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INTERNATIONAL VIEWPOINT AND NEWS

Geothermal energy systems: research perspective for domestic energy provision

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This article is focused on research demand for the environmental and economic sustainable utilization of geothermal reservoirs for base load supply of heat and electricity by Enhanced Geothermal Systems; additional emphasis is placed on the promotion of the underground storage of thermal energy. Solutions for minimizing the mining risk and for addressing challenges related to the successful development and to the safe operation of geothermal systems are proposed. This includes the development of new technology approaches and concepts for scientific monitoring of operational and environmental processes related to geothermal systems. These research and development efforts require large research facilities and infrastructures. In addition to thermal energy extraction from the subsurface, shallow and deep geothermal reservoirs can also serve as underground thermal energy storage systems. The large potential for medium and high temperature underground thermal energy storage systems remains to be further investigated and developed.

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Introduction

Geothermal energy has the capacity to contribute large amounts of base-load energy and to guarantee a safe and decentralized energy supply independent of imports while requiring only small surface areas and being poor on CO_2 emissions and practically inexhaustible. So-called "conventional" geothermal plants exploiting hot hydrothermal reservoirs have long been a fully commercial contributor to the energy provision in favourable tectonic, often volcanic settings such as Iceland or Tuscany/Italy. The concept of Enhanced Geothermal Systems (EGS), however, is a much younger approach to use the thermal energy stored in Earth's crust in non-volcanic environments and thus offers an enormous untapped potential. The EGS concept—often linked to faulted areas—includes artificial improvement of the hydraulic performance of a reservoir with the goal to use it for an economical provision of heat or electric energy.

Challenges of geothermal systems

There is an increasing awareness, that innovative technologies are needed to allow for an environmentally sound and economically feasible exploitation of geo-reservoirs (Kolditz et al. 2013). Tester et al. (2006) identified EGS as critical for the future of geothermal energy. EGS as major future resource for co-generation of heat and electricity has not yet reached the level of maturity necessary for a widespread industrial application. A commercialization of

Fig. 1 Geothermal research platform Groß Schönebeck with 2 deep boreholes (*blue* and *red* well heads in the foreground), the experimental hall (*centre left*), and the 3-step Organic Rankine Cycle power plant (*centre right*)

the EGS approach requires massive investments in research and development. This includes a substantial increase of the number of demonstration projects and of the operational experience with EGS (Huenges 2010). The geothermal plant in Soultz-sous-Forêts, France, in the granitic subsurface of the Upper Rhine Graben demonstrates the technical feasibility of the EGS approach (Gerard et al. 2006). This EGS site is worldwide unique since it applied innovative and successful stimulation techniques to create three vertical reservoir levels. More than 20 major stimulations have been conducted at this site without evidence of considerable seismic activities that could have created local opposition. Generally, operations can be often interrupted due to maintenance and lack of reliability of technical parts. The geothermal research platform "Groß Schönebeck" (Fig. 1) follows the EGS concept in deep sedimentary structures using reservoir stimulation techniques. However, its long-term performance proved to not be sustainable due to chemical precipitations. In the Landau EGS project, reservoir engineering was successfully performed and the geothermal plant has been connected to the grid. However, its operation is limited by restrictions of the injection pressure by the regulatory authorities due to occurrence of seismicity.

The geothermal research institutes of the Helmholtz Association compiled the research demand in Germany for underground heat extraction and storage. Major challenges facing the successful deployment of enhanced geothermal systems are the: (1) localization of potential reservoirs prior to drilling, (2) minimization of the risk of failure in combination with the high investments in survey and drilling, and (3) long-term operation and management with respect to the aggressive chemical environment due to the produced thermal waters. Development of EGS systems is also hindered by low public acceptance of geothermal plants due to possible seismicity. Also, legal and regulatory issues are often a major hurdle even when technological issues are solved. Geothermal energy is also a challenge for social sciences (Gross 2013). The challenges for underground thermal energy storage (UTES) systems are manifold and range from quality control by long-term monitoring and assessments of associated environmental impacts for shallow and aquifer systems to conceptual development of high-temperature systems.

