

Heat-Storage in Deep Hard Coal Mining Infrastructures

Rolf Bracke, Gregor Bussmann

GZB - International Geothermal Centre, Lennershofstr. 140, 44801 Bochum, Germany

rolf.bracke@geothermie-zentrum.de

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ABSTRACT

The project aims to develop heat storing technologies in the subsurface infrastructure of hard coal mines. By end of 2018 the last productive deep hard coal mine in Germany - Prosper Haniel – in the Ruhr-Area will be closed down. That mine is the last one of more than hundred already closed coal mines in the industrial heart of Germany with more than 6 Mio inhabitants in a mélange of 50 cities. Although most of them are plugged at the surface many mines still have left major parts of their subsurface infrastructures – especially open parts of former galleries and working faces. Due to the large dimensions of tens of km² per mine, depths of max. 1.500m at rock temperatures up to 50°C the mines have the potential to become an enormous geothermal reservoir for seasonal heat storage. Wasted heat from fossil fired power plants, garbage incineration and industrial production processes in the Ruhr Area may be stored during the summer season together with non-used heat from solarthermal plants on brownfield sites in cities. During winter time this heat will be used directly in single construction complexes and in city areas that are not connected to the existing district heating grids. Numerical simulations and technical investigations focus on the prototype Hard Coal Mine Prosper Haniel in the City of Bottrop; with: Identification and testing of new, cost-effective construction principles, Enhancement of storage density with innovative materials and heat transfer media; Optimization of seasonal storage concepts for large building complexes and new urban development areas; Placement of closed-loop hydraulic circulation systems in accessible areas of the mine; Connection to the existing district heating grids; Enhancement of the energy efficiency of electricity-driven combined heat-and-power production systems and of heat extraction processes in district heating systems. For the conceptual modelling and for the dimensioning of an appropriate heat-storage in the subsurface infrastructure of the mine most relevant geotechnical, hydrogeological and geophysical parameters for the Prosper Haniel Hard Coal Mine are investigated. The total mining area is 165 km² and the subsurface galleries have a total length of 151 km at a maximum depth of more than 1200 m with more than 40°C. There are 3 vertical shafts leading into the mine. Assuming that only 1% of this area may be used for heat-storage and a thickness of the storing geological formation of 100m the total storage capacity is ca. 100 GWh/K.

1. INTRODUCTION

The fundamental conversion of the energy system in Germany until 2050 represents an immense technological and economical challenge. A broad political, public and economic majority in Germany is asking for the intensified use of renewable energies and improved energy efficiency. Beside electricity production from renewable sources, thus, enhanced thermal storage capacities will become an important component of the converted system. A flexible management of the power and heating grids and a varied range of different storages technologies is required to maximize the potentials of the mostly volatile renewable energy sources. In this context innovative storage technologies will become the key technologies. Heat that is produced in abundance during certain periods can be stored temporarily in seasonal heat storages and may used in the cooler months.

In parallel to the development of the renewable energy sector, conventional sources – like the hard coal production - are slowly decreasing since decades. The existing active and closed-down shafts and galleries of the German coal mining industry, especially in the core area of the Ruhr district, are providing excellent infrastructural conditions for the implementation of seasonal heat stores. Due to the large dimensions of tens of km² per mine with depths of max. 1.500m and rock temperatures up to 50°C the mines have the potential to become an enormous geothermal reservoir for seasonal heat storage.

The conceptual plan is to store wasted heat from fossil fired power plants, garbage incineration and industrial production processes in the Ruhr Area during the summer season together with non-used heat from solarthermal plants on brownfield sites in cities. This heat may be directly used during winter time in single building complexes and in city areas that are not connected to the existing district heating grids. One precondition is the presence of a fully accessible and, if possible, active mine. Until their final closure in 2018 three mines of the german hard coal mining industries are left in operation. About 50 open deep shafts are still existent. Their operation is needed for workers and passenger transportation, coal mining, the ventilation and the dewatering of the pits.

One option is the implementation of closed-loop hydraulic circulation systems in accessible, active areas of the mines. The advantage of closed systems is that heat transfer fluids can be circulated at low energy input for pumping and without major maintenance. This is in contrast to open systems, where large amounts of energy are needed for pumping thermal waters from greater depths to the surface. Very often the pumping costs will be higher as the returns from the heat-usage.

