are two individual 3-D geological models.

The first comprises the porous reservoir for seasonal storage at a depth of about 1,300 m and is modeled on the basis of a depth-migrated 3-D seismic survey and data from more than 25 wells with a depth > 1,000 m MD (Bauer et al. subm.). It comprises the reservoir of the Meletta sandstones with a thickness of a few meters, which is overlain and underlain by impermeable, confining marl layers. The model covers a volume of 5 x 8 x 3 km. The topography is represented by a digital elevation model with a resolution of 30 m. The interpretation of the seismic data and the 3-D geological modeling was carried out using Petrel subsurface software (Schlumberger Ltd.).

The latter model of the fractured reservoir at depth is part of a larger 3-D geological model for the Karlsruhe area with a volume of 33 x 10-16 x 7 km. In addition to the above data, it includes a further 17 wells and 33 2-D seismic lines. The seismic interpretation was performed with OpendTect (dGB Earth Sciences B.V.) and the 3-D model was created with the geological modeling software SKUA GoCAD™ (Aspen Technology Inc.). It includes the base of the Tertiary, Jurassic, Keuper, Muschelkalk and Buntsandstein sediments as well as the major Stutensee and Leopoldshafen faults. The thickness of the damage zone was empirically determined to 200 m according to Choi et al. (2016), depending on the displacement amount of the thrust faults which can be around 900 m in case of the Leopoldshafen fault. Note that the base of Buntsandstein marks the boundary to the crystalline basement rock, which in our case incl. The topography is represented by the digital GTOPO30 elevation model of the USGS (2018).

Both geological models have been transferred into a 3-D finite element mesh, all tetrahedrons, for further numerical studies using COMSOL Multiphysics® Finite Element software. A mesh refinement was performed around the wells to approximately 1 m. General procedure of meshing was exporting the triangulated surfaces of the 3-D geological model (relevant formation tops and fault surfaces) and intersect them using CAD software (Rhinoceros 3D®) into a solid volume model including representing all layers and faults. The main normal faults were extended to volumes according to their damage zone thickness.

The model of the fractured reservoir at depth is discretized into 2.5 million elements. It extends over a volume of 15 x 16 x 8 km. An additional mesh refinement to approximately 1 m was performed in the damage zone of the faults. The model of the porous storage volume is discretized into 1 million elements. It extends over a volume of 5 x 5 x 1.9 km. Here, an additional mesh refinement was performed in the sandstone layers.

4. NUMERICAL MODELLING OF HEAT CYCLING

For the two sub-models, the flow and heat transport were calculated for various management scenarios using COMSOL Multiphysics® Finite Element software. Due to the licensing situation in the study area, well for heat extraction are restricted to the Mesozoic layers. The two models are numerically connected via a single node that represents the heat exchanger and connects to the district heating (Zwickel et al., 2022). At the surface Dirichlet boundary condition with a constant mean annual surface temperature of 10°C is applied. At the lower boundary of the models a Neumann boundary condition of constant heat flux of 60 mW m^{-2} are used.

4.1. Heat extraction from the deep fractured reservoir

The drilling target of the deep fractured reservoir are Mesozoic branch faults in the hanging wall of the main normal faults. They are rooted in the crystalline basement, reach the Tertiary base and show displacements of up to 100 m. Permeabilities are assumed to be increased in the hanging wall due to the presence of a damage zone of up to 200 m. The permeability of the damage zone was estimated to be $1 \cdot 10^{-13}$ m² based on the temperature distribution in the Leopoldshafen-20 well. The full set of final parameters are provided in Table 1 and table 2.

The calibration of the model bases on bottom-hole temperature measurements. Temperature adjustment was achieved by varying thermal conductivities, heat production rates in the basement, and basal heat flux. The simulation indicates that, with a production rate of 25 L/s, pressure differentials on the main faults remain below 2 MPa. The production temperature is approximately 180°C.

About 9 MW thermal output was calculated by the modeling, the result was round-off and therefore includes a buffer for uncertainties and heat losses.

4.2. Heat storage in porous reservoir at intermediate depth

The heat storage reservoir of the Meletta beds were developed by horizontal screens of the injection and production wells in a depth of around 1300 meters. In the Tertiary formations faults are estimated to be sealed and limit the lateral extent of the reservoir. Low permeabilities and thermal conductivities of the cap rock insulate the sandstone reservoir.

Given the significant influence of permeability on the effectiveness of the reservoir, a variant was calculated with a reservoir permeability of 25 mD (mean permeability of a well close to the modelled production well), where 5 L/s were injected and produced. The second scenario includes a permeability of about 70 mD (Stricker et al. 2020) allowing extraction/injection rates of 10 L/s.

Injection and production modeling was performed over a period of 10 years heating up the underground storage system to a plateau of performance according to Stricker et al. 2020. The output of the reservoir is approximately 2.7 MW for a pumping rate of 10 L/s, and it is 1.25 MW for 5 L/s.

