Large rock caverns for heat storage in district heating networks – A comparative study for the city of Salzburg

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ABSTRACT: Large heat storages play a key role for the implementation of renewable energy and industrial waste heat in heat distribution networks. One option is to use underground space for large heat storages. In this paper a case study for large underground heat storages in the heat distribution network of Salzburg is presented. Possible locations for large underground heat storages along the existing heat distribution network were identified, also based on the geological conditions. Two locations were selected and the temperature distribution in the underground around the heat storage cavern was numerically simulated using COMSOL with the aim to determine the energy losses and the temperature change at the ground surface. The results showed that the energy losses can be reduced considerably by >70% compared to insulated steel tank storages and that the surface temperatures are not much influenced by the heat storage below.

Keywords: heat storage, rock cavern, shaft, numerical simulation, energy losses.

1 INTRODUCTION

For the incorporation of additional large heat storages into existing heat distribution networks, certain criteria shall be fulfilled:

- The storages need to be located close to the existing heat distribution network to minimize (a) construction costs for new pipelines and (b) heat losses along pipelines during operation.
- The storages need to be located close to the heat generators and/or large diameter distribution pipelines to allow for high load capacities.
- To avoid heat exchangers between the network and the storage, which cause energy losses during operation and which are costly and frequently to refurbish, the heat storages need to be at a defined elevation to allow for the appropriate pressure and back-pressure in the heat distribution network. For the case of Salzburg the "zero" pressure elevation is at around 412 m asl. (depending on the location in the network) and the maximum excess pressure in

in the range of 35 m. Hence, the top of the storage cavern has to be at a level of app. 447 m asl.

- The cavern should have a competent rock overburden of at least 100 m to (1) reduce heat losses and temperature effects on the surface and (2) to minimize support by activating rock strength.
- The access tunnels to the caverns shall be as short as possible to reduce construction costs and the access should be located along an existing road in order to minimize costs and effects to the surrounding nature.
- Furthermore, nature deserving protection such as springs and other protective nature should not be located above and close by the location of heat storages.

Based on these boundary conditions, four locations were identified in and around Salzburg. The existing heat distribution network together with the heat supply stations is shown in Figure 1(a). In Figure 1(b) is the geological map of that area shown and the four locations identified are marked.

2 LARGE HEAT STORAGES IN ROCK CAVERNS – CASE STUDY SALZBURG

The four locations identified in and around Salzburg have significant different characteristics:
Location 1-Gaisberg (Fig. 1b) is located in a high mountain close to the city. However, neither the heat distribution network nor the heat supply stations are close by. Hence, this location, although close to the city and in massive Dolomite and Chalkstone (Dachsteinkalke), has some disadvantages.