To ensure the highest possible capacity and utilization of an underground storage system, their integration in large-scale urban development projects with appropriate consumer structures is required. Therefore the city of Bottrop has been selected as a reference site. Bottrop has been appointed as a model city for a comprehensive energy-efficient urban conversion in 2010 ("Innovation City") and has Prosper-Haniel as one of the last active coal mines in Germany. Within the Innovation City process, the heat storage concept will play a central role in the energy conversion of selected urban districts to higher efficiencies and lower CO₂-emissions. The research topics of an underground heat storage project have been defined as:

- Identification and testing of new, cost-effective materials, insulations and construction principles for seasonal underground thermal energy storage,
- Enhancement of heat storage density with innovative materials and heat transfer media,
- Optimization of seasonal storage concepts for heating and cooling applications for large building complexes and new urban development areas,
- Connection to the existing district heating grids,
- Enhancement of the energy efficiency of electricity-driven combined heat-and-power production systems and of heat extraction processes in district heating systems.

The central aim of the R&D project is to develop a technically and economically feasible thermal storage concept for the energetic use of a mine on the example of the Prosper-Haniel Coal Mine in Bottrop. The project is funded by the German Federal Ministries BMWi, BMU and BMBF "Initiative Energy Storage" program. Project partner is the RAG AG.

2. STATE OF THE ART

2.1 Thermal reuse of underground mines

Any investigation of thermal reuses of subsurface mining infrastructure requires a distinction between the utilization of backfilled and non-backfilled areas of the pit. If backfilling of an abandoned mine is still in the planning phase, the thermal reuse can easily be scheduled in advance. In contrast to this already backfilled mines have to be re-opened for reuse, which becomes extremely expensive. Therefore most backfilled abandoned mines will be completely flooded or filled with air. The possibilities for thermal reuse of flooded, underground mine workings are shown in **Figure 1**.

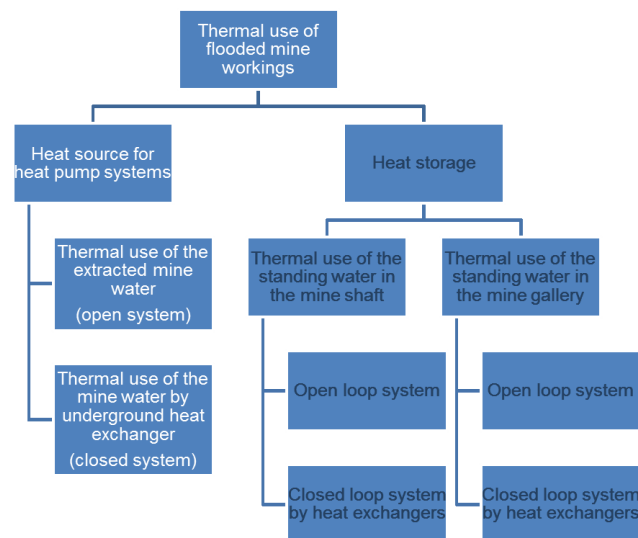


Figure 1: Thermal use of flooded mine subsurface infrastructure

The idea to gain thermal energy from existing and abandoned coal mines has been pursued by the R&D community since quite a while. Well known projects in Central Europe are:

- The Mijn-Water-project in Heerlen / Netherlands with an already completely flooded and not accessible coal mine. The reservoir has been developed with directional drilling designs. The warm mine water is pumped into a district heating system via a central heat pump.
- The SANAA-building at Zeche Zollverein in Essen / Ruhr-Area. The complex is heated by warm mine water which is obtained from the local RAG drainage.
- The use of mine water of the former mine Robert-Mueser in Bochum / Ruhr Area as an energy source for the heating of two schools and the Main Fire Station Bochum.
- The installation of a closed loop heat exchanger in an abandoned mine shaft of the mine Auguste-Victoria in Marl / Ruhr-Area.
- Reiche Zeche, Schloss Freudenstein, Marienberg (Freiberg mining area / Erzgebirge)

These projects reflect all currently contemplated geothermal development types (cf. **Figure 2**). The "open" concept of the Mijn-Water project was associated with relatively high costs for the reservoir development with additional boreholes. It is unlikely to be transferred to the situation in the Ruhr area in the next years, since the drainage will be continued in a reduced level even after the closure of the last mines in 2018. Thus, the thermal use of mine water from existing water drainages - such as in Essen or in Bochum - is energetically and economically more efficient as the investment and energy costs for pumping the water does not have to be considered.

