# VESTA Malm – high temperature ATES in the Malm reservoir of the greater Munich region

**Thorsten Hörbrand[1], Maximilian Mayr[1], Kilian Beichel[1], Wolfgang Lex[1], Thomas Jahrfeld[1]**
SWM Services GmbH

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**Abstract**
Energy storage is one of the key challenges of the energy transition. This applies particularly to thermal energy, where demand is subject to large seasonal fluctuations while effective storage is challenging. Seasonal thermal energy storage makes surplus energy from the summer months available in the cold season where heat demand increases. Thermal storage is essential to expand geothermal usage from base load towards peak load in metropolitan areas. The VESTA Malm project aims to overcome the challenges of very high temperature heat storage in reactive carbonate formations. The aim of this project is to prove the technical feasibility for the realization of a demonstrator project in the metropolitan area of Munich. The key challenges of this project are: (1) To find suitable treatment methods to prevent formation damage due to precipitation of carbonate minerals from the injected brine. (2) To improve the recovery of stored heat in a karstified aquifer with irregular porosity distribution. (3) To provide an economically optimized well configuration setup, which respects the demands from production engineering (e.g., frequent pump changes) (4) To provide a concept on how to supply the necessary temperature to the heat storage project and how to integrate it in the existing district heating network.

## 1. Introduction

The South German Molasse basin is one of the most favourable geothermal regions in Germany due to the presence of the prolific Upper Jurassic Malm Aquifer. In the Munich city area, its top of the aquifer is found at depths between 2000 – 2800 m with reservoir temperatures of 80 °C – 110 °C. The aquifer extends to the south towards the alps, where temperatures reach grater 140 °C at a depth of more than 4000 m. In the Greater Munich region, there are to date 18 operational projects with > 40 wells. They typically yield 50 l/s – 120 l/s and are therefore perfectly capable to supply municipal district heating networks with geothermal energy.

With ongoing geothermal development in the German Molasse basin, base load in the district heating network of Munich will in the foreseeable future be covered by geothermal energy and waste incineration. To further expand the supply of geothermal energy into average and peak load of district heating, heat storage must be considered. While it is generally possible to operate classic geothermal doublets only for average and peak load, this is not an optimized concept, as the wells are not used during base load times. A HT-ATES (High-Temperature-Aquifer-Thermal-Energy-Storage) can bridge the gap between average and peak load. During summer, excess heat, which would otherwise be lost, is stored in the Malm aquifer. During winter, this storage is then depleted allowing for a higher energy output during peak demand. The typical storage temperature for the HT-ATES in the Munich region ranges from 100 to 140 °C. The maximum temperature is limited by the temperature of an existing steam network, which serves as a high temperature heat supply source.

The storage potential for one HT-ATES in the greater Munich region is in the order of 5-35 $MW_{th}$., which amounts to 20 – 150 GWh per year if the ATES is producing for 6 months per year. It depends on the production rate of the ATES and the temperature delta during recovery (Figure 1).

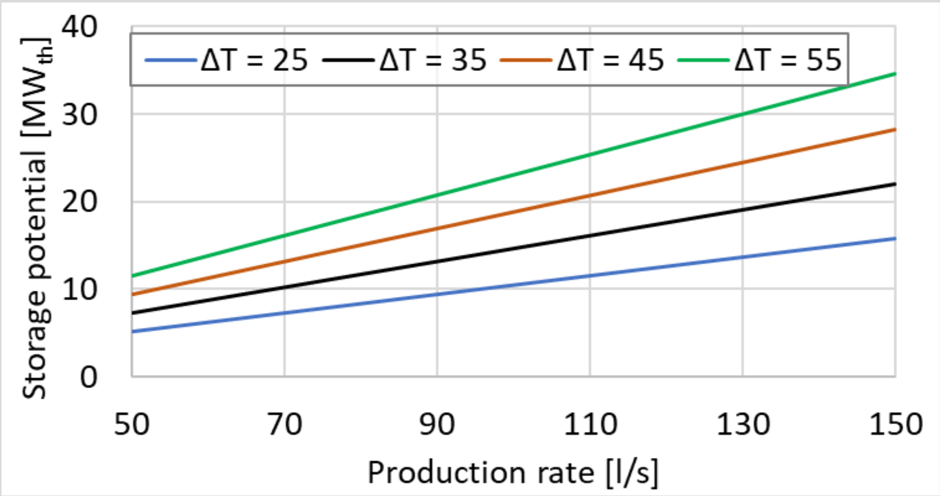


Figure 1: Storage potential (heat) of an HT-ATES in the Munich region, depends on production rate and the temperature delta between recovery temperature and reservoir temperature.

