Reutilization of mine water as a heat storage medium in abandoned mines

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Abstract
The development of innovative storage technologies as well as the use of sustainable low grade heat and cold sources are essential to expand the use of renewable energy sources. The utilization of mine water as a geothermal resource and/or as a thermal energy storage has the potential to play a key role to reach the ambitious climate goals set by the COP21. Flooded mines represent major low temperature geothermal reservoirs, which also provide large-scale seasonal thermal storage capacities. These characteristics enable the development and dissemination of renewable energy systems and the improvement in energy efficiency of conventional systems.

Keywords: mine, thermal, energy, storage

Introduction
At the end of 2018, the last operative hard coal mine in Northrhine-Westphalia (Germany), Prosper-Haniel, is going to be closed down, plugged and abandoned. Large amounts of subsurface infrastructure, resembled mainly by open parts of former galleries and mining faces are going to be flooded after the mine is abandoned and therefore have the potential of becoming an enormous geothermal reservoir for seasonal heat storage. At the moment a seasonal heat storage within an abandoned hard coal mine has not yet been realized in Germany. Therefore the HT-MTES (High Temperature-Mine Thermal Energy Storage) project (feasibility study) of the International Geothermal Centre (in cooperation with RAG AG and delta h Ingenieurgesellschaft mbH) would lead the way within the sector of renewable energy storage systems. This R&D project is funded by the German Federal Ministries BMWi, BMU and the BMBF “Initiative Energy Storage” program. The aim of this project is to create a technically and economically feasible conceptual model of a HT-MTES for the energetic reuse of the hard coal mine Prosper-Haniel, which is situated in Bottrop (Germany).

The conceptual model (fig. 1) is based on the storage of seasonal unutilized heat during

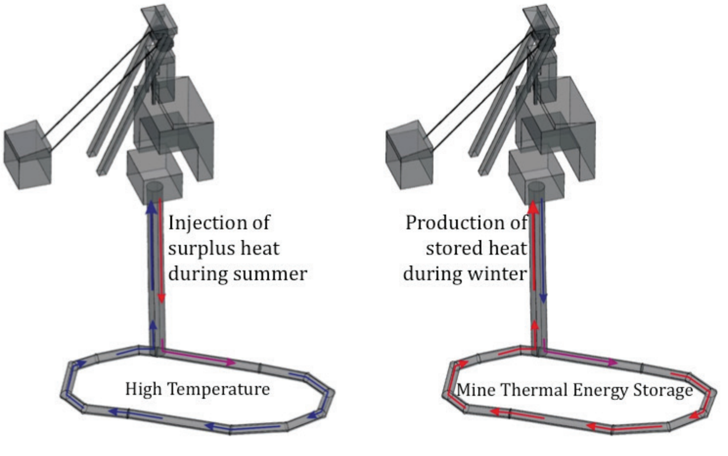

Figure 1 Conceptual model of a HT-MTES (GZB)