Table 1: Hydraulic parameters used for the thermo-hydraulic modelling of the individual units of the two models, the deep fractured reservoir and the porous reservoir for heat storage.

Unit	Permeability (m^2)	Porosity (%)

Tertiary marls	$1\cdot10^{-18}$	15
Tertiary sandstones	$2.5\cdot10^{-14} – 6.6\cdot10^{-14}$	15
Jurassic/Keuper (claystones)	$1\cdot10^{-18}$	15
Muschelkalk (limestone)	$5{,}9\cdot10^{-15}$	2,7
Buntsandstein (sandstone)	$1\cdot10^{-15}$	3
Permian (conglomerates/sandstones)	$1\cdot10^{-16}$	5
Basement (granite/metamorphic units)	$5\cdot10^{-16}$	5
Damage zone of faults	$1\cdot10^{-13}$	15

Table 2: Thermal parameters used for the thermo-hydraulic modelling of the individual units of the two models, the deep fractured reservoir and the porous reservoir for heat storage.

Unit	Heat conductivity ($W\ m^{-1}K^{-1}$)	Heat capacity ($MJ\ kg^{-1}K^{-1}$)	Heat production rate (μWm^{-3})
Tertiary marls	1.4	2.4	0
Tertiary sandstones	2.5	3.15	0
Jurassic/Keuper (claystones)	1.4	2.4	0
Muschelkalk (limestone)	3.2	2.2	0
Buntsandstein (sandstone)	3.3	2.2	0.3
Permian (conglomerates/sandstones)	3.3	2.2	0.9
Basement (granite/metamorphic units) and damage zone of faults	3.25	2.2	0.9-2.13

5. UP-SCALING TO THE CITY OF KARLSRUHE

In summary, our results show that the share of renewable geothermal heat energy at KIT-Campus North can be increased from 25 % to about 65 % by storing the excess heat. Assuming that technical problems such as scaling can be solved, we are currently in the process of scaling up the storage system to the city of Karlsruhe with peak and base loads of around 250 and 30 MW.

A comparison of the layout of the district heating network of the city with the location of depleted oilfields reveal the city district of Knielingen as optimal location for further studies (Figure 2). Similar to the subsurface condition at the DeepStor site, the sandstone reservoirs of the Niederrödern Fm. the wells reach bottom hole temperatures of 63 to 90°C at depths of about 1450 to 1500 m.

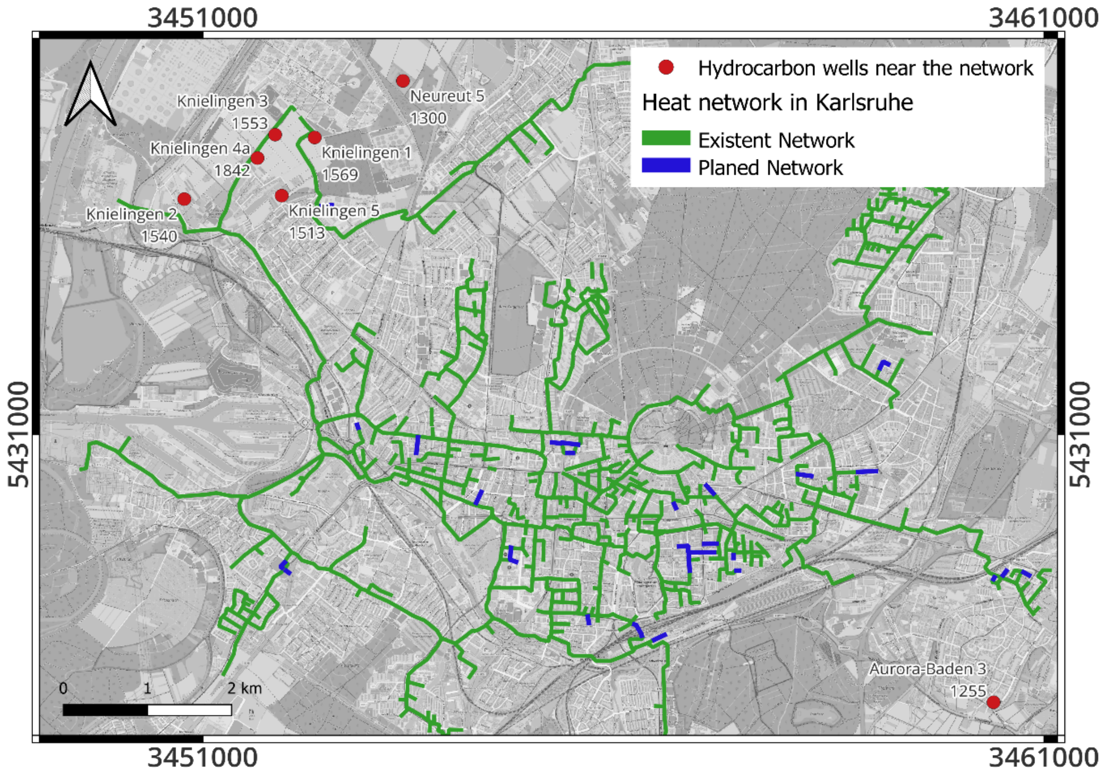

Figure 2: The district heating network of the city of Karlsruhe and the locations of the wellheads of the former oilfield Knielingen.