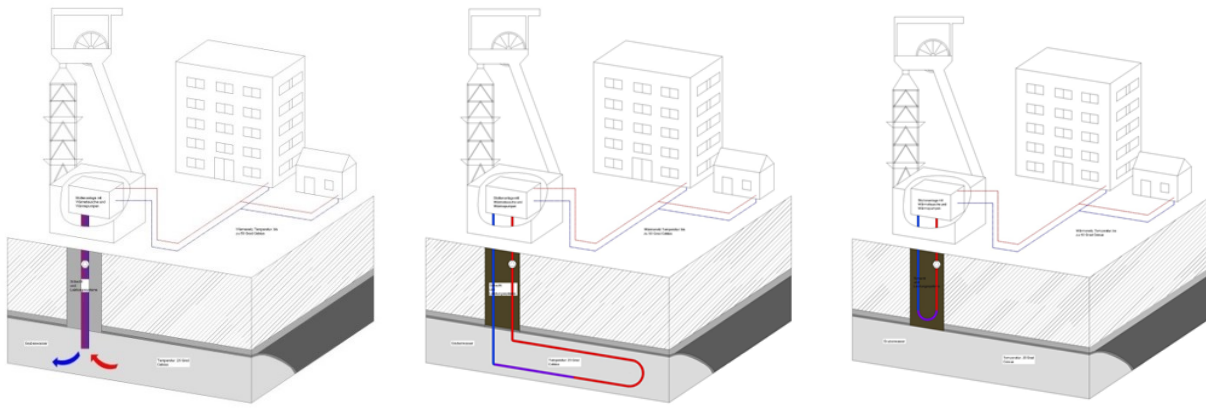


Figure 2: Open and closed loop geothermal extraction systems in coal mines

One particular challenge for using mine waters is the chemical composition and the high salinity of the geofluids - with special demands on the material composition of the heat exchangers. Waters from coal mines are highly mineralized and mixed with partially larger particles. In cases where already existing central mine drainage systems may not be used an exclusive intervention and extraction of deep ground water resources for energetic uses is currently not economic in the Ruhr Area. Here, the current depth of the water level at 700-1000m and the pumping costs are simply too large.

The "closed-loop" heat exchanger solution is exclusively to the shafts. But the heat extraction capacity of approximately 50-70 kW – according to the depth of the shaft - is quite limited. In **Figure 3** international projects to a thermal utilization of mines are summarized, including the depths and the pumping rates. It shows also the details for thermal performance and the required capacity of the feed pump.