Experience from existing geothermal plants in Europe shows that the technology required for a successful plant operation principally exists. However, there is huge demand for technological developments, which is especially true for reservoir engineering and in particular for stimulation methods. Understanding the involved complex and interacting processes is a prerequisite for technological progress. In contrast to virtually all large-scale types of industrial utilization of underground systems, there is no geothermal in situ research laboratory. It is proposed that a unique research platform should probably be installed in a former mine, which will enable a systematic in situ investigation of engineering activities during all phases, from geothermal reservoir creation to operation in a crystalline basement complex. Such an experimental performance allows for optimization and control of various stimulations techniques.

The above presented challenges and resulting fields of research are summarized in Fig. 2 and show that research into geothermal systems is multidisciplinary, which involves geoscientific disciplines, material science, and engineering as well as connects to social and environmental sciences.

Objectives of geothermal research and development

Exploration and reservoir characterization

Geophysical exploration is critical for identifying favourable settings for geothermal activities and provides key parameters related to temperature, porosity and the existence of fluid pathways and hence, is essential for assessing the hydraulic and thermal system (Tenzer et al. 2010; Kastner et al. 2013). State-of-the-art exploration techniques for geothermal resources include seismic images of the subsurface that are sensitive to the structure of the setting,

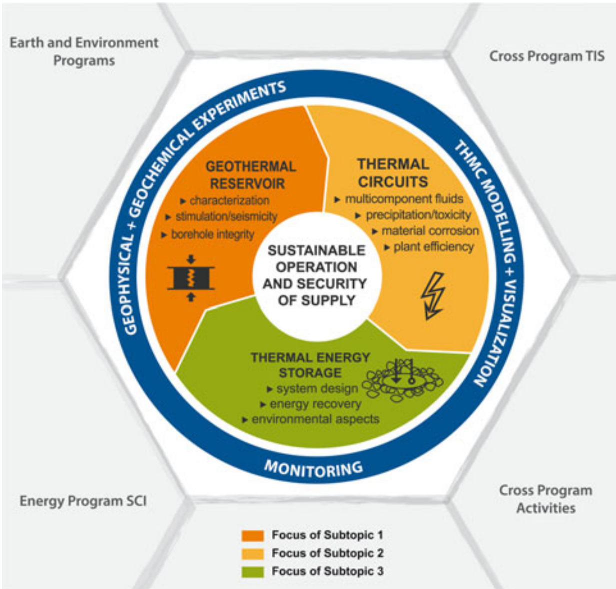

Fig. 2 Integrated approach of the research perspective "Geothermal Energy Systems" and its interaction with other research activities of the Helmholtz Association: Earth and Environment; Technology, Innovation and Society (TIS); and Storage and Cross-Linked Infrastructures (SCI). Methodological research topics involving experiments, monitoring, modelling and visualization tightly link the research foci. All research activities are performed in close collaboration with associated disciplines

to electromagnetic methods and to electrical resistivity contrasts (between the low resistive injected fluids and the higher resistive host rock). These images can be used as a supplementary tool to delineate reservoir boundaries. Temperature profiles, thermal conductivity and heat capacity values from wells are used to determine on-site heat flow density to provide basic geothermal information. Regional models of subsurface temperature distribution help to discriminate favourable sites for EGS. The potential hydraulic settings are investigated by analysis of the 3D geometry and kinematic evolution of fault systems and fracture networks. The structural settings favouring geothermal activity generally involve sub-vertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the least principal stress. Regional stress field determination preferably requires information from wells such as the analysis of borehole breakouts and drilling induced fractures.

Access to geothermal reservoirs and reservoir engineering

The improvement and adaptation of drilling methods is critical for a geothermal future. Research approaches are required to reduce associated costs, drilling risks such as borehole and formation damage. Meeting these challenges will help overcome some of the major hurdles in the development of geothermal projects, as the drilling usually presents the sole most expensive part of development, while the risk of a low productivity presents one of the main concerns in the financing of a geothermal project.

An essential objective is enhancing the reservoir and—at the same time—reducing seismic hazard by developing soft stimulation methods. This requires new in situ experiments at special designed research sites and appropriate interpretation and sophisticated modeling tools to evaluate the coupled processes in fractured rock. Particular emphasis has to be placed on geochemical alterations, thermo-mechanical and hydro-mechanical effects as well as their impact on reservoir evolution, e.g. fracture characteristics. Collected data and on-site investigations will enable model validations. Improved strategies for scheduling and designing hydraulic treatments have to be found.

