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Seasonal heat storage in partially flooded mines - In-situ investigations at the Freiberg, Saxony, site

Lukas Oppelt[1,2], Thomas Wenzel[3], Mareike Bleidiessel[3], Patrick Heinrich[3], Alireza Arab[4,2], Rebekka Wiedener[4,2], Christian Engelmann[4], Chaofan Chen[5,6,2], Frank Schenker[4], Tobias Lotter[4], Thomas Schneider[4], Friedrich Hellmuth[4], Martin Binder[4,7,2], Thomas Nagel[5,6,2], Thomas Grab[1,2], Tobias Fieback[1,2], Traugott Scheytt[4,2]

[1] Technische Universität Bergakademie Freiberg, Chair of Technical Thermodynamics, 09599 Freiberg (Saxony), Germany

[2] Freiberg Center for Water Research (ZeWaF), Freiberg 09599, Germany

[3] DBI Gas- und Umwelttechnik GmbH, 04229 Leipzig (Saxony), Germany

[4] Technische Universität Bergakademie Freiberg, Chair of Hydrogeology and Hydrochemistry, 09599 Freiberg (Saxony), Germany

[5] Technische Universität Bergakademie Freiberg, Chair of Soil Mechanics and Foundation Engineering, 09599 Freiberg (Saxony), Germany

[6] Helmholtz Centre for Environmental Research – UFZ, Environmental Informatics, 04318 Leipzig, Germany

[7] University of Basel, Hydrogeology / Applied and Environmental Geology, 4056 Basel, Switzerland

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Abstract

Currently, about half of the energy consumption of Germany is spend on heating and cooling, and only about 19% of this energy is generated from renewable sources. In order to decarbonise the overall energy supply, it is essential to integrate seasonal heat storage systems. The aim is, for example, to store excess heat during summer (e.g., from solar thermal energy) for use in winter. One possibility can be the use of partially flooded mines as so-called thermal energy storage (TES) systems, in that specific case known as Mine TES (MTES).

As part of the BMBF-funded R&D project 'MineATES', an in-situ laboratory was set up at the Reiche Zeche (Himmelfahrt Fundgrube mine in Freiberg, Saxony). In the underground mine, thermal energy was injected into (charging process) and extracted from (discharging process) a test storage reservoir of approx. 21 m³ volume using a mobile heat pump test rig. The effects on the surrounding rock (Freiberg gneiss), the water chemistry and the technical infrastructure (e.g. heat exchanger plates) were analysed using more than ninety temperature sensors, numerous water analyses and continuous monitoring of control parameters.

The first test series show that temporary heat storage is possible, with both the test reservoir's water body and the surrounding rock acting as a combined storage medium. With regard to the latter, a measurable temperature change at a distance of more than two metres from the test reservoir was demonstrated within a few days. However, considerable heat losses occur during the storage process. The main causes are thought to be losses due to flow through the basin and advective-dispersive heat transport within the rock matrix (mainly along the geologically determined fracture structure), and evaporation and heat transfer losses across the large (relative to storage volume) water surface.

In parallel to the in-situ investigations, the necessary interplay between mine storage and surface heat supply was analysed. Using GIS-based modelling, potential sources for waste heat from

industry, active cooling of buildings, or solar thermal energy were systematically recorded and their possible coupling with heat storage in the mine was investigated. For the exemplary analysis of the city of Freiberg (Saxony), four preferred areas including the old town were identified and analysed. The results show that the share of renewable heat supply can be increased by about 20% through the implementation of MTES.

Motivation and project objectives

The supply of heating and cooling is currently still heavily dominated by fossil fuels. In 2023, only 19% of the required heating and cooling energy was generated from renewable energy sources. Biomass accounts for that share with more than 80% (AEE 2024) In Saxony, the share of renewables is even lower: in the first half of 2024, only 6% of the heating and cooling energy required was produced from renewable energy sources. More than 90% of the heating energy is currently provided by natural gas and lignite (StLA Sachsen 2024).

More emphasis could be placed on solar thermal energy to increase the share of renewable energy sources. In Germany, this has a directly technical potential of around 16 billion kWh (BUND Bundesarbeitskreis Energie 2013), of which around 9 billion kWh were used in 2023 AEE 2024). At the same time, fossil fuels should be used more efficiently by re-using waste heat from industrial processes (e.g., metal processing). However, both energy sources lack a sufficient demand-availability ratio. With the main demand for heat being in winter, solar thermal energy is mainly available in summer. Industrial excess heat is partly available all year around, but due to the variability of energy consumption, there is not always a demand for energy to remove the waste heat at all times of the day and the year.

This shows that energy storage is essential, ideally over longer periods (seasonal storage). One option for this storage technique could be non-operational underground mines as part of MTES systems. There are more than 10,000 of potentially suitable mines in Germany, spread across 14 of the 16 German states. These mines have often been flooded after closure and, therefore, offer comparably large volumes of water for potential heat storage. Here, too, it would make sense if surpluses from the summer could be stored for the winter.