## 2. Challenges for a HT-ATES in the Malm Aquifer

### 2.1 Geology

The Malm aquifer in the South German Molasse Basin consists of Upper Jurassic carbonates, which are up to 600 m thick. The sequence is composed of alternating shallow marine limestones, dolostones and marls. They can be grouped into two facies associations: (1) massive (fossil-rich build ups) and (2) bedded facies (layered basin sediments) (Meyer and Schmidt-Kaler, 1990). The evaluation of data from numerous wells and analogue studies reveals a highly heterogeneous reservoir system in both vertical and horizontal directions. The hydraulic properties of the reservoir are controlled by multiple features, such as primary facies, diagenesis, fractures, faults and intense karstification.

Hydraulic evaluations of existing wells indicate that: (1) porous and partially permeable rock matrix provides the hydraulically active reservoir volume; (2) intense karstification plays an important role for a better connection of the boreholes to the reservoir matrix and is often responsible for the most productive inflow zones of a well. The karstifications are mostly strata-bound and thus generate a significantly higher horizontal than vertical permeability. Three preferentially karstified levels, each with a thickness of a few tens of meters, can be identified within the Malm aquifer. They appear to be karstified because of a combination of primary facies properties as well as the sequence stratigraphic framework (that places the paleo water table at these levels during post depositional sub-aerial exposure). It is assumed that each karstified interval has the potential to create a well interconnected hydraulic network that is better connected in an SSE direction.

In summary, the hydraulic properties of the reservoir are mainly controlled by the presence of porous and permeable rock bodies that are interconnected by intense strata bound karst networks.

### 2.2 HT-ATES well configuration

In contrast to classic geothermal doublets, Ueckert and Baumann (2019) developed a triplet concept for an ATES in the greater Munich region. This concept comprises three wells per ATES, which serve different purposes (Figure 2).

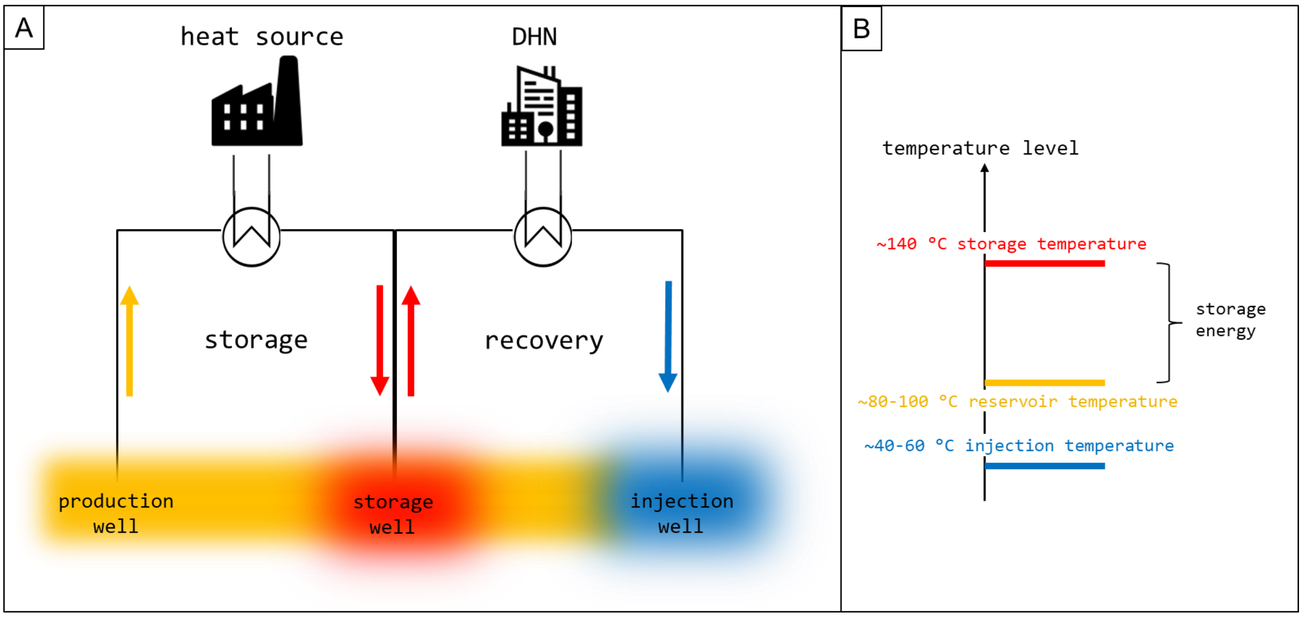


Figure 2: A: Schematic explaining the operating principle of a HT-ATES triplet. B: temperature levels of the triplets during operation. Only a part of the total energy is provided by storage