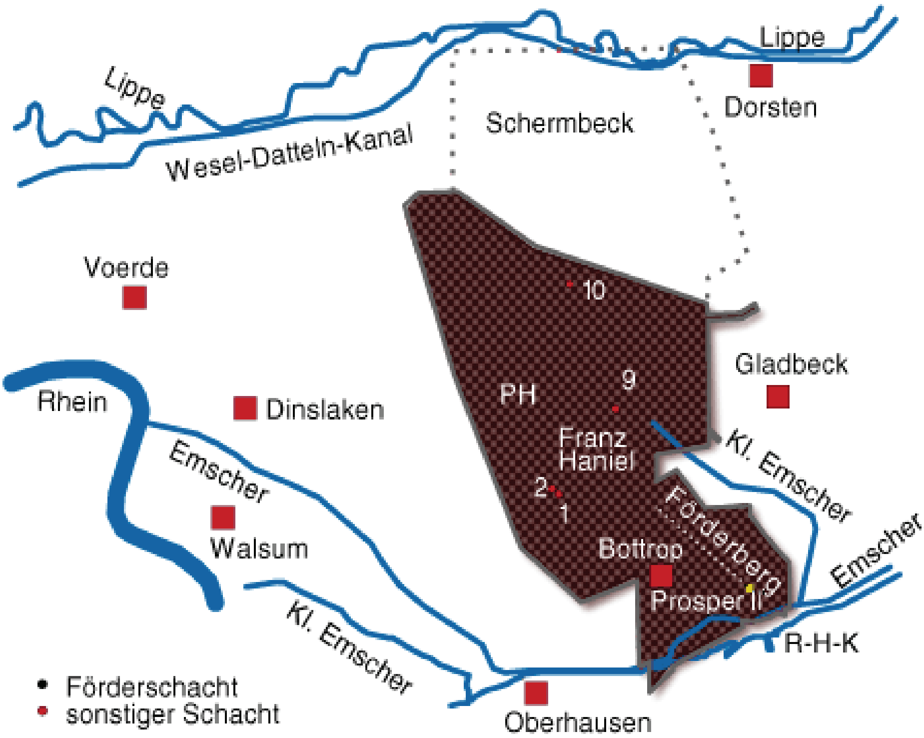

***Figure 2** Location of Prosper-Haniel within the Ruhr area (RAG AG)*

the summer from solar thermal power plants, industrial production processes or CHP plants within the mine layout and to utilize the stored heat e.g. through the distribution of a district heating grid during the winter, when there is a high heat demand.

For the implementation of such a HT-MTES within a former hard coal mine, the corresponding infrastructure measures and appropriate circulation applications have to be developed. Precondition for this development is the presence of a still active and fully open mine, which is resembled by the hard coal mine Proper-Haniel. As a foundation for the implementation of a mine thermal energy storage, the undisturbed rock temperatures range between 30°C and 50°C (Leonhardt 1983) within the galleries and mining faces that are going to be flooded, after the mine is abandonment. The total mining area consists of 165 km^2 (see brown area fig. 2) and the subsurface galleries have a total length of 141 km, at a maximum depth of –1159 m NHN.

A HT-MTES needs to have a large mine water volume, in order to store vast amounts of heat. At the same time, it has to be reliable, cost efficient and should be integrated into existing urban frameworks. In order to meet economical requirements, a HT-MTES needs to be operative in the range of 40 to 50 years. Depending on the utilized heat source and its application, different heat capacities, mass flows and temperature levels would be encountered within the mine thermal energy storage. All affected components need to be suitable for the intended operations and their possible resulting stresses. If the seasonal heat storage is operated by several different heat sources, a careful coordination of the specific heat amounts and loading cycles of the relative source needs to be taken into consideration.

Current state of technology

The idea of obtaining thermal energy from an inoperative colliery has already been pursued for a long time, although to a comparatively limited extent. Up to this point a pilot plant has not been established, in which the possibility of thermal energy storage in a former colliery has been considered. Well-known executed projects concerning the utilization of mine water include:

- The Mijnwater-project in Heerlen (Netherlands), whereby an already completely flooded and no longer accessible mine layout was accessed through directional drilling technology.
- The building of the School of Design at the Zeche Zollverein in Essen (Germany), which is heated by 28°C warm mine water, originating from the mine drainage of the RAG AG.
- The utilization of mine water of the former Robert Müser colliery in Bochum (Germany) as an energy source for the heat supply of two schools and the main fire station in Bochum. Within this pilot plant the 20°C warm mine water, which originates from the mine drainage of the RAG AG from a depth of -570 m NHN, is being used.
- Seven operational mine water utilization plants in Saxony (Germany), which can be categorized as shallow geothermal reservoirs. A deep mine water project is currently being implemented at the West Saxon University of Zwickau, where mine water from a depth of 625 m below ground with a temperature of 26°C is planned to be extracted.

