# A guidance for the optimal site location of Cavern Thermal Energy Storage (CTES)

Stefan Zelzer
*Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria*

Thomas Geisler (corresponding author)
*Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria*

Thomas Marcher
*Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria*

ABSTRACT: The production of energy using CO2-neutral methods faces an additional challenge to conserve surplus energy over longer periods of time and to be able to use it when required. One possibility for meeting this challenge is the use of CTES (Cavern Thermal Energy Storage). These CTES store surplus heat in the form of hot water and preserve it for a desired period. Many cities feature the necessary rock formations to build and operate these CTES. For this reason, a guideline has been elaborated that combines the most important geotechnical parameters with the local rock mass conditions. In addition, this guideline pays special attention to the geometric dimensions since these have a significant influence on the stratification of water within the storage medium. It is possible to make a first selection of possible sites and to investigate them in more detail with this geotechnical guidance.

*Keywords: Thermal Energy Storage, Underground Heat Storage, Site Selection Criteria, Thermal Stratification, Suitable Rock Mass.*

## 1 INTRODUCTION

In order to achieve a balance between fluctuating, intermittent energy supply and the changing heat demand, sensible heat storage is suitable for short- and long-term storage applications. The sensible heat storage with hot water makes it possible to store large amounts of energy over long periods of time in order to take advantage of the demand for thermal energy. The aim of this paper is to create a systematic guideline, collect and process the most important parameters to find possible sites for underground storage structures in suitable rock mass. Underground engineered rock caverns with defined geometry and dimension enable the storage of energy. Today, there is no general applicable method to estimate the usability of possible storage sites. Scientific research papers focus on underground thermal energy storage systems, by targeting stability- and thermal performance issues as coupled analysis. These papers contribute to gaining an enhanced economical design of the structure, but only few papers, e.g. Matos et al. (2019), shed a light on the importance of the optimal location for the storage facility. The general layout of this paper gives an overview on thermal energy storage systems, especially for CTES. Followed by discussing the energy demand for district heating systems, the key parameters for the site selection will be evaluated and visualized. It should be noted that this guidance deals with engineered cavities, excavated predominantly in hard rock with different geometries to use water as the storage medium.

## *1.1 Classification of Thermal Energy Storage Systems*

There are many different technologies and types how energy can be stored in the form of heat. Besides the technological point on how to store heat, short-term energy storage versus long-term storage of heat is one possible way to classify storage technologies regarding storage duration. The duration of short-term storage on average refers to days and weeks, whereas the long-term storage cycle takes up a full year (seasonal storage). The storage periods, which consist of loading, standstill and unloading phase, highly depend on the thermal profile of the energy source and the consumer (Hauer et al. 2013). Apart from the storage duration and operation temperature level, there are three types of thermal energy storage technologies (TES) in general, which are sensible-, latent- and thermochemical-heat storage technologies in combination with a storage principle. Sensible storage technologies for thermal energy above the surface, e.g. water tanks, are established as short-term storage in the range of weeks. Seasonal storage of heat refers to large volumes, which can economically be exploited underground. Underground storage systems (UTES) comprise PTES (Pit Thermal Energy Storage), which are excavated primarily underneath the ground surface and CTES (Cavern Thermal Energy Storage) are constructed in solid rock formations (e.g. >100 m overburden). Since the development costs for the pipeline of a district heating system are costly (construction and integration of the new pipeline to the existing network), one of the main points for the determination of the location for UTES in general is the distance to the district heating system. This point is crucial especially for CTES, because a suitable location can usually be found outside the main supply paths of the district heating network. This geographical requirement for CTES is explained in more detail in chapter 2.3. PTES facilities are constructed at shallow depths, predominantly in soils and can compete with CTES in terms of storage volume. The construction in urban areas requires an appropriate sealing and insulation system, due to the thermal loading. A detailed report concerning PTES is given by van Helden et al. (2022). Yet, the applicability of storage technologies highly depends on the demand of the region and the typologies of the site location. Beside this, there are restrictions for UTES projects in terms of environmental compatibility, which predominantly relate to the surface requirement and the groundwater management during construction.