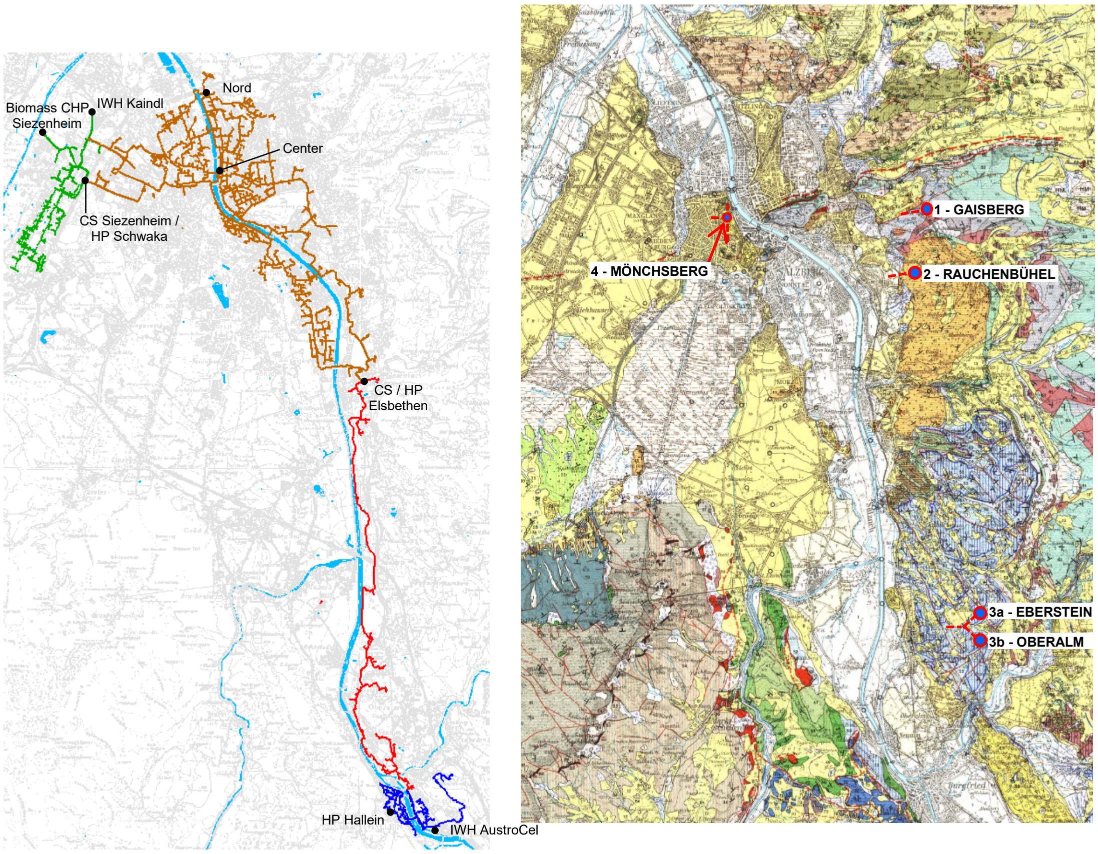

Figure 1. (a) Heat distribution network and heat supply stations of Salzburg AG in Salzburg and Hallein. (b) Geological map of Salzburg and Hallein with the location of potential heat storage caverns.

Location 2-Rauchenbühel is south-east of the city centre along the heat distribution network. The short access tunnel of around 800 m length passes through conglomerates (Gosau-Gruppe) and the storage caverns are located in chalkstone (Scheibelbergformationen) with an overburden of around 170 m. The elevation above the caverns is at around 620 m asl. From the technical point of view this is a good option, however, the location is in far distance to the heat generation stations and the traffic for construction works passes through living areas.

Location 3 is due to geological opportunities split into two options: **3a-Eberstein and 3b-Oberalm**. Chalkstone is already at the surface and with a short access tunnel of around 500 m the caverns can be situated and have already a rock overburden of around 250 m. This location in the south close to heat providing industry is also ideal from the operational point of view, the heat provider is an industrial company providing waste heat to the network which has needs for storage. The access area is an industrial area close to the highway and national road. And the geology allows for two locations e.g. a 1st phase and a 2nd phase of storage construction. Hence, this is selected as the ideal location in the surrounding of the city and is further discussed below. The proposed storage geometries and corresponding heat losses calculated are presented in Messerklinger and Smaadahl (2023).

Location 4-Mönchsberg is located in one of the two „city-mountains" of Salzburg, the Mönchsberg, which is the central mountains around which the city was developing and growing. Hence, this storage would be very central. However, the access to construction site is correspondingly difficult and the mountain is built of conglomerate rock which is not that competent. Due to the limited space and an overburden of only around 40 m (ground elevation of around 485 m asl.; top of storage cavern: 447 m asl.), for this location an additional storage geometry was developed and simulated with respect to heat losses. The results are presented below.