The thermal utilization of the mine water from existing mine drainage stations, as they are realized in Essen or Bochum (Germany), show the highest economic efficiency, as no additional pumping costs are being generated. Due to the lack of suitable customers and a not yet existing final planning security concerning the future locations of mine drainage stations after the end of active coal mining (end of 2018) and the renaturation of the Emscher, a further expansion currently only takes place to a limited extent. The "open" utilisation plan of the Mijnwater-project could be realized in the Netherlands, as the mine workings are already flooded after being closed down. In case of a mine water table < 80 m below ground, the proportion between the thermal energy obtained and the input energy (pumping energy) is to be assessed as positive, despite the low temperature of the mine water of about 28°C. Nevertheless, the mine water must be brought to a higher temperature level with the use of heat pumps. In contrast to the Mijnwater-project in the Netherlands, the mine water table in the majority of the central and northern Ruhr area, with a depth of approx. –600 m NHN below the surface (RAG AG 2015), is considerably deeper so that at water temperatures of up to 35°C, the energetic expense of the lifting is too high compared to the thermal energy obtained.

One way of increasing the efficiency is to increase the temperature of the mine water through the storage of seasonal heat in the mine layout, which has not been realized yet. Currently, merely a few medium-deep hydrothermal aquifer storages are in the planning stage or in operation in Germany. All of them are similar in regard of the temperature regime and the layer depth. Worth mentioning here are a project of the BMW Group at the plant Dingolfing (planning stage), the deep storage Neubrandenburg (in operation) and the energy concept Spreebogen (in operation).

Numerical modelling of the HT-MTES

Modelling hydraulic and thermal impacts on a regional scale for the HT-MTES project presented many challenges, including appropriate discretization of mine drifts as well as accurate modelling of layered aquifer systems. To accommodate the complex underground heat reservoir and its interaction with the surrounding aquifers and fault system, the finite element (FE) modelling code SPRING (König, 2014) was selected. SPRING includes a boundary condition specifically to describe mines or separate mining fields within a finite element mesh and to couple their hydraulic and thermal behaviour to the surrounding rock mass (fig. 3) and aquifers. The software was first published in 1970 and has undergone a number of revisions. SPRING uses the finite-element approximation in solving the ground-water flow and transport equations. Different model layers with varying thicknesses, including the pinching out of a layer, are possible.

In order to predict the impacts of both historic mining operations and future thermal impacts, a detailed conceptual model of the aquifer systems and a three-dimensional model of the mine drifts were incorporated into a regional numerical heat and transport model. The model was used for dimensioning of the reservoir layout as well as for optimization of flow rates, dam positions and temperature profiles (fig. 4).