During the load cycle, the "load cycle production well (LPW)" produces water at reservoir temperature. This water is then externally heated and injected with temperature greater than reservoir temperature into the "storage well". During the recovery cycle, the storage well produces the water with temperature greater than reservoir temperature. The water is injected into the "recovery cycle injection well (RIW)". While the "storage well" is active in both cycles, the other two wells are only active during one of the two cycles respectively. The triplet concept has thermal and chemical benefits for the HT-ATES. Due to the fact, that the LPW has a higher temperature than the RIW, less energy must be supplied to reach the same storage temperature (or the storage temperature is higher in comparison with a HT-ATES doublet). The triplet concept can therefore energetically be seen as an "enhanced geothermal doublet", from which geothermal energy and storage energy is produced. The chemical benefits only hold true, if $CO_2$ is used for chemical inhibition, as it prevents the necessity to increase the rates of $CO_2$ injection after each storage cycle (see the next chapter for details).

Ideally, an ATES would be integrated in a multi-well project with e.g., 5, 7 or more wells. These mutli-well systems are the current default development plan for future geothermal projects of SWM, following the success of the Schäftlarnstrasse project with 6 wells from one drill site (Dirner, 2022). The integration into a multi-well system offers multiple benefits: The storage well can be selected among multiple wells and the most promising candidate for high thermal recovery coeffiecients based on geologic and geophysical logging can be selected. Furthermore, multi-well projects allow the bundling of injection streams, so that the LPW can potentially also be in operation during the winter season with the use of injection pumps. For example: in the 7 well scenario, which comprises one ATES and 4 additional wells (2 producers and 2 injectors), the LPW, the storage well and two further production wells (=4) wells can potentially inject into 3 injection wells with the use of injection pumps. This would allow a continuous operation of the LPW and further enhances the power output per capital expenditure.

## 2.3 Scaling and formation damage

For HT-ATES, minerals with retrograde solubility pose a high risk for scaling and formation damage (reduction of rock permeability in the reservoir). The reason for this behaviour is that the heating of the brine prior to reinjection perturbs the chemical equilibrium. From the retrogradely soluble minerals, only carbonates are relevant for mineral scaling in an HT-ATES in the Malm aquifer. The geothermal fluid is strongly undersaturated with respect to earth-alkali sulphates (anhydrite, gypsum, barite, celestite) and heating the fluid does lead to negative saturation indices in hydrogeochemical simulations with respect to those minerals. In contrast, severe carbonate scaling is expected when the brine is heated to the envisaged storage temperatures (delta > 20 K).

To deal with carbonate scaling, two different inhibition methods can be used. $CO_2$ inhibition was successfully used in a field test for an HT-ATES in the Malm aquifer (Ueckert and Baumann, 2019) and was further evaluated during the EvA-M and EvA-M2 projects (Broda et al., 2022). $CO_2$ acts as an acid, which lowers the fluid's pH and counters supersaturation of carbonates triggered by heating. The key challenge for $CO_2$ inhibition is the hardening of the fluid which is a result of dissolution when the conditioned water has been in contact with carbonate rocks in the reservoir. Hardening describes the process of increased amounts of dissolved Ca, Mg and $CO_3$ in the fluid due to carbonate dissolution. In an ATES doublet, the hardened water would be reproduced during the storage cycle. Due to the higher amount of dissolved carbonate species, a higher amount of $CO_2$ would be required for conditioning. After few storage cycles, the necessary amount would be too high to be economically and technically feasible. This problem can be avoided by using the triplet concept (Figure 2), where the conditioned water is permanently disposed of in the RIW.