County	Project	type of use / mine	depth [m]	flow temperature [°C]	thermal output [kW]	pumping rate [m³/h]	supply object	status	literature
Germany	Zeche Heinrich, Essen	sump pumping in Coal mine	335-480	19.5	ca. 250	20	nursing home	closed after operating (1984)	Hall et al. (2011), Grab et al. (2010), Wieber and Ofner (2008)
Germany	Zeche Zollverein	sump pumping in Coal mine	ca. 1000	33	max. 790	ca. 30	Sanaa-Gebäude (museum)	operating (2000)	Hall et al. (2011), Wieber and Ofner (2008)
Germany	Marienberg	ore mining	107	12.4	690	120	adventure pool, recooling of CHP	operating (2007)	Hall et al. (2011), Grab et al. (2010), Wieber and Ofner (2008)
Germany	Alter tiefer Fürstentolln	flooded mine	60	10.2	126	21.6	Schloß Freudenstein (castle)	operating (2009)	Hall et al. (2011),
Germany	Ehrenfriedersdorf	tin mine	100	ca. 10	95	n/a	High school	operating (1994)	Grab et al. (2010), Wieber and Ofner (2008)
Germany	Ehrenfriedersdorf	tin mine	110	ca. 10	120	22	visitor mine	operating (1997)	Grab et al. (2010), Wieber and Ofner (2008)
Germany	Auguste Victoria, Marl	closed loop system in a shaft (coal mine)	700	n.a.	70	n.a.	residential building	operating (2010)	unpublished
Germany	Reiche Zeche, Freiberg	flooded mine	228	18	260 (670)	56 (144)	TU Bergakademie Freiberg (university)	operating (2013)	Grab et al. (2010), unpublished
Germany	Robert Müser	sump pumping in Coal mine	570	21.1	max. 1600	max. 40	2 secondary schools and fire station	operating (2012)	unpublished
Germany	Zwickau	flooded coal mine	625	27	n/a	max. 70	Westfälische Hochschule	in process (2013-2015)	unpublished
Germany	Bad Schlema	flooded uranium mine	90	n/a	250	n/a	Schiller-Grundschule (primary school)	in process (2014)	unpublished
Netherlands	Heerlen	flooded coal mine	700	30 (heating)/ 16 (cooling)	700	79.2	residential buildings, shopping centre	operating (2008)	Hall et al. (2011), Malolepszy et al. (2005)
Norway	Folldal/Folldal Mine	closed loop (600 m long, DN 50)	600	n/a	18	n/a	n/a	operating (1998)	Hall et al. (2011)
UK / Scotland	Shettleston	Open loop in coal mine	100	12 or 18	n/a	n/a	16 residential buildings	operating	Hall et al. (2011), Watzlaf and Ackman (2006)
UK / Scotland	Lumphinnans	Open loop in coal mine	170	15.4	n/a	n/a	18 residential buildings	operating	Hall et al. (2011), Watzlaf and Ackman (2006)
USA	Park Hills, Missouri	Open loop in a lead mine; return well	133/120	14	113	16.9	office building (750m²)	operating (1995)	Hall et al. (2011), Watzlaf and Ackman (2006)
USA	Pittsburgh	flooded coal mine	n/a	13.6	n/a	n/a	church	operating (2006)	Korb (2012)
USA	Scranton, Pennsylvania	open loop (2 Wells), flooded coal mine	120	13.8 (Return: 16.1°C)	n/a	n/a	university (cooling)	operating (2010)	Korb (2012)
USA	Kingston Community Center	flooded coal mine	n/a	16.1	n/a	n/a	shopping centre	operating (1982)	Korb (2012)
Kanada	Springhill	Open loop in flooded coal mine	140	18	45	14.4	factory building (14000m²)	operating (1994)	Hall et al. (2011), Watzlaf and Ackman (2006)

Figure 3: Summary of international projects to a thermal utilization of mines (operating / in process)

2.2 Underground Thermal Energy storage (UTES)

Underground heat storages have to be classified into artificial subsurface cavern structures that are filled with water only or with gravels & water and into systems that use the natural underground and develop this with heat extractors like closed heat exchangers

(BHE) or water wells (aquifer). The classification of the following types of in the underground (cf. **Figure 4**) was taken from Reuss (2001):

- Storage medium water (convective heat transfer): Ground tank stores, rock cavern stores
- Storage medium soil (conductive heat exchange): borehole heat exchanger stores in loose and solid rock
- Storage medium base (combined convective and conductive heat exchange): aquifer heat stores, gravel / water stores