In close conjunction with this, new seismic monitoring methods need to be developed. To ensure that seismic monitoring reliably leads to an instrumental network design, real-time microseismic monitoring and ongoing modeling during all stages from fracture stimulation to operation have to be a key prerequisite. They will provide input for an early warning system (e.g. basic "traffic light system").

Operation of thermal water loops and corrosion and precipitation processes

A better understanding of the fluid/rock system interactions is essential for establishing an efficient anti-scaling concept to avoid matrix and fracture fillings and minimize radioactive pollution. This concept has to comprise all length scales from atomistic calculations through experimental investigations of the reactivity of the mineral/fluid-interface. Special attention has to be paid to micro- and macroscopic laboratory experiments on changes in rock transport properties, on radionuclide incorporation in scalings, and on the development of specific inhibitors, which prevent mineral precipitation within the plant and underground. The application and further development of a monitoring concept will ensure sustained performance of both the plant and the reservoir through rapid detection of changes of in situ conditions (fluid composition, permeability etc.).

To enhance the lifetime of geothermal plants, the interaction between flow and abrasion has to be investigated by simulations on a macroscopic scale. Before constructive measures can be taken, modelling approaches at micro- and macroscale extended by necessary corrosive modules have to be integrated on a simulation platform. In addition, the focus has to be set on the simulation of the downhole production pump. The simulations offer a way to identify processes leading to the failure of these pumps and help to specify the demands for future pump development.

Conversion of geothermal energy to power

The optimization of the working fluid is of key importance in the Organic Rankine Cycles of geothermal plants (Bu et al. 2013). Furthermore, developed simulation software needs to be validated by experiments under laboratory conditions as well as with real data from existing geothermal sites. Results will foster the development of new strategies to maximize net power output, taking economic aspects into account. New control strategies and optimized design of site-specific components including profound knowledge on physical and chemical processes such as scaling and corrosion have to play a central role in geothermal research.

Thermal energy storage in shallow and deep reservoirs

Both EGS plants and shallow geothermal systems provide energy throughout the whole year, but thermal energy demand varies strongly between seasons. Therefore, excess heat from energy production in summer should be efficiently stored and made available to district heating systems in winter, and vice versa. Natural underground systems can serve as UTES for heat and also chill between opposing seasons. A better understanding of long-term phenomena is required if the thermal regime of soils and groundwater is altered, including the study of microbiological communities. Profound knowledge of environmental impacts induced by heat storage in shallow and deep reservoirs is an important prerequisite for sustainable subsurface management.

Strategy for geothermal process understanding and technology development

Reliable access and engineering of potential geothermal reservoirs

The strategy for safe and effective reservoir accessing and engineering is illustrated in Fig. 3. Several groups are working on assessments of sedimentary basins from local to regional scales (Scheck-Wenderoth and Maystrenko 2013; Noack et al. 2010). The expertise involves the analysis of geological structures, the petrophysical and mineralogical/geochemical properties of the geological formations, as well as the terrestrial heat flow and temperature regimes (Norden et al. 2012). Data from borehole studies as well as from the application of surface geophysical surveys (Bauer et al. 2012) are used. New methods for downhole sensing at high temperatures are being developed (Reinsch et al. 2013). State-of-the-art geophysical exploration methods for geothermal resources were provided by the FP6 project I-GET and the resulting publications (Cumming and Bruhn 2010).