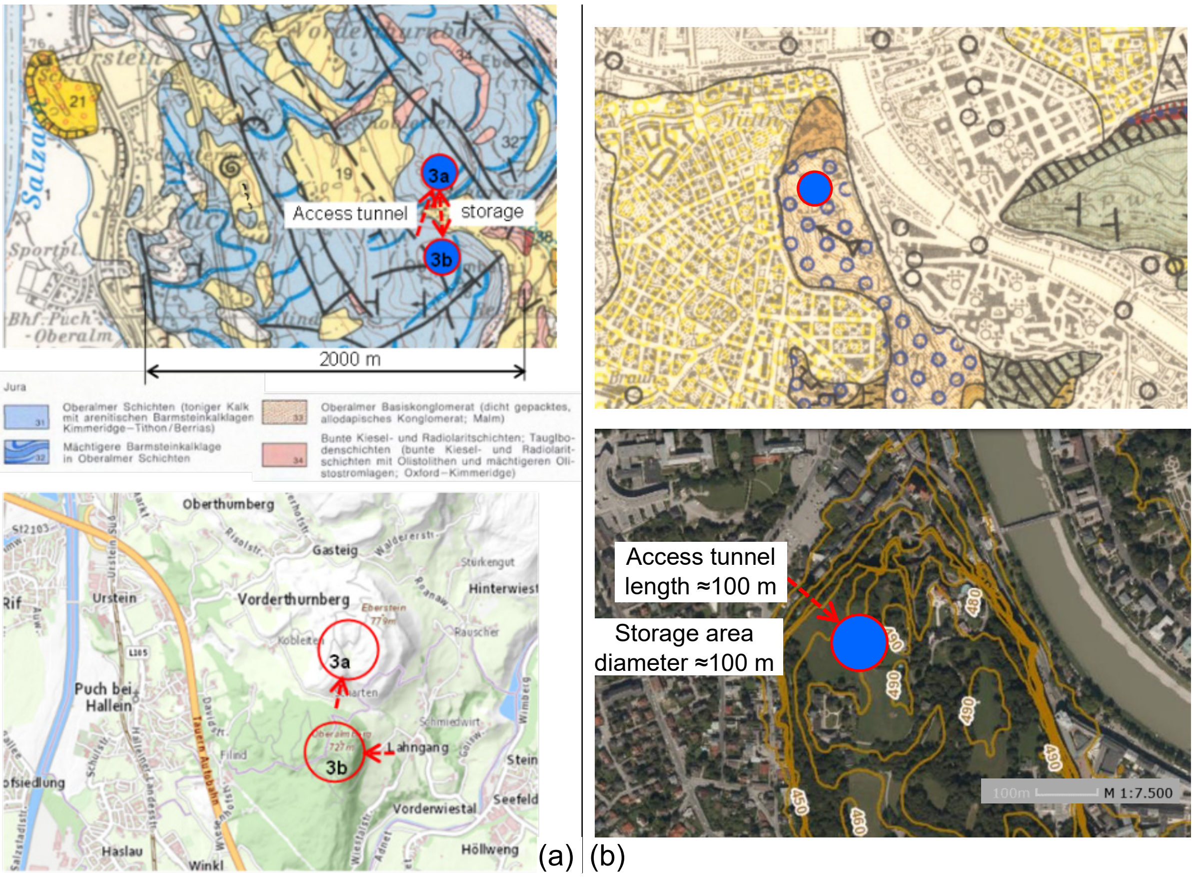

Figure 2. Selected storage locations: (a) 3a-Eberstein and 3b-Oberalmberg; (b) 4-Mönchsberg; top pictures: geological maps (from Geologische Bundesanstalt) bottom pictures: map of the area from SAGIS.

3 HEAT LOSS SIMULATIONS FOR THE LOCATION 4-MÖNCHSBERG STORAGE

The location Mönchsberg is a special case because the overburden for a cavern located within the pressure limits of the heat distribution network is only around 40 m. Hence, a separate model was developed with 4 large shafts of 18 m in diameter and 80 m in height for the heat storage and the surface of the Mönchsberg mountain which is approximated by a truncated cone as shown in Fig. 1.