## *1.2 Cavern Thermal Energy Storage (CTES)*

Cavern Thermal Energy Storage (CTES) can be utilized for a range of applications, where the central point can be assigned to the geologic conditions, which highly influence the economical design and effectivity of a structure. The application of CTES is suitable for both, liquid and gaseous media. The storage of liquid media, e.g. water, is flexible by choosing a suitable location within the rock mass. A benefit CTES has, applies for the expandability of the storage system. Therefore, it is possible to excavate an additional storage unit to gain more storage volume if required. The flexibility of this storage type is one of the key factors to face the security of supply. PTES are yet to be favored in future times, since the research for PTES gains momentum. In southern Denmark, in Vojens, the world's largest PTES with approximately 200 000 m$^3$ storage volume is in operation, which has been constructed in 2014. With 30 €/ m$^3$ water equivalent, a benchmark has been set for large seasonal thermal energy storage systems, which is an optimistic value for urban regions with similar dimensions (van Helden et al. 2022). This is a crucial point when it comes to land consumption because the need of floating sealings is important to utilize the surface above the storage unit. By contrast to the principle of PTES, CTES completely uses the available rock mass to store energy in the form of heat. The thermal performance of the storage unit has a crucial dependency on the height to width ratio, which is defined by (Park et al. 2013) as the aspect ratio. More importantly and before the thermal performance should be evaluated, the stability issue of the cavern is the driving parameter for the feasibility of the project. The evaluation of geotechnical input parameters for the stability analysis must be checked carefully in order to achieve an uninterrupted excavation sequence of the structure itself.

## 2 GUIDANCE AND KEY PARAMETERS FOR THE CTES SITE SELECTION

The guidance in the present study gives a comprehensive review on the key parameters for the heat storage in suitable rock mass. With that, authorities can make a first estimation to localize the available sites and do a more precise analysis on the applicability of the site. The challenges for the site selection ranging from geographical aspects over geological, geotechnical issues and focusing on the environmental and economic compatibility. The result should be an engineered rock cavity for heat storage and to use renewable energy sources in line with the above-mentioned criteria.

### *2.1 Demand of domestic energy sources for TES*

In order to supply the renewable energy to the energy demand, the share of renewable and a decreasing share of fossil energy, growing energy storage capacities are also required (Biermayr et. al. 2021). The evaluation of the regional heat demand is a crucial point for the dimensioning of the storage system at firsthand. In accordance with future scenarios, e.g. increasing growth of human population, it is recommended that the energy storage system can adjust on these scenarios. In case of a new construction for underground storage system, it is also well-advised to have a flexible design in line with the available energy source. Austria’s final energy consumption for heating households and water amounts to 29% in 2020. In numbers this results in 72 TJ final energy consumption for district heating systems, where 85% of the energy is directly used for water heating. The distribution in district heating systems is achieved by pipelines, which have a total length of 5.600 km all over Austria. In 2030, the length may increase by 1.000 km. 50 % of the energy sources are related to renewable energy, which is supplied by highly efficient power-heat coupling (cogeneration) facilities. Still 34 % of the energy is coming from natural gas, further 7 % result from thermal waste heat and another 7 % from other energy sources (BMK Österreich 2020). The report of potential for efficient heating- and cooling supply from 2022 stated, that the use of large thermal storage systems contributes significantly to the economic operation of the heating networks (Kranzl 2022).

### *2.2 Geographical criteria*

The general criteria for an economic construction of the storage structure itself is the predominant topography. A favorable case for large storage structures with heights of approximately 100 m would be steep slopes, since high overburden combined with relatively short access tunnels, would reduce the costs of the structure. The access tunnels provide the connection to the storage structure and should be constructed in way that all arising drainage-/ groundwater can be collected and drained through gravitational forces preferably without the intense use of pumps. For the accessibility, it is recommended to utilize available infrastructure. A point that comes along with the topography is the overburden and the resulting in-situ stress state. This is favorable also for water ingress via discontinuities and fault zones, which may also affect the thermal performance of the storage structure. The environmental and economic aspects may be the crucial point in terms of feasibility. Therefore, it is viable to construct the storage cavity above the ground water table. Environmental concerns for construction below the groundwater table can be solved with grouting and injections. The economical point in this case faces the additional costs for sealing. The durability of the lining and insulation materials in combination with hot water storage requires reliable testing procedures and high-temperature resistant materials to come along with the occurring conditions. For the integration of the TES in the district heating network, it is necessary to come as close to the distribution pipeline as possible. Longer distances to the distribution network increase the costs, therefore the pipeline construction paths must be kept short.