The presented study is part of the BMBF-funded R&D project MineATES (project number: 03G0910A), which is currently investigating several aspects related to the conditions under which a non-operational, flooded mine is suitable for MTES. The aim of the project is to develop a guideline that will make it possible to characterise mines regarding their potential as heat or cold storage reservoirs using seterminable input parameters such as volume flow, temperature and population density. As can be seen in Figure 1, the following points are combined:

- In-situ monitoring at the Reiche Zeche (Freiberg) laboratory site to determine and analyse the thermal, hydraulic and hydrogeochemical effects of energy storage on mine water and surrounding rock.
- Pilot scale experiments at the heat exchanger interface to systematically evaluate the efficiency of mine heat storage and to derive recommendations for optimised heat exchanger design.
- Development and application of adaptive numerical simulation tools to complement the experiments, to evaluate process upscaling and for easy characterisation of the mine sites.
- Investigate the dynamic relationship between heat/cold supply and demand: potential storable heat and cold surpluses and possible consumers of stored energy.

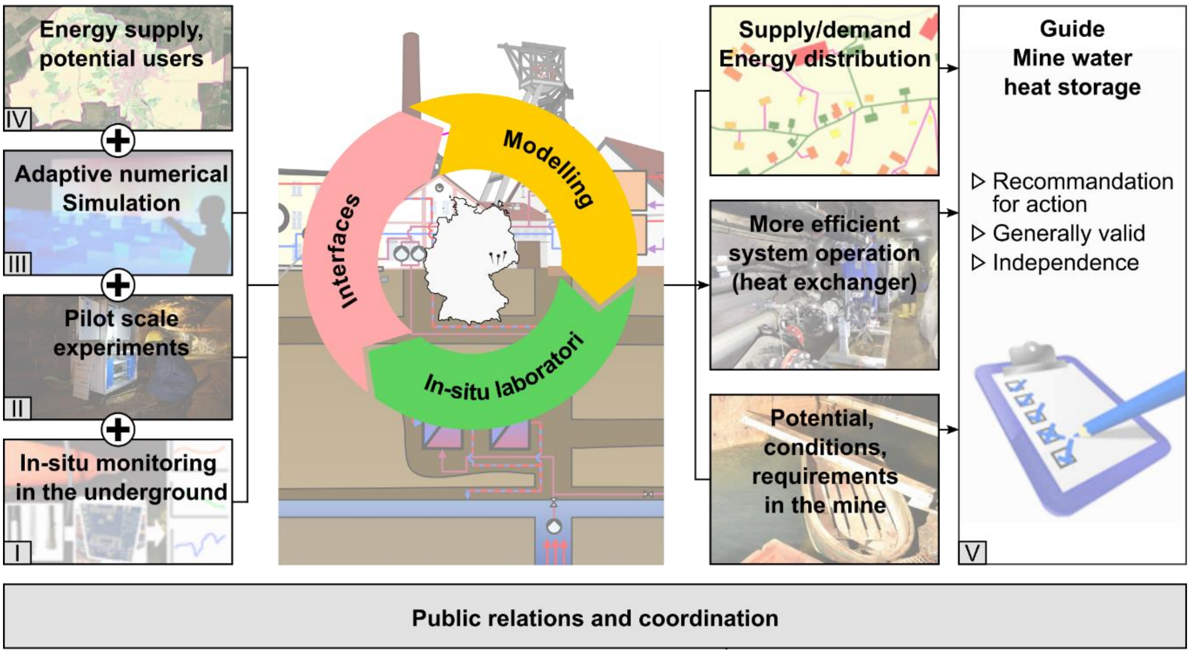

Figure 1 Schematic structure and focal points of the MineATES project

In-situ laboratory at the Reiche Zeche mine – Controlled simulation of MTES systems

The former Reiche Zeche silver mine in Freiberg (Saxony, Germany) is a central research site in the presented research study. Investigations related to MTES were already carried out there in the 1990s, showing that storage efficiencies of around 50% can be achieved (Schaberg 1998). For the MineATES project, a water reservoir with a volume of approximately 21 m³ was selected for MTES test cycles performing both heat and cold storage, based on the first test in the 1990s. A more detailed description of the basin and the test environment can be found in Chen et al. 2024.