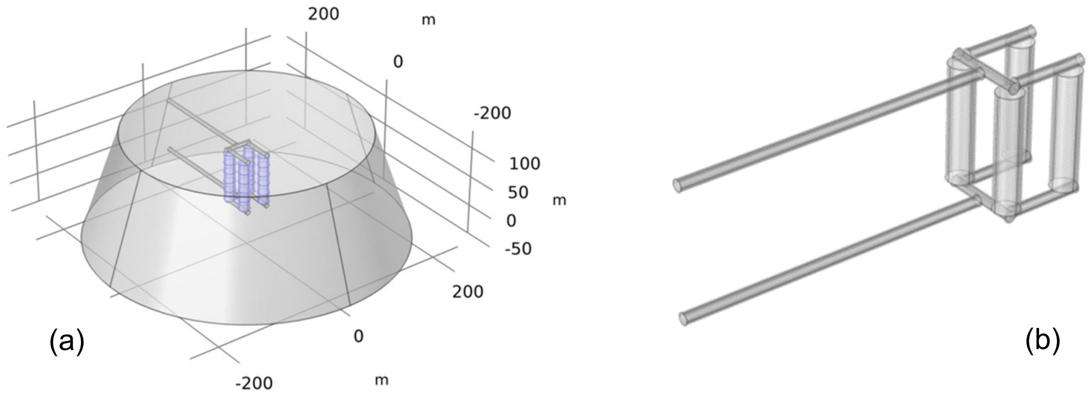

Figure 3. Geometry of the simulation model: (a) geometry of the Mönchsberg with the heat storage inside. (b) geometry of the four shafts of 18 m in diameter and 80 m in height.

COMSOL was used for the numerical simulation of the heat distribution in the rock surrounding the caverns over 100 years of operation. The heat conductivity coefficient λ of the rock was varied between 2.6 and 3.6 W/(m*K) to account for the variation in geology. The temperatures in the heat storage tanks were based on the principle of stratified storage. In the lower area (metres 0 - 32) 55°C and at the top (metres 48 - 80) 97°C. In the middle area (metres 32 - 48), a sinusoidal convergence of the two layers was assumed as the annual course: $T(t) = 21*\sin(2\pi*t[1/a])) + 76$ [°C].

The rock temperature was initially defined as 8°C. The ambient temperature was defined as a sinusoidal curve with an annual average temperature of 8°C and an amplitude of 20°C. The emissivity ε of the surface was assumed to be 0.88 and the heat transfer coefficient h with 20 Watts per square metre Kelvin.

At site 4-Mönchsberg, due to the low cover of the reservoirs, the temperature increase near the surface is a challenge and was also red out from the simulations (Tab 1 and Tab. 2). To minimise the temperature increase in the rock, the use of thermal insulation was investigated. Polystyrene extruded foam with a thermal conductivity λ = 0.04 W/(m*K) was assumed as the insulation material. In the realisation, the material and the insulation thickness can deviate, as only the thermal resistance of the insulation layer is decisive and not its geometry. These investigations were numerically simulated for the thermal conductivities 2.6 and 3.6 W/(m*K) to cover a wide range of rock types.

Table 1. Temperature increase in the subsurface of the Mönchsberg after 100 years (**λ = 2.6 W/(m*K)**).

Depth under Surface		2.5m	5m	10m	20m
No Insulation	K	1.89	3.90	8.00	16.69
0.3m	K	0.91	1.84	3.94	8.92
0.4m	K	0.76	1.52	3.30	7.59
0.5m	K	0.63	1.28	2.81	6.58

Table 2. Temperature increase in the subsurface of the Mönchsberg after 100 years (**λ = 3.6 W/(m*K)**).