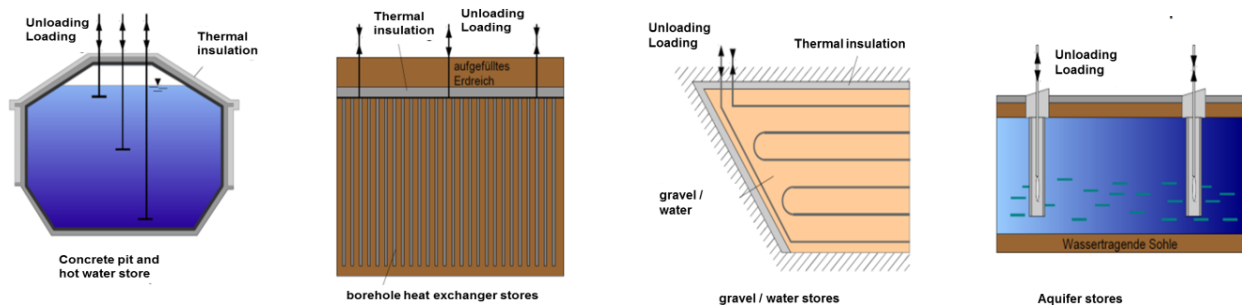


Figure 4: Underground thermal energy storage concepts

3. REFERENCE SITE: PROSPER-HANIEL COAL MINE IN BOTTRUP

Prosper-Haniel in Bottrop was selected as a reference location for the development of a thermal storage concept in mine infrastructures. It is one of the three remaining coal mines of RAG and will stay active until 2018. The total mining area is 165 km² and the subsurface galleries have a total length of 151 km at a maximum depth of more than 1200 m. The undisturbed rock temperatures reach 40-45°C. There are four vertical shafts - Prosper 9/10, Franz Haniel 1/2 and a conveyor drift ("Foerderberg") - leading into the mine. Assuming that only 1% of the mining area may be used for heat-storage and the thickness of the storing geological formation is 100m, the total storage capacity is ca. 100 GWh/K. The fact that this is an active and fully accessible mine provides a huge advantage in terms of a geothermal development and use as a thermal storage.

The construction of the galleries in the relatively dense carboniferous rocks created increased hydraulic permeability. These improve the heat transport capability of the substrate significantly. At the same time a comparatively simple access and technical development of the mine is possible through active and open shafts and drifts. Some of the heat is already available during the active mining: about 4 million cubic meters of water are pumped every year at temperatures around 25 - 30 °C from a depth of 1,000 m as part of the mine drainage at shaft Franz Haniel 2. Uses of a temperature difference of 10 K could already provide a thermal output of 5.3 MW and a heat quantity of 46,000 MWh/yr. The above-mentioned mine water quantity will not remain permanently available according to the current plans. After the closure of the mine in 2018 the water drainage will be transferred to Lohberg (Huenxe), which is accompanied by a partial flooding of the mine.



Figure 5: Prosper-Haniel Coal Mine in Bottrop und 165 km² site plane of the mining claim (RAG AG)

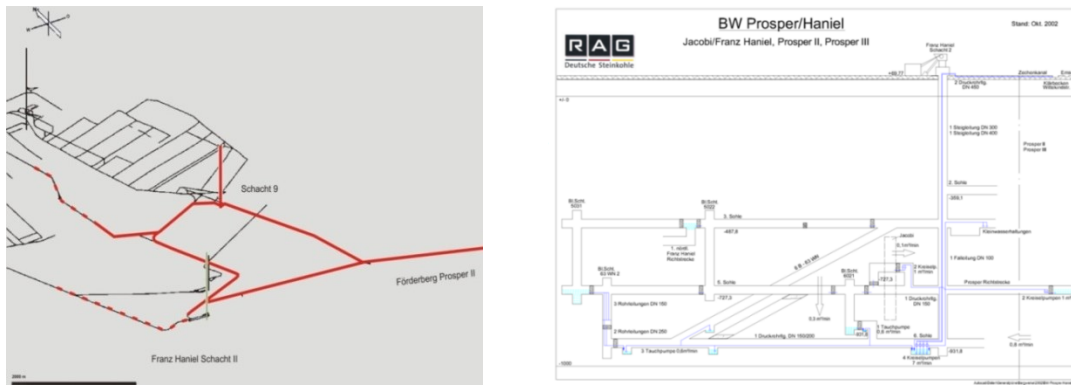


Figure 6: Gallery of Prosper-Haniel Coal Mine und profile section for shaft Franz Haniel 2 (RAG AG)

Due to the high population densities around the mine a superb possible user-structure is given for stored underground heat. It may be used to supply residential and commercial sites in the northwestern part of the Ruhr-Area. Among the potential neighboring customers are a) the planned residential area “Grafenwald-Sued” with 150 units and a heat demand of approximately 3,000 MWh/a at Prosper II, b) the supply of the former “Kau” with about 500 MWh/a and c) a commercial area at Franz Haniel 2. It would also be a proportionate supply of the largest commercial area of Bottrop, the “Zero Emission Park” with a current heat demand of 145,000 MWh/a, conceivable. In addition, a connection to the Ruhr-District Heating System and thus the seasonal storage of wasted heat from nearby coal fired power plants (eg >300 MWth from Scholven-PP) is possible. Furthermore, existing brownfield sites, especially the slag heap in the field Prosper II will be used by solar thermal energy systems and may be integrated into the storage concept.