More than 90 temperature sensors (Pt1000 type) were installed in the surrounding rock at a distance of up to 2 m from the edge of the water basin and connected to dataloggers to record heat dissipation in the rock. Originally, the reservoir basin had an open surface to the mine gear. To reduce heat energy exchange with the ambient air and minimize evaporative water dissipation, the basin was covered with an air chamber foil for the tests. As can be seen in Figure 2, mine water from another level of the mine (number 1 in the figure) is used via a heat exchanger (2) to bring it to a higher temperature level (target in the first experiment was 30 °C) in a mobile heat pump test rig via the heat pump (3, heating capacity ~ 3.5 KW) and then transferred to the storage reservoir via another heat exchanger (4). This simulates the thermal charging process. The then warmed-up reservoir water is subsequently used as a heat source with heat being extracted via the heat exchanger (4), i.e., the process is reversed. It is then transferred in the heat pump (3) to a temperature level between 30 and 40°C, which is typical for potential consumers, e.g. residential buildings, and then released via the heat exchanger (2) to the water (1), which flows into another mine level.

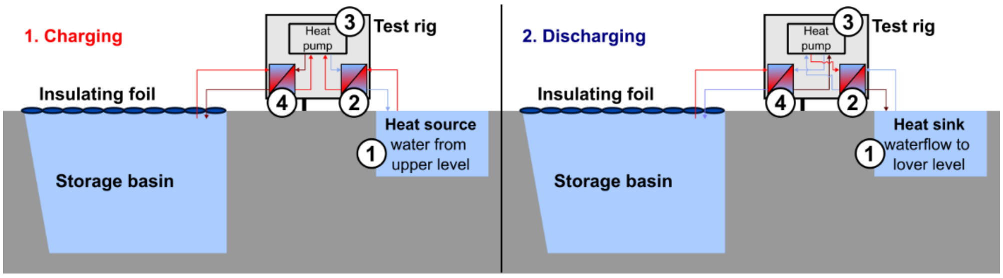

Figure 2 Test setup for the heat storage tests in the Reichen Zeche Freiberg colliery (Saxony)
(1) mine water heat source/sink, (2,4) heat exchanger, (3) heat pump

An initial synthetic numerical simulation of the reservoir basin showed an efficiency of around 45 to 55% in a scenario of 15 days injection and 15 days cooling (storage) at a target temperature of 40°C. The joints and cracks in the basin wall have a considerable influence. Doubling this would increase the thermal energy storage capacity by over 55%, but would result in approximately 12% less energy being recovered (Chen et al. 2024). Figure 3 shows the evolution of the reservoir temperature over the first storage period. It is clear that the target temperature of 30°C was not reached. At the end of the experiment, after 61 days of heating, temperature rose to approximately 26 °C.

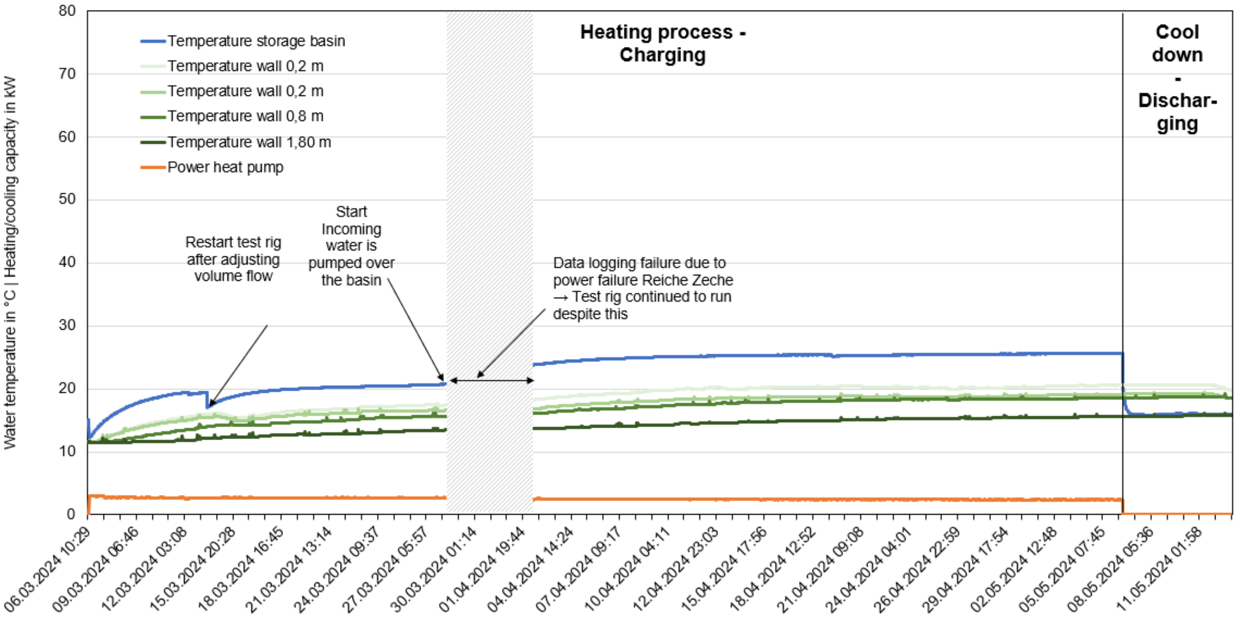

Figure 3 Temperature curve in the basin and the heating power of the test rig in the first test series (March to May 2024)