Depth under Surface		2.5m	5m	10m	20m
No Insulation	K	2.17	4.11	8.07	16.45
0.3m	K	0.80	1.58	3.36	7.65
0.4m	K	0.76	1.52	3.30	7.59
0.5m	K	0.63	1.28	2.81	6.58

The Figure 4a shows the distribution of temperature increase in the rock above the cavern. The simulation results show that the thermal conductivity of the rock has not a great influence on the temperature increase on the surface. This is possibly due to the large influence of climate and hence the air temperature on the surface to the surface near rock.

The use of an insulation layer at the surface of the heat storage cavern has a strong positive influence on the temperature in the rock. Thus, the potential negative influences on the environment can be minimised. In addition, the insulation significantly reduce heat losses.

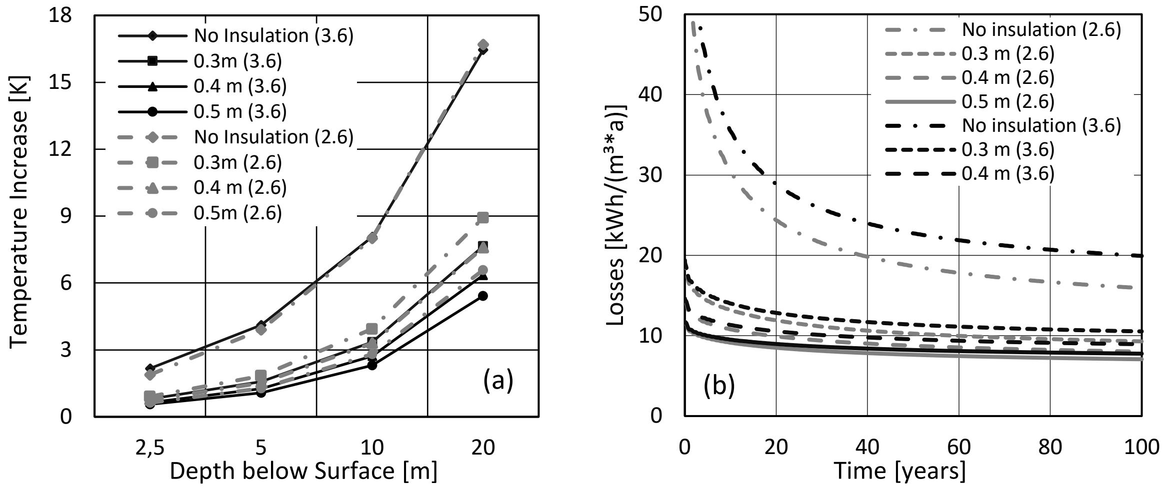

Figure 4. (a) Temperature increase in the rock above the heat storage after 100 years of operation. (b) Annual heat losses from the storage cavern in location 4-Mönchsberg – sensitivity study on the effect of insulation.

For the Mönchsberg location the energy losses of the heat storage were calculated directly using the heat fluxes normal to the surface of the reservoir (Eq. 1 and 2).

$$q'' = \int q''\, dA \qquad (1)$$

$$Q = \int q\, dt \qquad (2)$$

With: q'' Heat flux [W/m²]; q Heat transfer rate [W]; A Storage tank surface [m²]; t Time [s]; Q Thermal energy [Ws]

The simulation results of the heat losses (Fig. 4b) show, that without insulation, the annual losses decrease to around 10 kWh/year after 20 years of operation. With already 0.3 m of insulation at the surface of the storage the annual losses can be reduced by approximately 45%. A further increase in insulation thickness does not significantly reduce the annual heat losses anymore.