## 2.3 Geological/ Geotechnical criteria

Soft rock and soil conditions are not part of this study. Focus of this study lays on hard rock conditions with preferably unfractured hard rock with minor discontinuities. The imperviousness and the degree of fracturing plays a key role in minimizing the leakage (Matos et al. 2019). The aim for excavation of the underground cavity is to use the least support measures possible to meet the economical aspect of the project. To construct the storage system, it is viable to determine the dimensions and geometry of the structure beforehand. The requirements concerning the storage size and volume depend on the one hand on the present energy sources (waste heat, solar- and wind power) for the loading case and on the other hand on the demand for the unloading case. The demand for an urban area, e.g. Graz, does change over time and therefore it is recommended to construct geometries with the possibility to create additional storage volume. Figure 1 shows four different geometries, where two of them have the possibility to add additional storage volume. The ideal case for the increase of the storage volume is that the operation of the structure will not be influenced, while excavating another shaft. All geometries shown in Figure 1 have been analyzed as part of a project for possible thermal energy storage at sites in Austria. By doing that, different geometries (shafts and one spiral-shaped geometry with certain diameters) have been evaluated. Aim of the research was to define the horizontal (for shaft geometry) and the vertical (spiral-shaped geometry) distance between two shafts respectively the helix geometry from a geotechnical point of view. For one calculation, numerical codes in 2D and 3D were used to gain information on the displacements and the excavation behavior of the storage structures for different geotechnical input parameters. Secondly, a key wedge analysis has been performed, using the information on the orientation of joint sets from the geological data, to figure out the discontinuity driven failure modes. Due to the requirements of the project, no water table has been assumed and no water pressure has been applied to the underground cavern structures during the calculations. In line with the challenges of the evaluation for the structure, it has been shown that plasticity zones formed as the geotechnical input parameters with the used model have been reduced. Also, the initial stress state plays an important role, since the excavation leads to redistribution of the stresses around the excavated area and along with that, deformation will arise. Key parameters are therefore the initial stress state and the local rock properties. With that, it is recommended to have a coordinated determination of the geotechnical parameters for the desired location with laboratory testing (uniaxial compressive and triaxial strength) and in-situ measurements for geological characteristics as well as elastic properties of the rock mass. The results of the testing procedure can be used for further calculations to determine a favorable geometry for the local conditions. Another important aspect, which affects the stability of the structure, are discontinuities within the rock mass. Discontinuities face the problem with having no or very low strength and no cohesion. The properties of discontinuities (roughness, rock strength, filling, loading conditions) and the position in space are parameters for determining stability as well as possible water ingress.

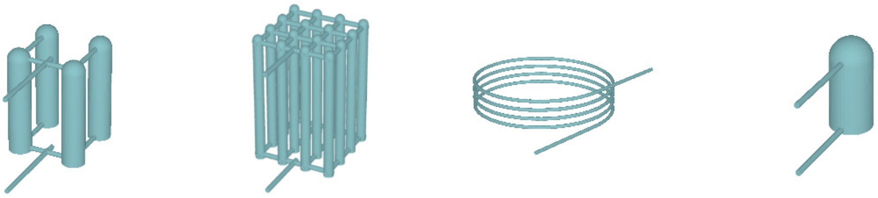

Figure 1. Possible geometries for CTES extracted from a current project (single- respect. multiple shafts and spiral-shaped).