Analysis of seismicity demonstrates temporal and spatial variability of the seismic reservoir response and the importance of seismic hazard analysis (Schoenball et al. 2012). In the framework of GEISER project (http://www.geiser-fp7.eu), detailed studies show that pre-existing natural fractures play a key role in the flow performance and are important for possible seismic hazards. While drilling the research well in Groß Schönebeck (a representative site for potential plant operations in the North German Basin), a number of lessons were learned in the application of methods adapted from oil and gas well technologies. The project revealed that the reliability of a drilling operation still requires comprehensive improvement, especially in drilling large diameters, in directional drilling, and underbalanced drilling. Existing stimulation techniques (Zimmermann et al. 2011) were adapted to the requirements of a geothermal reservoir, and water as well as gel-proppant stimulation treatments were successfully performed leading to a significant enhancement of productivity. The behaviour of the stimulated reservoir could be observed during subsequent hydraulic testing using a newly developed hybrid downhole logging system (Baumann and Henninges 2012). Nevertheless, extended circulation and injection tests have shown that the achieved enhancement in productivity was not sustainable, and a continuous thermal water loop could not be established as planned. Therefore, a revision of the applied stimulation concept is required.

Integrated geological characterization of pilot sites requires geology with structure and fault inventory, heat

Fig. 3 Strategies for safely and effectively accessing and engineering reservoirs involve the development of sophisticated exploration, drilling and stimulation techniques. Understanding of the complex processes during operation provides a sound basis for technology development

flow and temperature at depth, and petrophysical and mineralogical properties of the reservoir (Ollinger et al. 2010). Potential sites need to be defined that optimize the three key factors: permeability, temperature and stress regime. Lessons from successful but also failed projects need to be thoroughly investigated to continue a learning curve and not to fall into cost-intensive traps. Especially the fault and fracture system need to be characterized and its behavior during stimulations (Schoenball et al. 2012). Geophysics has to develop improved methods such as the improved vertical seismic profile (VSP) to image faults and the fracturing process with a particular focus on internal fault properties in order to get a quantitative joint interpretation. Improvements in multidisciplinary interpretation and integration will lead to a better linkage between geophysics and reservoir engineering.

Laboratory-based determination of constitutive equations including most important thermo-physical parameters will enter into new thermal–hydraulic-mechanical-chemical (THMC) models including fractures, fracture zones, and borehole (Taron and Elsworth 2010). Numerical modelling is an important tool for reservoir characterization and prediction (McDermott et al. 2006; Cacace et al. 2013). Modeling concepts need to be pursued that are optimized for the specific problem. With this view, OpenGeoSys (OGS) was developed as a modelling platform to simulate coupled THMC processes in porous media (e.g. geothermal reservoirs) (Kolditz et al. 2012b). First applications in geothermal reservoir modeling demonstrate the potential of solving multi-field problems in fractured media including uncertainty analysis (Watanabe et al. 2010). A key problem for long-term operation of geothermal systems is a better understanding of biogeochemical processes in shallow aquifers (Beyer et al. 2006) and under deep reservoir conditions (Shao et al. 2009). Novel numerical methods need to be adapted for the specifics of simulation of fractured geothermal reservoirs (Watanabe et al. 2012) and to be improved in terms of computational efficiency. But also further modelling concepts for fracture propagation or quantification of stress heterogeneities are required. As such, a discrete element model of naturally fractured rock with a pore fluid algorithm was developed in order to analyse different scenarios of high-pressure fluid injection (hydraulic fracturing) in deep petrothermal reservoirs and associated induced seismicity. The results suggest that cyclic reservoir treatment is a safer alternative to conventional hydraulic fracture stimulation as both the total number of induced events as well as the occurrence of larger magnitude events are decreased (Yoon et al. 2013). Combinations of monitoring and modelling platforms are envisaged to further improve the characterization of subsurface systems (Kolditz et al. 2012a).

Sustainable operation of geothermal plants

Geothermal energy conversion requires profound knowledge about the underlying processes that determine the sustainable and efficient operation of geothermal plants. This includes understanding corrosion effects, scaling formation and system engineering within the plant and underground, which is indispensable for an optimized and reliable operation of geothermal plants.

On-site experiments on scaling, degassing and corrosion were performed in the Molasse Basin, Soultz, and Groß Schönebeck. The results led to concepts for future component design and plant operation. Detailed mineralogical-geochemical investigations in combination with stable isotope studies indicate that bacterial sulfate reduction occurs, temporarily initiating sulfide precipitation from sulfate-rich fluids (Lerm et al. 2013). The layered structure of the scalings correlated well with the operation state of the plant. Observed abrupt redox changes with sharp sulfide/sulfate phase boundaries clearly demonstrated the need to unravel redox conditions yielding strong gradients in the thermal water loop. For example, redox reactions have occurred at the rock-casing-fluid interface yielding massive scaling of copper as observed at the Groß Schönebeck site.