An alternative concept for the inhibition of mineral precipitation is the use of polymeric inhibitors. In the research projects EvA-M and EvA-M2, the inhibitor NC47.1B was developed and tested specifically for use in geothermal doublets of the Malm aquifer. NC47.1B consists of polysaccharides and polyelectrolytes, which act as a threshold inhibitor, that prevents growth of microcrystalline precipitates. The efficiency of this inhibitor has been successfully verified in laboratory and field tests and is currently used in one of SWM's geothermal projects (Broda et al., 2022). To use NC47.1B for an HT-ATES, the degradation processes and the temperature distribution in the reservoir have to be better understood to exclude the possibility of formation damage.

## 2.4 Thermal recovery efficiency

Together with development capital and operating expenditures, the thermal recovery efficiency is the key parameter for economic feasibility of a HT-ATES. The thermal recovery efficiency ($R_T$) is defined as the ratio of heat energy recovered to heat energy injected and is always smaller than 1. Key parameters for the thermal recovery efficiency are the thickness of the permeable units of the aquifer (or net-to-gross porosity) and the density driven convection, which is induced by the difference in aquifer temperature and storage temperature. Convection is the dominant effect in highly permeable aquifers as the heat forms a plume at the top of the formation which can be hardly recovered. Therefore, thermal recovery efficiencies are usually lower for highly permeable formations than for low permeability formations.

The thermal recovery efficiency was evaluated for the Malm Aquifer in the GRAME project (Savvatis et al., 2018) using the simulation software ECLIPSE. Within this project, several well configurations, injection temperatures and permeabilities were tested for a homogenous aquifer parametrization. The results show that thermal recovery is high ($R_T$ = 0.66) when density effects are turned off in the simulation (Figure 3) and that the heat irrecoverably gathers at the top of the formation ($R_T$ = 0.09) in case the permeability is high and density effects are enabled (Figure 4). Both images show the heat distribution in the aquifer after the 40th annual storage cycle. The storage temperature in these scenarios was 57 K higher than the aquifer temperature.

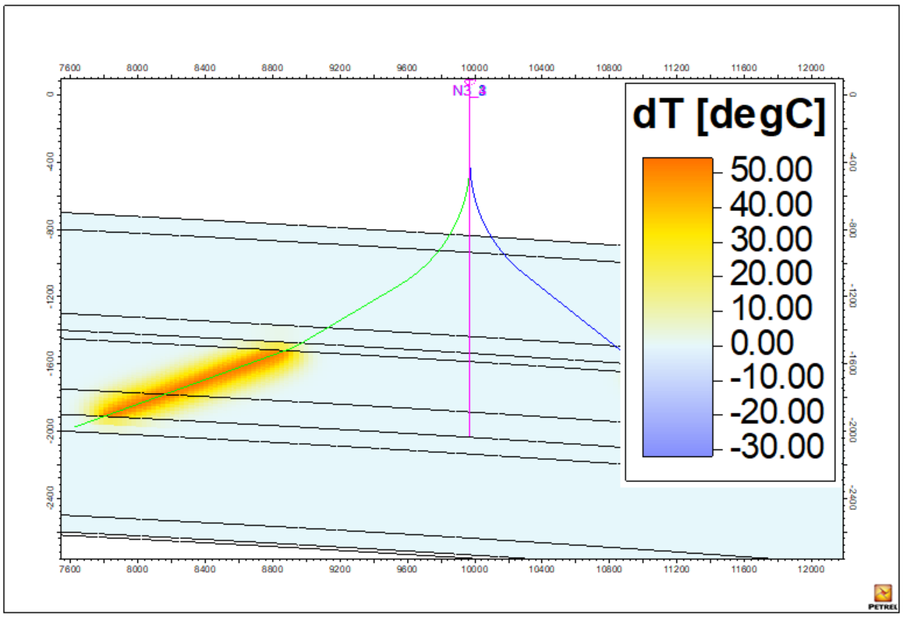


Figure 3: Heat distribution after 40 years in the aquifer when density effects are turned off.