Figure 7: Main drifts in Prosper-Haniel Coal Mine and the neighboring users structure (RAG AG)

4. SCIENTIFIC AND TECHNICAL WORKING OBJECTIVES

4.1 Technical criteria for the realization of seasonal heat storage in mine

Seasonal heat storage in existing subsurface mine infrastructures (shaft and gallery system) represents a possible innovative and permanent heat supply variant under the given conditions of the Ruhr area. It is a precondition that all necessary technical infrastructures inside the mine has to be implemented prior to the dropping of the mine (2018). The seasonal heat storage must have a large volume since large amounts of heat shall be stored. It also has to be operated reliably, constructed cost-effective and be integrated into the existing infrastructures. High demands are made on the materials of the subsurface heat exchangers. They result from high temperature stresses, humidity admission flow and cross sectional stability of the mine infrastructure. Materials and superstructures have to make sure that function is guaranteed over a period of 40 to 50 years.

It also requires a local utility to operate the large scale storage system. Depending on the heat source, different mass flows and temperature levels have to be managed. All affected components (storage construction, loading and unloading facilities, pipe

diameters, pumps, etc.) must be suitable for the intended operations and resulting loads. If the storage is loaded by several heat sources, care must be taken on a careful coordination of the amounts of heat, as well as on the loading and unloading times of each heat generator. Based on the results of Eickmeier (1999), the following technical criteria at Prosper-Haniel Coal Mine are intensively studied:

4.1.1 Identification and accessibility of adequate mining infrastructure

A seasonal storage in the mine requires locations that are linked to existing shafts; considering the geotechnical conditions, process safety and economic aspects of the construction. This may be infrastructure of the active part of the mine, workings in transition to closure or standstill of former areas of subsurface mining. The type and size of the mine working entry determines the available space for the incorporation of equipment and components (piping, heat exchangers, etc.). Such entry is important for repair and maintenance works in storage mode. In order to achieve a permanent stability the shafts of abandoned mine sites are backfilled. New entries to be constructed would result in enormous and disproportionate costs. Only maintenance-free technology can be used to build up a deep underground heat storage. To ensure a high operating reliability, the systems must be designed according redundant.

4.1.2 Geometry and orientation of the storage

The geometry of the usable volume of a mine is specified. It corresponds to vertical (shaft) or horizontal (gallery) cylindric bodies. The ratio of volume to surface is less favorable than those of artificial designs. However, the decisive factor is finally the size of the investment costs respectively the question of whether lower utilization rates may be offset by lower specific costs. Gallery and shaft storage mainly differ in terms of temperature layering during operation. Due to the lower height the temperature layer in horizontal storages is susceptible to currents, which can be caused by injection and withdrawal. A vertical storage geometry (shaft) has better conditions for a pronounced and stable temperature stratification. A first technical approach for utilizing a shaft storage represents inter alia the thermal activation of the still accessible vertical shafts about geothermal probes (Koaxial-/U-probes).