## 2.4 Thermal performance of CTES

A special point regarding the thermal performance of the storage structure comes along with the permeability and porosity of the rock mass and the corresponding water pressure. In general, the permeability of rocks refers to the stress state, joint spacing, orientation and aperture width. Also the permeability decreases with depth and confining pressure (Matos et al. 2019). The sealing of the structure must prevent the exchange of liquids from the rock mass to preserve the heat inside. The aim to store hot water efficiently, is to gain thermal stratification inside the storage structure. While extracting the heat energy of the storage facility (unloading), it is favorable to achieve a well stratified water column with a linear temperature gradient. This enhances the efficiency of the storage system in order to extract the desired temperature at a certain time. The heat losses and the factors influencing thermal stratification (degradation) during a standstill are described by Park et al. (2014). The degradation of the thermal stratification within a water column is governed by four mechanisms in general: The heat gain or loss to the rock mass (1), the heat conduction in the wall of the reservoir (2), the heat transfer between thermally stratified liquid layers (3) and the mixing due to kinetic energy during charging and discharging processes (4). Above the thermodynamical processes, the so-called aspect ratio, which defines the height to width (diameter) ratio significantly influences the thermal performance of the storage structure. Park et al. (2013) showed with numerical calculations, that silo-shaped caverns with an aspect ratio greater than 2.97, reached a maximum thermal stratification ratio of around 0.97 one day after the standby mode in the cavern shaft was initiated. The thermal stratification ratio represents the degree of stratification by the ratio of the mean temperature gradient at one point in time to the mean temperature gradient at the initial point in time. The calculations were performed by analyzing different standby times, where no (dis-) charging process of the storage unit happened. The results suggest a height to width ratio between 3.0 and 3.6 for a standby duration of 1-10 days.

## 3 GUIDANCE FLOW CHART

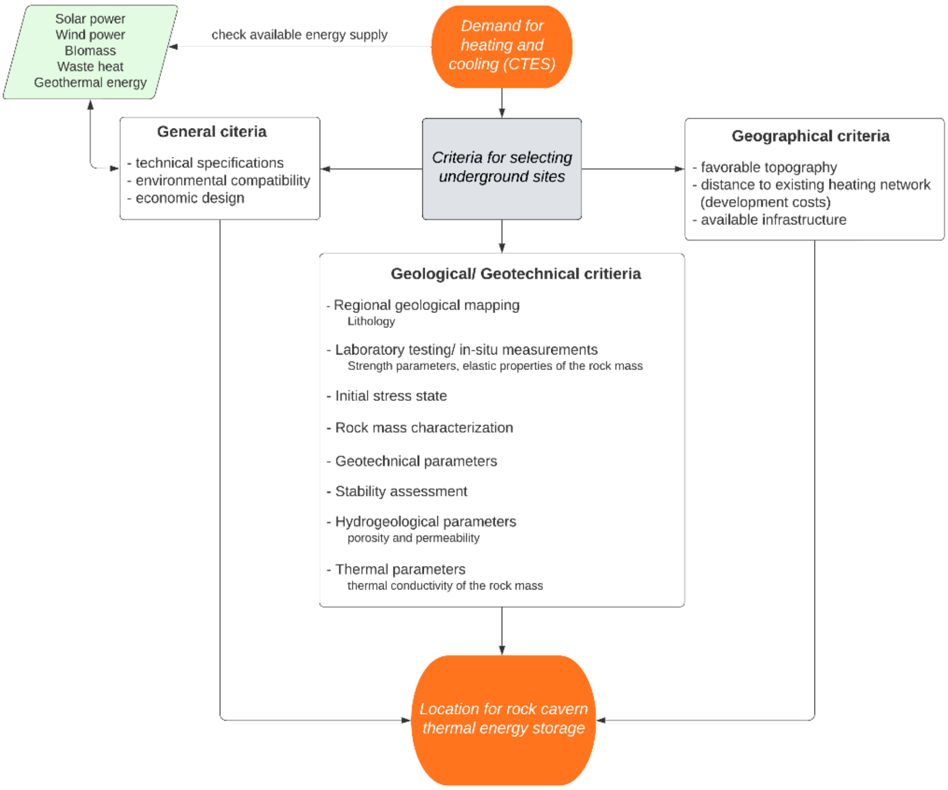

Figure 2. Guidance scheme for the selection of possible storage locations.