The temperature increase was also clearly measurable in the rock. As can be seen in Figure 3, at the end of the test, a temperature of over 20°C was measured at a rock depth of 20 cm. A temperature increase of over 5 K was also achieved at a depth of 1.80 m as a result of the storage. The heat balance of the reservoir shows that only a very small proportion (250 kWh) of the heat supplied (4,200 kWh) remained in the water (see Figure 4). The majority is in the surrounding rock, with a small proportion (< 4%) lost through the covering foil. There was also a large loss of stored heat due to water flow through the reservoir. As part of a follow-up experiment, the newly inflowing water was pumped over the reservoir basin eventually reducing the advective heat loss. However, it was not possible to prevent the flow completely, so every day new cold water flowed into the reservoir, which then had to be reheated, while already heated water flowed out. In summary, it can be said that the MTES system works and the storage efficiency is between 44 and 60 %, which is also in the same order of magnitude as the study by Schaberg 1998 and as the previous simulation results by Chen et al. 2024. However, the extent to which these results are comparable will only become clear in the next tests, when a target temperature of 40°C is also reached in the experiment.

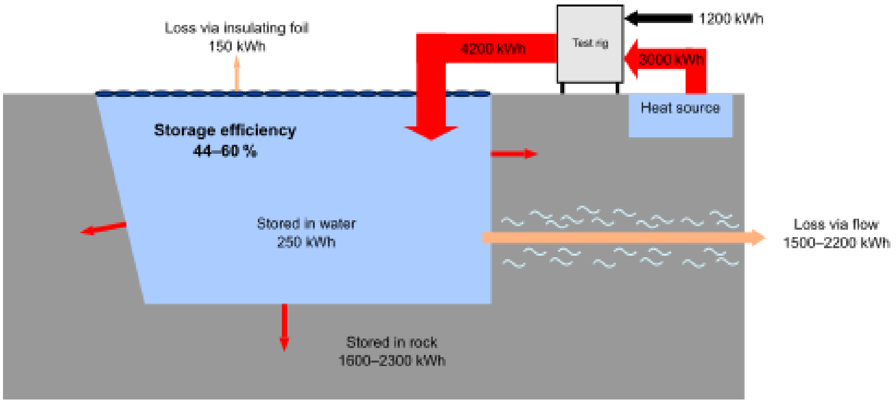

Figure 4 Heat balance of the first storage period (March-May 2024) in the Reichen Zeche Freiberg (Saxony)

Interface heat exchanger

Depending on the location, mine water can carry various contaminants such as dissolved and undissolved metals, suspended solids or bacteria. These contaminants can deposit in the heat exchanger (fouling) and conspicuously reduce the efficiency of the system. A biofilm of around 250 µm already reduces the amount of heat transferred by around 50% (Nandakumar and Yano 2003; Grab et al. 2020). For this reason, experiments have also focused on the heat exchanger. Among other things, it was investigated whether certain materials or coatings are less susceptible to fouling and therefore form fewer deposits. As described above, two types of water are used in the tests in the Reiche Zeche mine (see Figure 5).

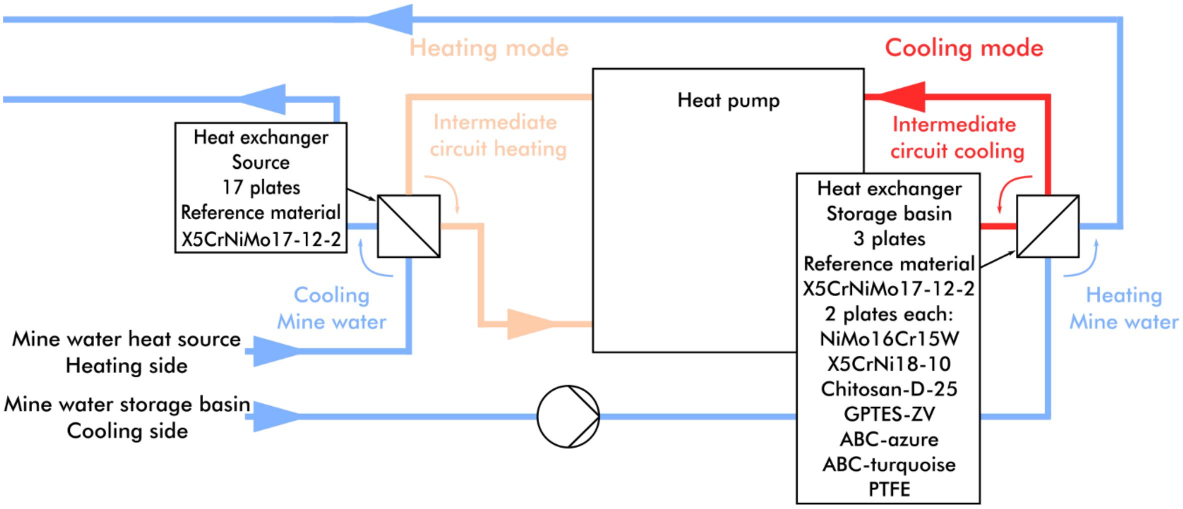

Figure 5 Flow diagram of the heat exchanger test rig at the MineATES storage reservoir in the Reiche Zeche Freiberg mine