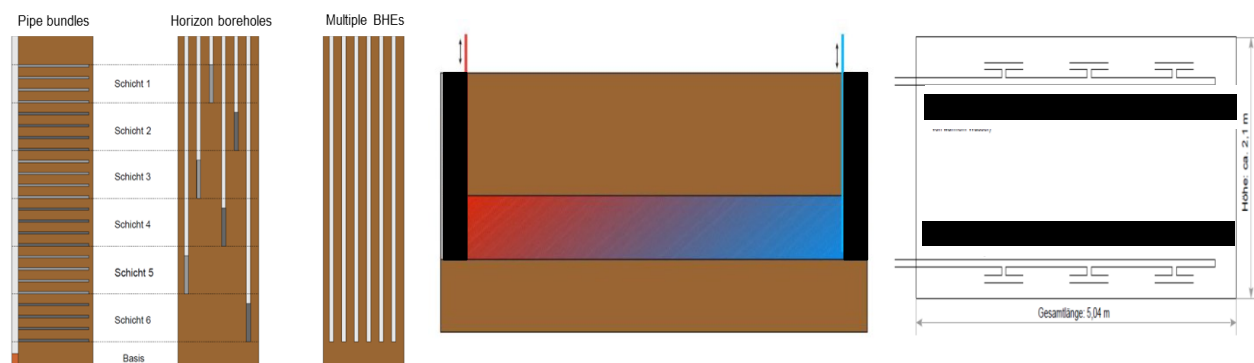


Figure 8: Geometry and orientation of the storage in mine workings

4.1.3 Open- and closed-loop systems

Open and closed systems may be used for the storage operation. In open systems, a direct exchange between the heat transfer medium and the heat storage medium occurs. Open systems can be used in layers of lower depths, e.g. in the near-surface use of a shaft. The water exchange can be realized via injection and extraction wells. Furthermore closed systems can be operated with significantly less pumping. For the implementation of a completely closed heat exchanger system into an existing mine, piping and header system materials must be used that can withstand the subsurface prevailing hydrostatic pressures of > 100 bar and possible mechanical stresses.

4.1.4 Adequate storage media

Different media may be considered for storage. The use of mine water is critical, because the chemical composition and the entrained suspended movement may cause problems on all units (e.g. incrustation), leading to a disproportionately high level of maintenance. Beside the use of fresh water, salt or minerals appear to be interesting alternatives to a water filling. Due to the low heat capacity, the storage volume of such a system must be increased compared to the storage volume of a water-filled system. A slow mixing of storage media with upcoming minewater must be avoided by sufficient impermeability of the system.

4.1.5 Safety of the cross-section stability

A major technical challenge is given by the fact that the extraction drift cannot be compared of expanding and long term stability with the main galleries of the mine. A danger of "overgrowing" or partial collapse of the extraction drifts is given. There are thus high demands on the material properties and the protection of the heat storage and exchanger systems by mechanical stresses. The precondition requires a detailed analysis of the mine infrastructure section to possible deformations and mine subsidences. The stability of the mine may have to be backed up by additional geotechnical measures. The use of water saturated gravel beds or the use of minerals can contribute this to the stability of the cross section.

4.1.6 Tightness of the storage system

There is a larger number of cavern sealing systems available, mostly based on synthetic material (e.g. geosynthetic membranes) or mineral based (e.g. shotcrete lining). The sealing differentiates between rock mass affiliated and non-affiliated procedures. However, in each specific case the optimum has to be found between financial cost and the desired tightness.

4.2 Technical examination of the heat storage & exchanger systems materials

The technical examination of the used heat storage systems in the mine includes identifying and testing of all geotechnical and outgassing-technical boundary conditions for the respective shaft. These analyzes have significant effects on the feasibility of the storage concept and on the necessary measures to ensure the cross section stability. A proper technical design of the storage concept is the decisive element for the shaft backfilling and the securing of the open shaft area. The following geotechnical boundary conditions have a significant influence on the feasibility and have to be checked in advance:

- Handling with existing leads
- Condition of the shaft extension
- Possible effects of the rock mass on the shaft extension
- Examination of possible shaft or gallery backfillings
- Possible water inlets
- State control of the shaft extension and the shaft pillar
- Outgassing-technical matters.

Besides the analysis of the geotechnical framework conditions there are material requirements to be determined for: storage system, backfill, backup, and sealing materials. The general requirements concerning chemical, physical and (rock mass) mechanical effects on the materials have to be determined by material investigations and tests.

4.3 Considered storage scenarios

In addition the technical criteria that have been discussed in section 4.1 the following additional influencing variables must be investigated:

1. hydrogeology
2. storage type
3. storage size
4. construction
5. loading and unloading
6. heat output
7. temperature levels
8. system integration
9. approval
10. operation and maintenance.

In accordance with previous work and the status of research on subsurface thermal energy storage the Figure 9 shown scenarios may be considered for seasonal heat storage in the Prosper-Haniel Coal Mine.