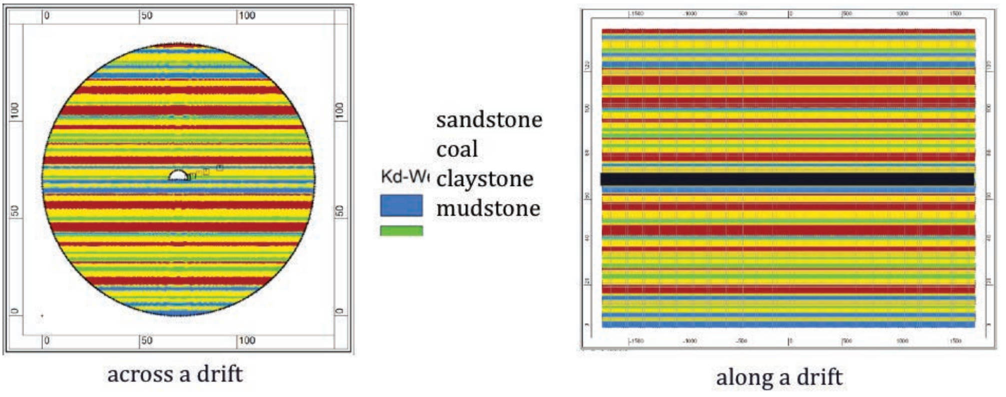

Figure 3 *Vertical cross sections of a conceptual drift model (delta h)*

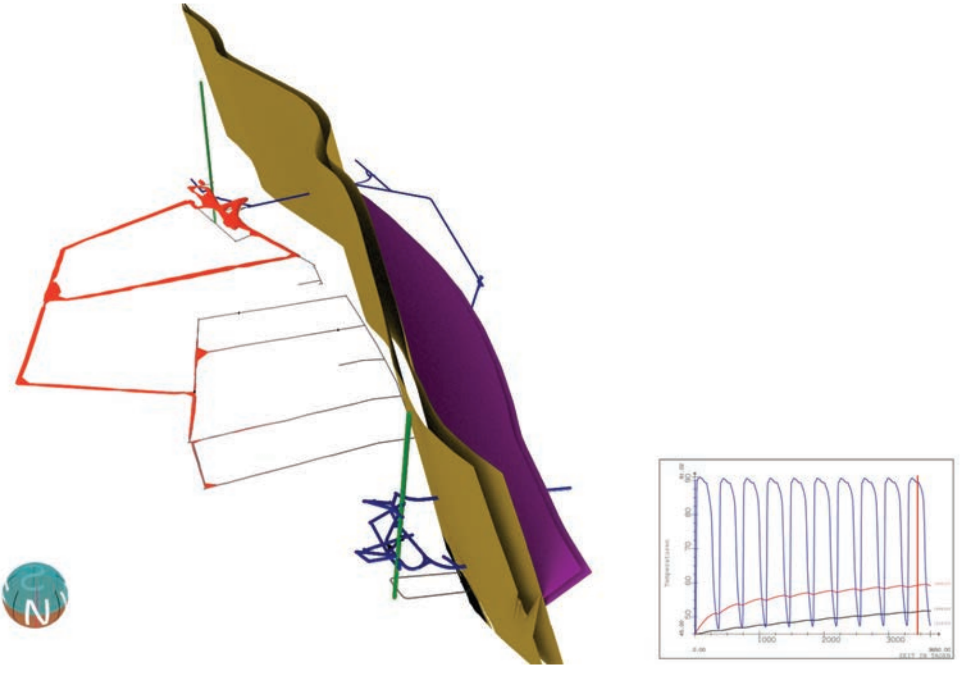

Figure 4 *Calculated temperature field of the HT-MTES with temperatures coloured from red (high) to blue (low), regional fault system in yellow/violet (delta h)*

HT-MTES - Prosper Nord

The fact that Prosper-Haniel is still an open and active hard coal mine facilitates numerous advantages for the development and exploitation of a mine thermal energy storage system:

- Increased hydraulic properties are encountered, due to the presence of former mining areas and galleries within the relatively dense carboniferous rock. This infrastructure substantially enhances the heat transport capability of the underground.
- Open shafts and drifts allow a comparatively easy accessibility and technical feasibility of a mine thermal energy storage during the closure phase.
- A positive customer structure is anticipated, due to the high population density within the vicinity of the mine.

The seasonally stored heat could be utilized to supply the surrounding residential and commercial areas, e.g. through a coupling with the Ruhr district heating grid or with the integration into the "InnovationCity Ruhr" process. Consecutively, the main conceptual model of the HT-MTES within the Prosper-Haniel hard coal mine is illustrated below and described in further detail.

The following conceptual model consists of the HT-MTES within the mining area "Prosper Nord" between shaft 9 (Prosper IV) and 10 (Prosper V) (see fig. 2). Based on the mine water drainage concept of the RAG AG, the hard coal mine Prosper-Haniel will be completely flooded up to –687 m NHN by 2035 (RAG AG 2015). Out of this reason, the drifts on level 7 could be utilized as a mine thermal energy storage in the future. In this case, surplus heat would be injected into the storage via shaft 9 during the summer, stored within the drifts of level 7 and reproduced via shaft 9 during the winter. It must be ensured that the in fig. 5 (red) illustrated drifts are to the greatest possible extent hydraulically decoupled from the rest of the mine layout by dams, in order to increase the efficiency of the overall storage capacity. An interference with the planned mine drainage on level 6 should be avoided by all means, as this will be the main flow paths of the mine water through Prosper-Haniel towards the prospective central dewatering station Lohberg (Drobniewski 2016) in the future. Therefore, suitable dam positions (fig. 5; magenta) have been local-