The characteristics of the water from the upper level (heat source), which was used as a heat source, are shown in Figure 6. With regard to possible deposit formation, the elements aluminium, arsenic, iron, manganese and zinc are particularly relevant (Grab et al. 2020; Ussath et al. 2020; Oppelt et al. 2022). Hereby, manganese and zinc in particular have higher concentrations in the mine water heat source.

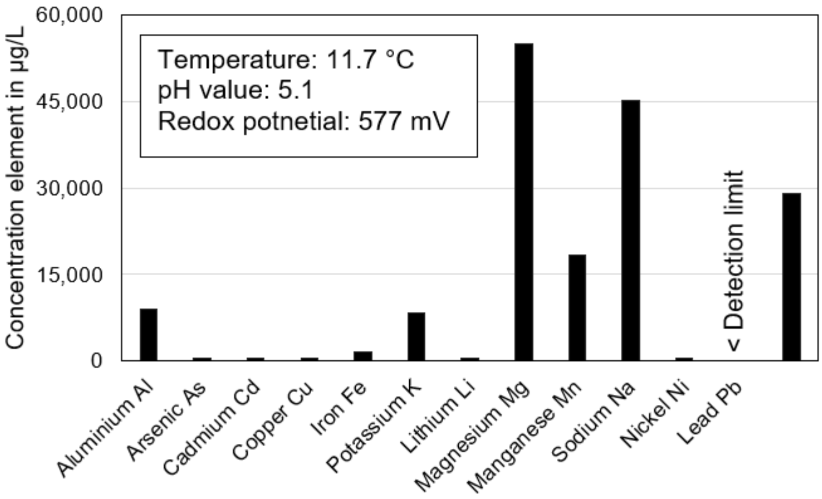

Figure 6 Characteristics of the mine water heat source (heating side)

The characteristics of the mine water on the side of the heat reservoir (see Figure 7) show that this water contains high levels of magnesium and zinc. Of the metals that have a major influence on the formation of deposits, zinc, manganese, aluminium and iron are the most abundant. Arsenic was below the detection limit.

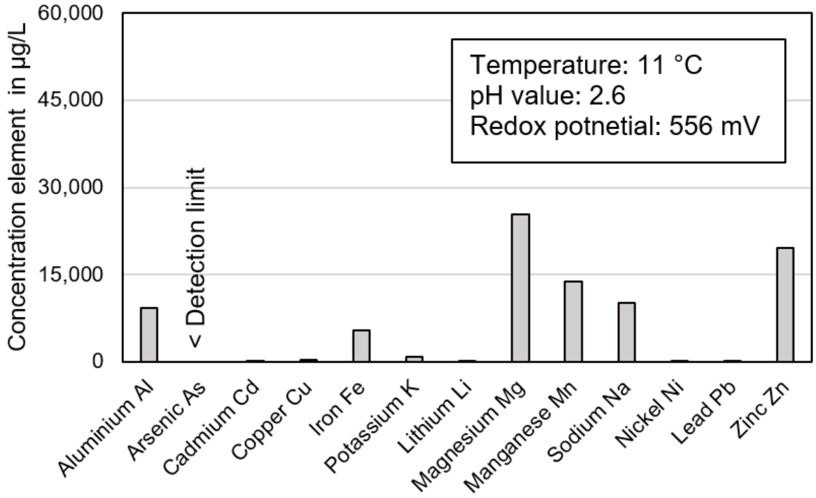

Figure 7 Characteristics of the mine water storage basin (cooling side)

Given these hydrochemical settings, two different heat exchanger configurations were tested during the experiment. On the source side (mine water is cooled by heat extraction), the heat exchanger was fitted with 17 uniform plates of the reference material (AISI 316 = X5CrNiMo17-12-2) to determine if plate positioning influences the deposit amounts. This was to ensure that the results of the other planned tests (with variable materials) could be used to compare the surfaces without a correction factor. In addition, eight pairs of plates with different materials / coatings (reference material, two stainless steels, five coatings) were tested on the storage side (cooling mode: mine water heated by heat supply).

The results in Figure 8 show that plate positioning in the heat exchanger alone is not relevant, i.e., it does not indicate any tendency related to the deposit amounts. It is therefore possible to compare the results for the formation of deposits on the different surfaces without the need of a correction factor. At the test site, the deposits in the heat exchanger at the mine water heat source result in an average reduction in transferable heat flow of 24%.