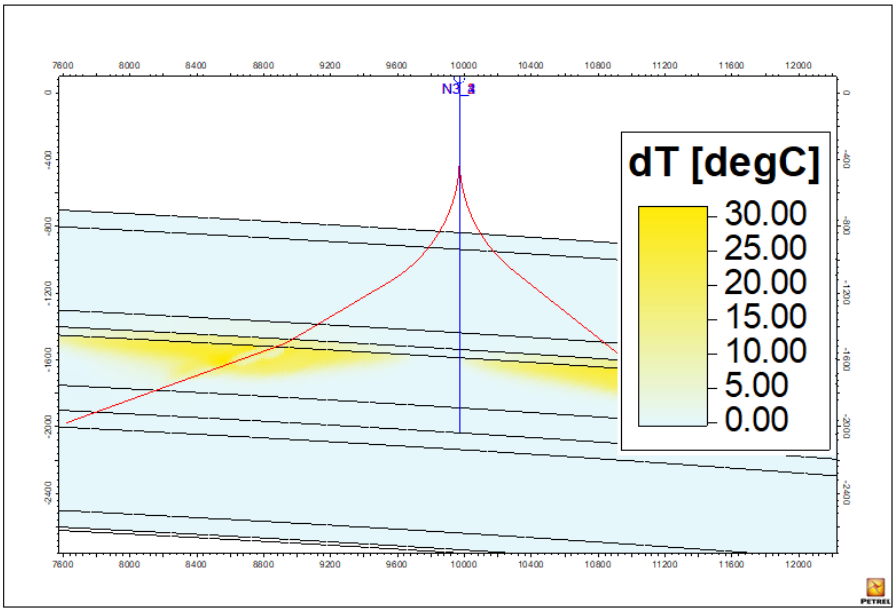


Figure 4: Heat distribution after 40 years in the aquifer when density effects are enabled, and permeability is high.

## 2.5 Techno-economic analysis

For the techno-economic analysis, a performance prediction (thermal output, electricity demand and coefficients of performance (COP)) of an aquifer storage system in the Munich area were simulated. These parameters are decisive for the economic efficiency of heat generation, as the heat production costs are the relevant factor for the integration of the plant in the generation park. The plant with the lowest heat production costs gets the highest operating time, etc. An overview of the process for the performance calculation is shown in Figure 5.

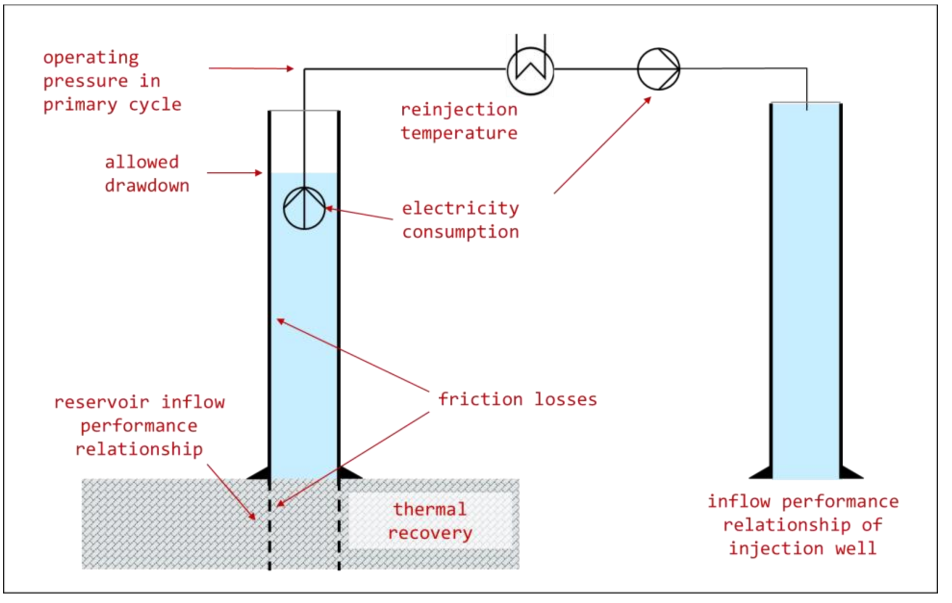


Figure 5: Overview of the model for the primary geothermal production cycle.

For the calculation, a site in the north of Munich was considered, which has an aquifer temperature of about 85 °C. The following conditions were applied:

- The temperature of the aquifer is about 85 °C and the injection temperature is 62 °C.
- The thermal recovery was set to 60 % and assumed to be constant throughout the withdrawal phase.
- Like the injection phase, the withdrawal phase lasts 6 months.
- The processes shown in Figure 5 were considered.