ACKOWLEDGEMENTS

This work is part of the subtopic "Geoenergy" in the program "MTET - Materials and Technologies for the Energy Transition" of the Helmholtz Association. We would like to thank Schlumberger Ltd. and Aspen Technology Inc. for the academic licenses of their respective modelling softwares.

REFERENCES

Baillieux, P., Schill, E., Edel, J.P., Mauri, G.: Localization of temperature anomalies in the Upper Rhine Graben: insights from geophysics and neotectonic activity, International Geology Review, 55, 14, (2013),1744-1762.

Bauer, F., Grimmer, J. C., Houpt, L., Hertweck, T., Schill, E.: Basin development and stress field change in the central Upper Rhine Graben (SW Germany): constraints from 3D-seismic data, Basin research, (subm.).

Böcker, J., Littke, R., Forster, A.: An overview on source rocks and the petroleum system of the central Upper Rhine Graben. International Journal of Earth Sciences, 106, (2017), 707–742.

Choi, J. H., Edwards, P., Ko, K., Kim, Y. S.: Definition and classification of fault damage zones: A review and a new methodological approach. Earth-Science Reviews, 152, (2016), 70-87.

Fleuchaus, P., Godschalk, B., Stober, I., Blum, P.: Worldwide application of aquifer thermal energy storage—A review. Renewable and Sustainable Energy Reviews, 94, (2018), 861–876.

Fraunhofer ISI: Baseline Scenario of the Heating and Cooling Demand in Buildings and Industry in the 14 MSs until 2050, Report, (2017), available online: https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.3andD3.4.pdf.

Frey, M., Bär, K., Stober, I., Reinecker, J., van der Vaart, J., Sass, I.: Assessment of deep geothermal research and development in the Upper Rhine Graben. Geothermal Energy, 10, 1, (2022), 18.

Genter, A., Cuenot, N., Goerke, X., Bernd, M., Sanjuan, B., Scheiber, J.: Status of the Soultz geothermal project during exploitation between 2010 and 2012. Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2012).

Geyer, M.; Nitsch, E.; Simon, T.: Geologie von Baden-Württemberg, (2011), 5th Edition. Stuttgart – Mainz, Schweizerbart.

Grimm, M.C., Wielandt-Schuster, U., Hottenrott, M., Grimm, K. I., Radtke, G., Berger, J.-P., Ellwanger, D., Harms, F.-J., Hoselmann, C., Picot, L., Weidenfeller, M.: Regionalgeologische Darstellungen, Oberrheingraben. *Deutsche Stratigraphische Kommission (ed) Stratigraphie von Deutschland IX. Tertiär, Teil, 1*, (2011), 57-132.

Holstenkamp, L., Meisel, M., Neidig, P., Opel, O., Steffahn, J., Strodel, N., Lauer, J.J., Vogel, M., Degenhart, H., Michalzik, D., Schomerus, T., Schönebeck, J., Növig, T.: Interdisciplinary Review of Medium-deep Aquifer Thermal Energy Storage in North Germany. Energy Procedia, 135, (2017), 327–336.

Pirkenseer, C., Spezzaferri, S., Berger, J.-P.: Reworked microfossils as a paleogeographic tool. Geology, 39, (2011), 843–846.

Pirkenseer, C., Berger, J.-P., Reichenbacher, B.: The position of the Rupelian/Chattian boundary in the southern Upper Rhine Graben based on new records of microfossils. Swiss Journal of Geosciences, 106, (2013), 291–301.

Sauer, K., Nägele, R., Tietze, R.: Geothermische Synthese des Oberrheingrabens zwischen Karlsruhe und Mannheim (Anteil Baden-Württemberg); Geologisches Landesamt Baden-Württemberg, Freiburg im Breisgau, (1981).

Schill, E., Genter, A., Kohl, T., Cuenot, N.: Enhancement of productivity in the Soultz EGS site by 20 hydraulic and chemical stimulation experiments and long-term circulation, Geothermics, 70, (2017), 110-124.

Vidal, J., and Genter, A.: Overview of naturally permeable fractured reservoirs in the central and southern Upper Rhine Graben: Insights from geothermal wells, Geothermics, 74, (2018), 57-73.

USGS: USGS EROS Archive - Digital Elevation - Global 30 Arc-Second Elevation (GTOPO30), (2018)

Wirth, E.: Die Erdöllagerstätten Badens, Geologische Abhandlung Landesamt Baden-Württemberg, 4, (1962), 63-80.

Zwickel, P., Bauer, F., Schätzler, K., Steiner, U., Waczowicz, S., Hagenmeyer, V., Schill, E., 2023. Integrated concept of local heat transition using geothermal heat production, aquifer storage and optimization of distribution network. Proceedings, European Geothermal Congress, Berlin, Germany (2022).