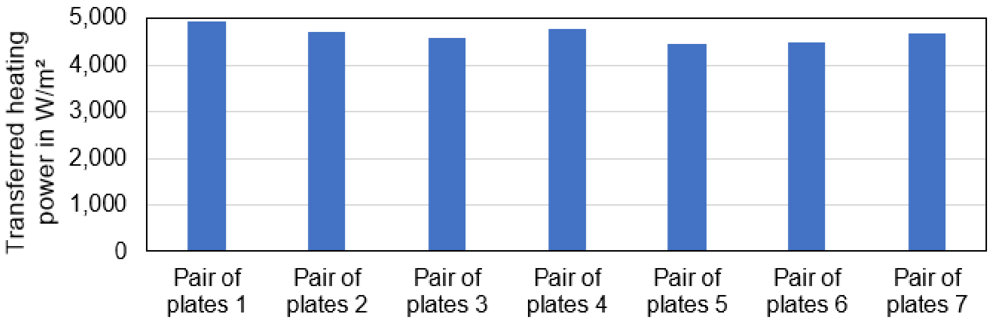

Figure 8 Transferable heat output per plate pair via the heat exchanger (mine water heat source)

The anti-biofouling coatings, the PTFE coating, the stainless steels and the reference material are at a similar level for the different materials on the mine water storage basin side (see Figure 9). NiMo16Cr15W performs best, with deposit thicknesses on this material being ~ 10 % less than on the reference. This represents a relative improvement of 22%. The chitosan coating performs best, with deposits on this material being 29 percentage points lower than on the reference material, a reduction of 67% compared to the standard material. The GPTES-ZV coating (also based on chitosan) performed considerably worse than the reference material, with 15% more deposits forming on it compared to the reference material. It was found that the coating did not adhere to the plate, came off, and mixed with the deposits as the test progressed. The average reduction in transferable heat flow was 40%.

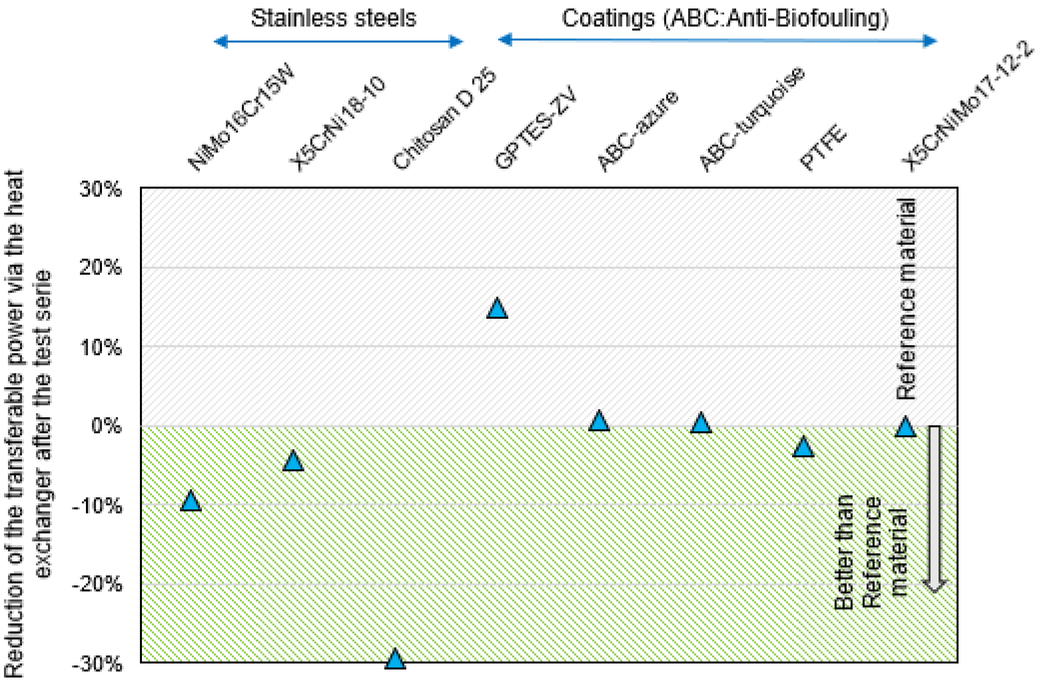

Figure 9 Results of the test series for the different materials in the heat exchanger on the storage side (mine water storage basin)

An analysis of the fouling deposits on the plates is shown in Figure 10. It can be seen that the deposits in both waters are dominated by iron, with mine water 1 (heating side) also containing aluminium, arsenic and zinc. Note the logarithmic scale on the ordinate; the iron content of mine water 2 (storage basin) is more than 5 times higher than that of mine water 1 (heat source). Most of the other elements are below the detection limit. Note also the Bal value, which is also above 400,000 ppm for both. Bal stands for balance and is the sum parameter for all non-measurable elements. A high Bal value indicates, among other things, a high amount of organic matter (biofilms, etc.) in the deposits.