4 HEAT LOSS SIMULATIONS FOR THE LOCATION 3 STORAGE: 3A-EBERSTEIN AND 3B-OBERALM

At site 3, three geometries for the heat storage caverns were simulated (Fig. 5). The numerical simulations of the caverns in the rock were performed, assuming that the overburden at that site is high enough that the heat propagation over 100 years is not affected by the rock surface. Thus, the thermal energy losses ΔQ could be calculated with the energy increase in the rock (Eq. 3).

$$\Delta Q = \Delta\theta * V * c_p * \rho \qquad (3)$$

With: $\Delta\theta$ Change in temperature [K]; V Volume [m³]; c_p Heat capacity [J/(kg*K)]; ρ Rock density [g/cm³]

Figure 5 shows the annual energy losses of the three different storage geometries for two different thermal conductivities of the rock (λ = 2.6 and 3.6 W/(m*K). The selected thermal conductivities cover the upper and lower limits of the rock types likely to be encountered in Salzburg.

The annual thermal losses are higher at the beginning of operation and reduce over the time. Thus, a thermal storage in solid rock becomes relatively more efficient the longer its lifetime. This is due to the heated rock, since the temperature gradients become smaller and smaller over time. The thermal conductivity of the rock has a significant influence on the heat propagation in the rock, which has a long-term effect on the temperature gradients.

The comparison of the heat losses for the three geometries shows, that for the four big shafts the annual losses after 100 years of operation are approximately 56 % lower than for the Helix.

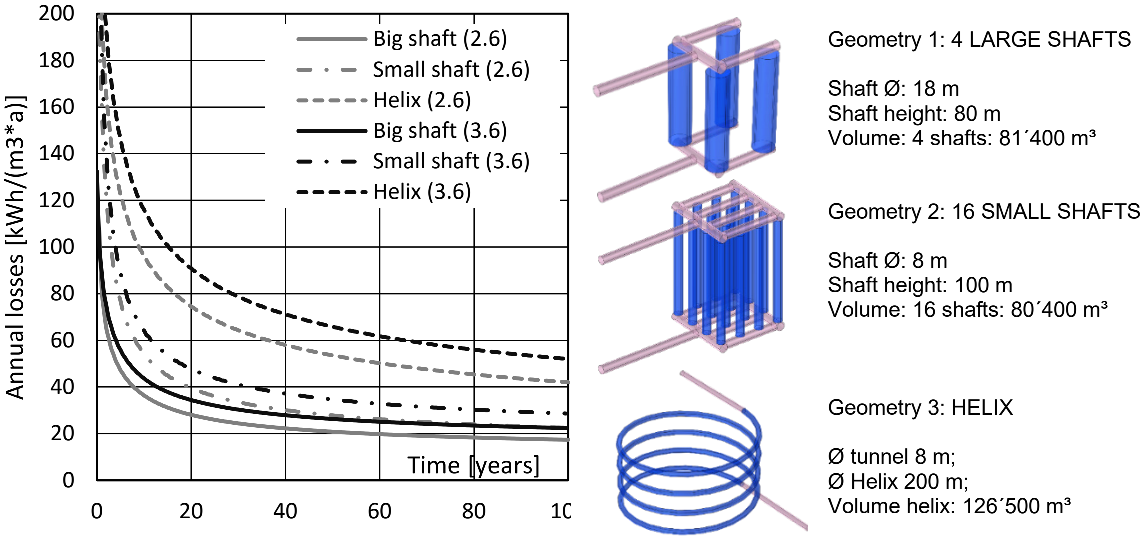

Figure 5. Heat losses of the storage over 100 years of location 3-Eberstein and Oberalm.

5 SUMMARY AND CONCLUSIONS

The city of Salzburg has great potential to further expand its district heating network and contribute to the energy transition. For a smooth energy supply by means of surplus energy and industrial waste heat, heat storage facilities play a decisive role. As a space-saving and durable solution, thermal water storage in solid rock were identified at four locations. Due to their longevity, the costs and efficiency of storage facilities can be optimized. In rock, energy quantities can be stored that are difficult to achieve in open-air storage facilities. Thermal losses and the heating of the rock can be minimized by installing thermal insulation. Hence, large heat storages in rock caverns can play a key-role in large heat storage facilities for the energy transformation of heat distribution networks.

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