So far no process has been established to prevent scaling completely. A concept for an inhibitor system has been designed recently to prevent calcite growth (Ukrainczyk et al. 2013). The study underpins the need to develop inhibitors in dependence on the composition of the geothermal fluid and the kind of mineral precipitation. Recently, an in situ and on-site physicochemical monitoring program was established to characterize the processed brine using selected metals. Several mechanisms were proposed for the dissolution of metals in oxygen-free CO_2 solutions. In order to identify suitable materials for demanding geothermal applications, an in situ brine monitoring and analysis campaign was performed (Mundhenk et al. 2013). Corrosion mechanisms that will most likely occur in geothermal environments could be discerned, including pitting and uniform corrosion.

Substantial expertise has been gained in developing phase-field models and high performance parallel simulation software to study microstructure evolutions for different classes of materials, under the influence of various physical fields (e.g. elasticity, plasticity and fluid flow) and processing conditions. Remarkable effort has recently been made to derive a quantitative phase-field model for phase transitions in multi-component systems (Choudhury and Nestler 2012). A 3D parallel solver of the reaction–diffusion equations coupled with a computational fluid dynamics (CFD) solver was implemented. In terms of operation optimizations, CFD models to simulate technical components such as pumps, heat exchangers and turbine as well as fully coupled simulations of the thermal water loop and conversion cycle were developed; special focus is addressed to heat transfer and the physical properties of the brine.

On basis of an Organic Rankine Cycle, an innovative power plant concept was developed in order to investigate transient and partial load behaviour of a low temperature power cycle. In several case studies, the whole process chain of a geothermal plant, from reservoir engineering to energy conversion, has to be investigated. In particular, chemical constraints during operation and their impact on the system have to be enlightened and instruments for operational control have to be developed. Technical system components such as downhole pumps have to be improved based on advanced process understanding through analytic laboratory and in situ measurements as well as novel modelling techniques.

Underground storage systems in urban areas

Multi-spatial data has to be combined with geospatial high-resolution geological, hydrogeological, geophysical and petrophysical information to assess possible effects of the use of shallow geothermal energy. This will form a sound basis for future works on testing, development and enhancement of heat transport models under actual geo-hydraulic conditions, for the definition of monitoring schemes and finally for scientifically based guidelines for subsurface thermal management (Kranz and Frick 2013).

To further develop and optimize aquifer storage systems, site- and application-specific storage configurations have to be developed in cooperation with university and industry partners. Special emphasis needs to be on operational reliability and environmental safety. With the aim to optimize reservoir exploration and storage design, the respective database has to be enhanced. Laboratory experiments with regard to fluid-rock interactions and reactive transport have to be carried out focusing on a reliable and safe storage operation. Socio-economic studies are important to convey in conjunction with enrolling technological concepts in order to support the long-term deployment of geothermal energy in both shallow and deep reservoirs.

Conclusions

After the Fukushima disaster, Germany decided to step back from nuclear energy completely by 2022 and strongly develop renewable energy resources instead. Without any doubt, geothermal energy belongs to those alternative candidates for providing stable base loads in both heating/cooling and electricity supply. In order to utilize the potential of geothermal energy resources (Kohl et al. 2005), further research efforts and technology development are necessary to make geothermal systems a significant contribution to Germany's future energy base. For this purpose, the Helmholtz Association included *geothermal energy systems* prominently into its new research program on renewable energies and is inviting universities and other research institutions from Germany and abroad to participate in this geothermal initiative. The research topics focus on the exploration and accessing of reservoirs, on reservoir engineering and plant operation, including conversion of heat and the development of comprehensive system analyses. The pillars of research are interlinked with cross-cutting issues such as laboratory and field tests, modeling and monitoring. The Helmholtz Association does not offer only its research infrastructure for research collaboration but also supports the establishment of new forums for geothermal research as a whole while fostering interdisciplinary research between natural, engineering and social sciences. Only an organized joint effort of research and a concerted strategic approach of research organizations together with industry partners will lead to significant progress in the next years.

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