In summary, the test clearly showed that deposits quickly formed both in the heat exchanger on the storage side and in the other water used as the heat source for the test (test duration 2 months). This led to a reduction in the transferable heat flow of 25% (mine water source) and 39% (mine water storage).

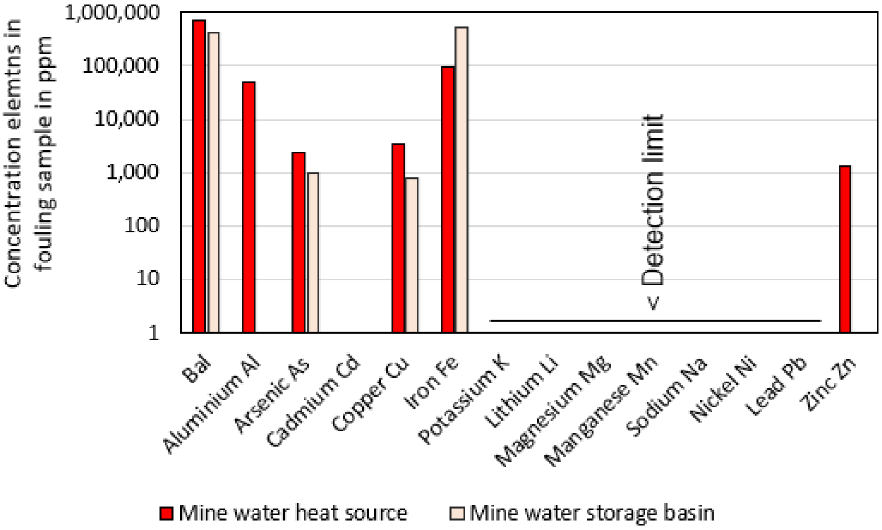

Figure 10 Results of the solids analyses of the deposits in the heat exchangers

Combination of storage potential and energy requirements

In addition to simulations and experiments undertaken for the underground storage situation, the study is also investigating the above-ground energy situation. Here, key issues are the availability of potential consumers and the possibility of using geothermal energy for heat storage. Using the example of Freiberg, the MineATES project is analysing which districts could be suitable for a combination with mine water heat storage.

The following criteria have been defined for the selection of suitable areas:

- Number of significant heat consumers ≥ 5
- Heat demand density > 30 KWh/(m²a)
- Annual heat demand > 10 GWh/a

Based on these criteria, preferred areas (named F1 to F4) were identified for Freiberg, as shown in Figure 11 (left). The methodology used to determine the heat demand and related results are described in Wenzel et al. 2024 and Heinrich et al. 2024

Four possible sources were considered in order to estimate possible heat quantities for storage:

1. solar thermal potentials in the study area, in particular solar thermal roof potentials
2. cooling demand per building for residential and non-residential buildings,
3. industrial waste heat potential from industrial operations, in particular from the metal, food, glass and paper industries, and
4. surpluses and shortfalls of renewable electricity volumes, particularly from photovoltaics and wind