In contrast to a conventional geothermal doublet, where the COP is the thermal output ($P_{th}$) divided by the power consumption of the ESP ($P_{ESP}$) and the injection pump ($P_{IP}$), the calculation for the ATES must be modified. The ATES COP calculation considers the different energy expenditures during the loading and unloading phase. The COP is the thermal output ($P_{th}$) divided by the sum of the electricity expenses of the withdrawal phase ($rec$) and the injection phase ($store$).

$$COP_{tot} = \frac{P_{th}}{(P_{ESP} + P_{IP})_{rec} + (P_{ESP} + P_{IP})_{store}} \quad (1)$$

The ATES is compared with two conventional doublets at the same location (Figure 6). While the ATES consists of three wells, two doublets consist of 4 wells. The results of the performance prediction show that an aquifer storage with an injection temperature of 140 °C can provide a higher peak thermal output than two conventional doublets. In addition, the COPs of the ATES are significantly higher than the COPs of a double doublet. The strong dependence of the COPs on the flow rate results from the quadratic relationship of the drawdown (and thus the power demand of the electric submersible pump (ESP)) with the flow rate. The bend in the curve of the COP at about 65 and 110 l/s arises from the power requirement of an injection pump for injecting the thermal water, which is required at around 65 °C during hot injection (summer) and at about 110 l/s during cold reinjection (winter).

For medium and peak load coverage, the plant is running only a part of the year. For this demand situation, the performance forecast shows that an ATES may be better suited for supplementing the generation fleet, as it produces more energy with less wells than a conventional doublet in the same region. It has to be taken into account, that heat supplied for the storage cycle of the ATES is not “free of charge” and comes with an associated cost, which must be considered in further economical simulations.

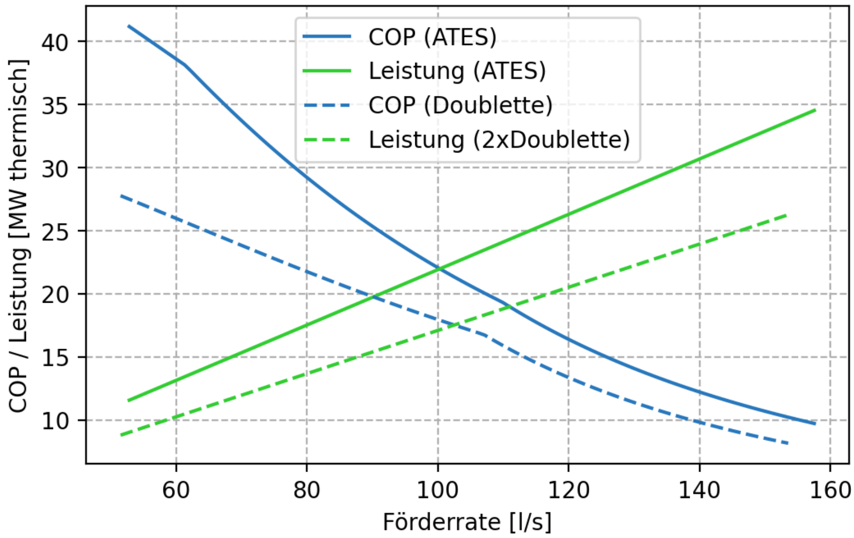


Figure 6: Thermal power (Leistung) in green and coefficient of performance (COP) in blue as a function of the production rate (Förderrate) in a region where the reservoir temperature is ~85 °C.

## 2.6 Integration into the district heating network

The search for appropriate locations for a HT-ATES is more complex than for other (geothermal or conventional) thermal power stations. In addition to factors like the restrictions of the underground reservoir, available drilling locations or the connection to the district heating network (DHN) with adequate capacity, there must also be a connection to the heat source with sufficient power and supply temperature. This usually requires the HT-ATES to be in a certain proximity to the heat source. Potential heat sources in Munich are: (1) Heat of the municipal waste-to-energy plants: As the municipal waste is processed all year round, the thermal energy output from the waste-to-energy plants is constant during the year. In the summer, with very low energy demand in the district heating network, the excess heat could be stored in a HT-ATES. This heat is supplied into a steam network with about 140 °C. (2) Excess heat of geothermal plants located south of the city of Munich (deeper reservoir with high temperatures > 130 °C). This thermal energy is planned to be transported to the southeast of the city of Munich via hot water pipelines. During summer there will be little demand for this energy source and excess energy could therefore be supplied to a HT-ATES. The temperature level would be about 130 °C. (3) Excess (waste) heat of CHP plants (e.g., gas turbines or combined cycle power plants). These power plants produce electricity and heat. While the electricity is still needed in the summer months, heat production in excess of the demand must be disposed of by using water from the Isar river as a cooling medium. This heat could instead be stored in an HT-ATES.