1. storage geometry and orientation	horizontal in the galleries		vertical in the shaft	
2. storage system	open storage system	closed storage system	open storage system	closed storage system
3. storage medium	fluid (e.g. tap water, mine water, heat transfer fluid)		fluid (e.g. tap water, mine water, heat transfer fluid)	
	solid (e.g. gravel fill, clay suspension, lean concrete)		solid (e.g. gravel fill, clay suspension, lean concrete)	
4. storage connection	open cycle in and out of storage		open cycle in and out of storage	
	closed cycle (heat exchanger system)		closed cycle (heat exchanger system)	

Figure 9: Variant matrix of possible mine heat storage concepts for the location Prosper-Haniel in Bottrop

4.4 Numerical simulation model

The aim is to develop a numerical simulation model for the Prosper-Haniel Coal Mine which enables reliable exploration and exploitation of the geothermal potential after flooding. In addition to the simulation calculations for sizing (for both: the open and the closed system) sensitivity analyses must be performed. For the dimensioning and optimisation of the underground heat storage a simulation tool is required that can visualise the hydraulic, thermal and geological conditions within the mine mostly realistic and practical and that simulates the heat input and withdrawal from the underground storage. For this purpose, a numerical subsurface model must be created that represents the fluid and heat transport within the specific mine elements (shafts, galleries and crossways). A further task of the model is the thermal hydraulic connection of the mine to the surrounding rock formation with its naturally given geological heterogeneity. The difficulty of the numerical figure is the analysis and implementation of the physical processes occurring at different time scales. Fast processes in the system are the hydraulic flow within the heat probe (for closed systems) and the flow in the anthropogenic cavities (shafts, galleries, interrupted areas). For these processes and for the coupling of

the heat transfer from the probe to the mine opening on an inner boundary condition, small time steps are required (seconds to minutes).

The relatively slow flow processes in the geological system have to be imaged by large time steps of several days. The challenge is to map the thermal processes and their different time scales sufficiently accurate, but still numerically stable and at reasonable costs. Even the very large spatial variability of permeability is extremely challenging. Between the flow processes in the open mining structure, the collapsed areas, the fault zones and fractures and the porous matrix scale differences of up to 8 orders of magnitude. In this project, the implementation is integrated into the hydraulic system modeling software SPRING, which already includes all the tools for the specific hydrogeological modeling in mining. In particular, the SPRING code provides the ability to map flooding processes of mines. Model technically each mine is to be defined as a fully drained, unsaturated, 3-dimensional zone. The program is enhanced by an integrated box model. This enables the setup of an accurate accounting of all relevant quantities of water for each time step at any time. Based on a predetermined definition of the relationship between volume and water level in the mine, the water level in the mine will be automatically calculated with the box model, and the value returned to the main calculation process to adjust the hydraulic boundary conditions at the mine.

5. CONCLUSION

New thermal storage capacities can be developed in subsurface mining infrastructures. They are needed for the large scale expansion of renewable energies on the heating sector in metropolitan areas. Therefore fundamental understandings for thermal storage of energy in mines have been developed and must be expanded. The specific aim of this applied research project is to realize a prototype plant at the Prosper-Haniel Coal Mine, based on the findings and make an important contribution to the conversion of the energy system of the City of Bottrop. If the technical and economic feasibility can be demonstrated, an extension of the heat storage at Prosper-Haniel to other mines or regions is conceivable. The transferability of this project on numerous locations in Germany and around the world offers a perspective far beyond the targeted pilot project itself.

The project results are useful for other applications: such as cold storage, heat extraction, underground pumped-storage. Numerical subsurface models and the dimensioning of the storage systems simulation tools need to be developed with complex thermal and hydraulic couplings. These software tools can also be used in other projects for underground heat storage as well as in the disciplines of geothermal energy and reservoir modeling. Any use of the knowledge gained about the technical issues, such as the geothermal development of mines and the research for new heat exchangers, pipe materials, filling and insulating materials for increasing the efficiency of future heat storage and geothermal projects is conceivable.

The coal mines in the Ruhr Area provide the largest artificial networked mine workings worldwide. After finishing their activities in the Ruhr area from 2018 a reuse of this underground infrastructure including the expertise in the mining technologies that has been built up over decades will be endeavor for science and industry. It may also play a key role in the conversion of the 2.500 MWth district heating system in the Ruhr Metropolis which is the largest hydraulic network in Europe.

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