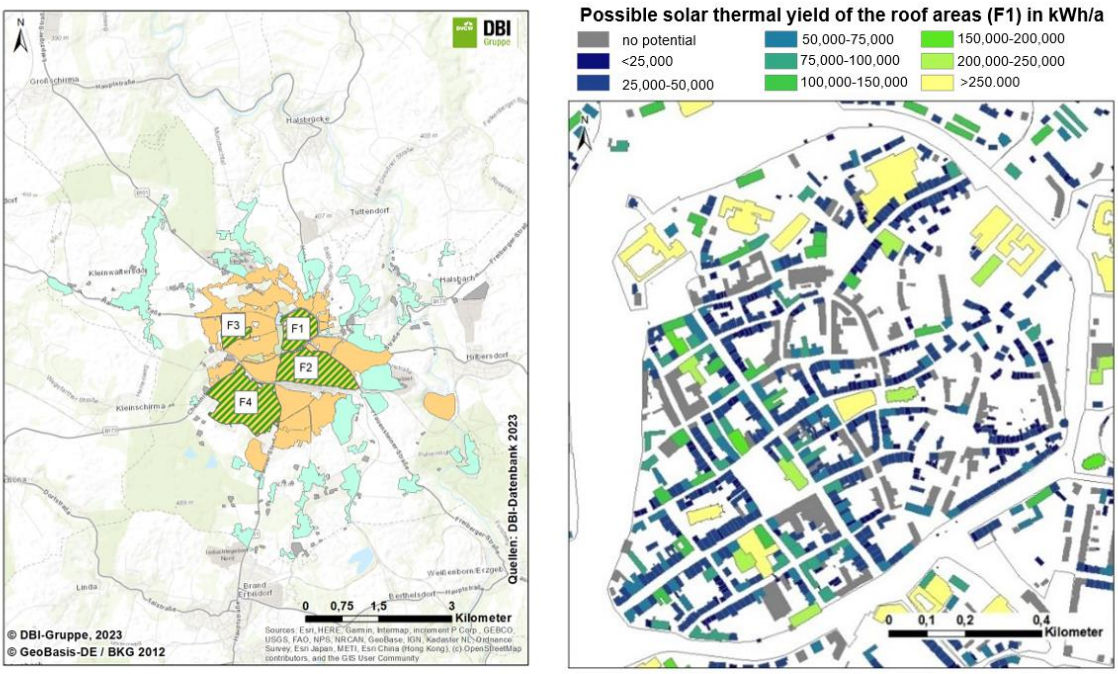

Figure 11 Characterisation of the Freiberg site according to the criteria for the energy situation (left) and results of the calculation of possible solar thermal yields on the roof areas of preferred area 1 (F1)

Figure 11 (right) shows the solar thermal potential for the selected city centre district (F1). Theoretical solar thermal potential would be available particularly for the large roof areas of school buildings or a shopping arcade. It was assumed that 50% of the roof area could be used due to its orientation and that 75% of this 50 % would be used. For the example district F1, this would result in a theoretical solar thermal yield of ~ 46 GWh / a, which could be used directly or stored in a potential mine water heat storage tank in case of surplus. Theoretically, therefore, the entire annual heat demand of the district (44.25 GWh) could be met from renewable sources via the solar thermal system in combination with an ideal mine water heat storage tank (efficiency = 100%). In addition, this analysis has not yet considered how the required output could be provided by storage. However, in addition to solar thermal energy, there are the supplementary energy sources described above, e.g., the cooling requirements of the buildings in summer. The heat that needs to be dissipated in the summer could also be temporarily stored in the mine water reservoir for the winter. The city centre (F1) in particular offers potential for cooling buildings due to the presence of the shopping arcade. Outside the city centre, there is also waste heat potential from industry. This can be used in the other districts if necessary. However, the actual use or extraction of this theoretically available heat is problematic. In the case of surpluses resulting from the curtailment of renewable electricity, storage in heat storages (e.g. MTES) is always in competition with other uses for the renewable electricity, such as hydrogen production.

Nevertheless, it is clear that there are quantities of heat available that can make a conspicuously contribution to decarbonising the energy supply if seasonal storage is possible. Even if only the waste heat (7.5 GWh / a) from summer cooling and half of the theoretical solar thermal potential (23 GWh / a) were stored, district F1 could be supplied with 58% renewable heat with a storage efficiency of 50%. Without storage, but with the same level of solar thermal expansion stage, the district could be supplied with 40% renewable heat. Only 4% of the heat dissipated by the building cooling system could be used.

Conclusion and summary

As part of the MineATES project, two heat injection and two heat extraction processes were carried out in a partially flooded mine. Both simulations and experiments show that efficiencies in the order of 50% are possible. The simulations show a relatively large influence of fractures on the amount of heat that can be stored and the storage efficiency. The practical storage tests were influenced by a flow through the storage tank, which meant that the planned maximum temperature could not be reached. In order to achieve higher temperatures in further tests, a heating rod was added to the setup to heat the tank with an additional 8 kW in addition to the heat pump. From the initial tests on the heat exchanger, it can be concluded that there is a problem with fouling at the Freiberg site (-24 and -40 % transferable heat output over the test). The fouling is evenly distributed throughout the heat exchanger. The positioning of the plates has no effect. Tests with different materials in the heat exchanger showed that a chitosan-based coating is recommended for the storage tank.

An analysis of the surface structure for the Freiberg site shows that four preferred areas would be suitable for the integration of a mine water heat exchanger. The detailed analysis of the city centre district shows that the storage facility would increase the regenerative share of the heat supply by 18 %, but this value is also highly dependent on the sources considered and the assumptions made. Overall, it can be seen that different (waste) heat sources are needed to achieve considerable storage volumes. Currently, the heat demand at the considered sites is still conspicuously higher than the cooling demand, so that storing the waste heat only for cooling in summer does not have a major impact on the heat supply in winter.

Further storage trials are currently being carried out at Reiche Zeche in-situ laboratory in Freiberg. At the same time, comparative tests are being carried out at the Ehrenfriedersdorf and Annaberg-Buchholz mines. The results so far show that heat storage in mine water can play an important role by increasing the regenerative share of the heat supply and that the technology works in principle. Depending on the location, the components that come into contact with mine water, such as the heat exchanger, are subject to high chemical loadings, for which technical countermeasures need to be developed. In addition, it is necessary to further analyse which existing and which upcoming heat potentials can be used and tapped for storage, respectively.

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