The district heating network in Munich consists of multiple different subnetworks. Each subnetwork has a specific temperature level and an individual load curve (Figure 8). The demand is seasonally variable and excess energy is only available in late spring and summer. With increasing base load coverage by geothermal energy, the excess energy window could potentially further expand into spring and autumn. However, thermal energy displacement is limited by the hydraulic capacity of the subnetwork connections. As an alternative to the proximity to the heat source, the ATES can also be placed in proximity to a high temperature DHN. Currently only the steam network in central Munich (dark green area in Figure 7) fulfils the high temperature criterion. The ATES must therefore be either located close to a high temperature heat source or somewhere in the proximity to the steam DHN. Based on these criteria, the ATES target region as shown in Figure 7 was identified.

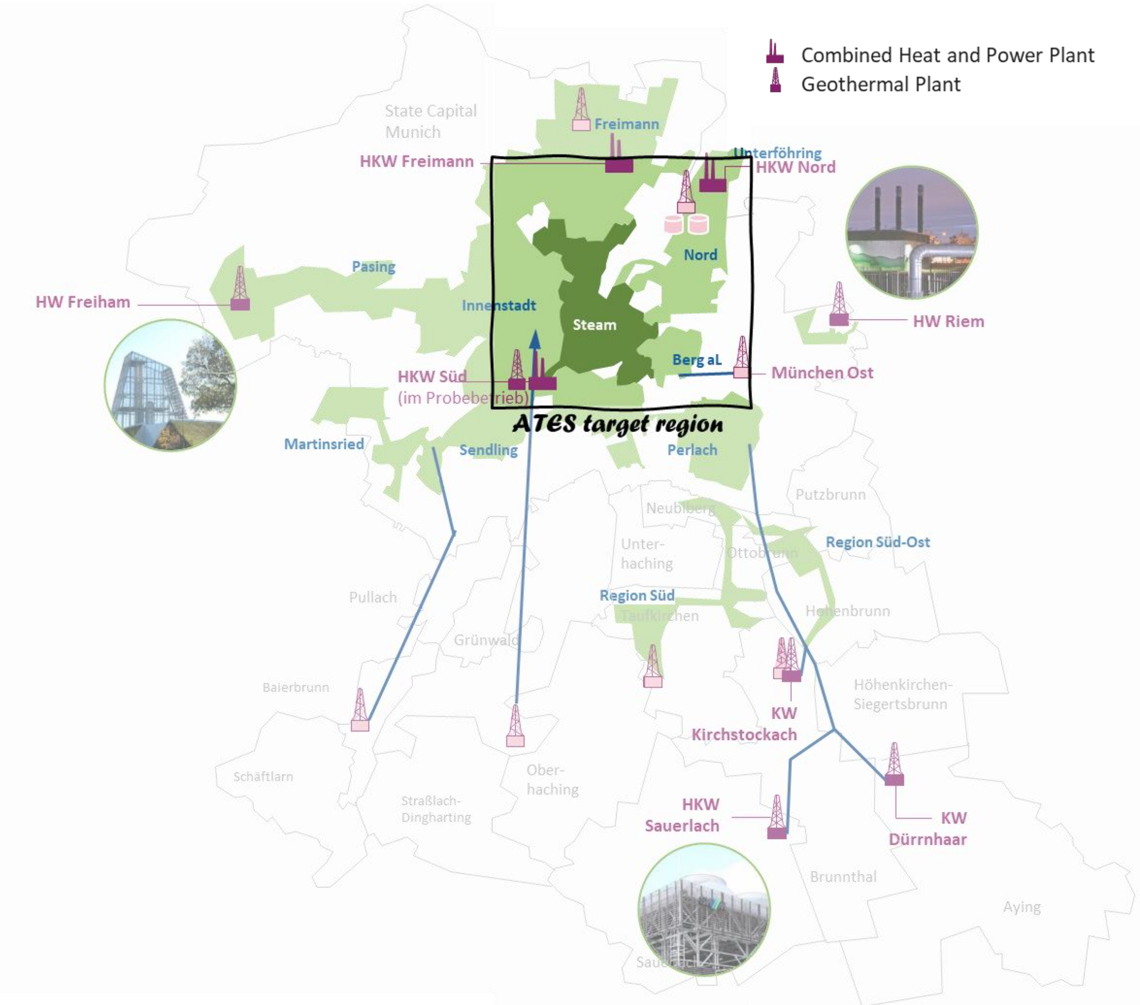


Figure 7: Geothermal development and district heating networks (green) in the greater Munich area. The target region for an ATES due to favorable reservoir conditions and proximity to the heat source is highlighted.