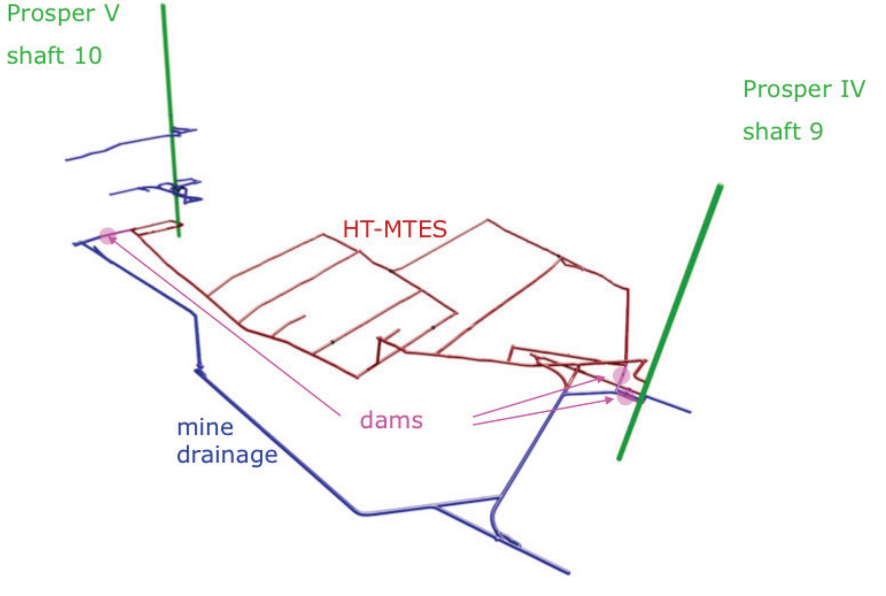

Figure 5 *HT-MTES (red) within the mining area "Prosper Nord" (delta h)*

ized and verified within the SPRING model of the HT-MTES. Based on the injection with a maximum temperature of 90°C (Jagert et al. 2018) for 6 months and a storage volume of 252.000 m^3, the conceptual HT-MTES would have a storage capacity of 12.8 GWh/a. After ten years, the SPRING model revealed a storage efficiency of up to 84 % for the proposed HT-MTES.

Additionally, a surface line between shaft 9 (Prosper IV) and shaft 2 (Franz Haniel) would have to be installed, in order to couple the HT-MTES with the existing district heating grid. Since 2014, an extended mine gas utilization plant has been put into operation at shaft 2 (Franz Haniel), for which a 3.3 km long mine gas transportation line has been installed between shaft 9 (Prosper IV) and shaft 2 (Franz Haniel). This plant could act as a possible heat source for the HT-MTES, as the cooling water of the cogeneration unit produces temperatures in the range of approx. 90°C, which could be directly utilized for storage purposes.

Conclusion

The development of diversified storage capacities will have a great impact on the future promotion of renewable energy sources. Within the Ruhr area, unused mine structures in combination with available unutilized surplus heat from power plants and industrial processes, resemble a vast potential for large heat storage capacities. Out of this reason, fundamental research in the field of seasonal heat storage in abandoned mines has to be conducted for further technology development and establishment of large scale storage systems. The aim of this feasibility study is to conceptualize a mine thermal energy storage system for the hard coal mine Prosper-Haniel. Until the end of 2018 Prosper-Haniel is still in operation, so that specific underground measures (dams, tubings, etc.) for a mine thermal energy storage are possible to be conducted. The HT-MTES could be prepared based on the results of the feasibility study during the three-year closure phase after 2018, when the production has ceased. Once the mine layout is fully flooded by 2035, the HT-MTES could be connected to the Ruhr district heating grid. In the case of a technical and economical implementation of the HT-MTES, the design and operation results of the seasonal heat storage within an abandoned hard coal mine, would be scalable to other locations in Germany and worldwide.

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