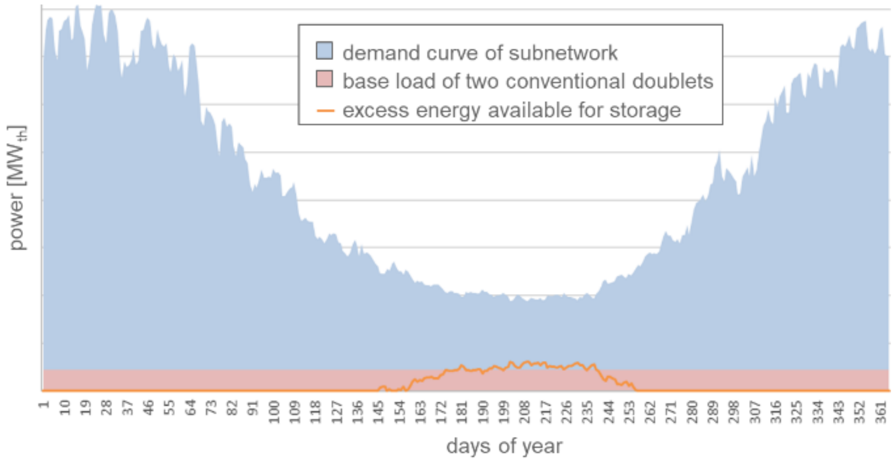


Figure 8: Exemplary demand curve of a subnetwork.

### 2.7 Production technology

Due to the favourable hydraulic conditions in the Malm Aquifer, production rates are generally in the order of 70 to 130 l/s. The initial water level of the wells is typically several tens to several hundreds of meters below the surface level as the reservoir pressure is below hydrostatic. These conditions require the use of electric submersible pumps (ESP) to achieve high production rates. Due to the mode of operation of a HT-ATES, two different wells have to be equipped with electric submersible pumps throughout one year (one storage cycle). Each change of the ESP is associated with high costs, which arise from downtime of the plant, labour, and crane/rig costs. In order to decrease the costs for pump changes, SWM GmbH together with Max Streicher GmbH developed a mobile workover rig (Barenth, 2019). The options for an HT-ATES are: (1) To regularly change the ESP and accept the associated costs. In this case, connectors for the production tubing must be selected, which reduce wear and tear of the connectors. (2) To install two ESPs (one in the storage well and one in the load-cycle producer). During the load cycle, the water would have to be injected past the ESP of the storage well and during the recovery cycle, the ESP in the load-cycle producer would not be used. For this option, the VESTA project aims to evaluate, whether it is feasible to use the pump as a turbine for generating electricity from the reverse rotation of the ESP.

Further challenges which affect all setups are the flexibilization of the production system. While operating the ESP at about 40 – 100 % of its load is generally feasible, the optimal storage setup would allow for quickly turning the storage well on and off. This is a major challenge, especially at temperatures in the range of 140 °C, where the ESPs and cables are often taking damage when being turned on and off. This vulnerability at high temperatures is attributed to the high temperature changes in the wellbore between the (hot) production state and the cooled off state when the well is idle.

## 3. Conclusion

The VESTA Malm project aims to find a solution for the challenges encountered by a megawatt-scale HT-ATES which must be integrated into the existing energy infrastructure of a large urban agglomeration. It aims to provide an integrated concept at selected pilot locations as an important step towards construction. To develop a concept for a HT-ATES, the following topics need to be addressed:

(1) exploration of the reservoir (geology)
(2) simulation of TH, THM and THC processes (reservoir engineering)

(3) construction of the wells (drilling engineering)
(4) wellbore hydraulics and production technology (production engineering)
(5) construction of a thermal power station (process engineering)
(6) long term operational safety of the plant
(7) integration/optimization of the use of an ATES in conjunction with the existing generation park
(8) economic feasibility

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SWM Services GmbH, Emmy-Noether-Straße 2, 80992 München
hoerbrand.thorsten@swm.de