The guidance flow-chart gives the key parameters for the site selection and concludes the above-mentioned parameters for engineered underground rock CTES. Figure 2 above shows the guidance for the site selection of engineered rock caverns for thermal energy storage. In line with the demand, it must be checked, which type of energy sources is available and can be integrated to the heat storage system. The technical specifications of the distribution network control the temperature and pressure levels in the system. By defining the key parameters for the geographical respectively geological and geotechnical criteria, it is possible to make a first site selection for the Cavern Thermal Energy Storage System.

## 4 CONCLUSION AND OUTLOOK

A comprehensive review on the site selection of cavern thermal energy storage systems has been elaborated by defining the key parameters for the heat storage structure. The key findings show that the geological conditions at site play a significant role whether a site is appropriate for rock cavern heat storage or not. Therefore, a systematic rock mass characterization program is recommended to detect possible weakness zones in the proximity of the desired rock cavity. This includes mapping of the desired area to limit the possible sites and do deeper research on areas with appropriate rock formations. The geotechnical and rock mechanical characteristics of the storage structure refer mainly to deformation issues. The local stress state and the redistribution of the stresses around the excavated cavity define the need of support measures and remaining rock pillars in case of multiple shafts or spiral geometries. Economic and environmental issues are no less important than rock mechanical aspects. Since the pipeline development for district heat network is costly, the location of the storage site is restricted to the vicinity of the distribution network. The geographical criteria aim for favorable topographies like steep rising slopes, which allow the construction of short access tunnels and have an adequate overburden in this regard. At last, the thermal performance of the rock mass should be evaluated further to gain better knowledge on the thermal behavior while heat storage, especially in fractured rock mass. Further research topics concerning the influence of support elements and sealing issues for certain rock mass should be further investigated.

## REFERENCES

Biermayr et. al., (2021): Energiespeicher in Österreich. Online verfügbar unter https://nachhaltigwirtschaften.at/resources/nw_pdf/schriftenreihe/energiespeicher-in-oesterreich-marktstatistik-2020.pdf, zuletzt geprüft am 21.02.2023.

BMK Österreich (2020): Fernwärme. Online verfügbar unter https://www.bmk.gv.at/themen/energie/energieversorgung/fernwaerme.html, zuletzt aktualisiert am 18.02.2023, zuletzt geprüft am 18.02.2023.

Hauer, Andreas; Hiebler, Stefan; Reuß, Manfred (2013): Wärmespeicher. 5., vollst. überarb. Aufl. Stuttgart: Fraunhofer-IRB-Verl. (BINE-Fachbuch).

Kranzl, Lukas (2022): Bewertung des Potenzials für den Einsatz der hocheffizienten KWK und effizienter Fernwärme- und Fernkälteversorgung. Online verfügbar unter https://austrian-heatmap.gv.at/fileadmin/user_upload/FW_KWK_Endbericht.pdf, zuletzt geprüft am 18.02.2023.

Matos, Catarina R.; Carneiro, Júlio F.; Silva, Patrícia P. (2019): Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. In: *Journal of Energy Storage* 21, S. 241–258. DOI: 10.1016/j.est.2018.11.023.

Park, Dohyun; Kim, Hyung-Mok; Ryu, Dong-Woo; Choi, Byung-Hee; Sunwoo, Choon; Han, Kong-Chang (2013): The effect of aspect ratio on the thermal stratification and heat loss in rock caverns for underground thermal energy storage. In: *International Journal of Rock Mechanics and Mining Sciences* 64, S. 201–209. DOI: 10.1016/J.IJRMMS.2013.09.004.

Park, Jung-Wook; Park, Dohyun; Ryu, Dong-Woo; Choi, Byung-Hee; Park, Eui-Seob (2014): Analysis on heat transfer and heat loss characteristics of rock cavern thermal energy storage. In: *Engineering Geology* 181, S. 142–156. DOI: 10.1016/J.ENGGEO.2014.07.006.

van Helden, Wim; Leusbrock, Ingo; O'Donovan, Keith; Reisenbichler, Michael; Riegler, Thomas; Knabl, Samuel et al. (2022): gigaTES Abschlussbericht. Online verfügbar unter https://www.gigates.at/images/Appendix17_publishable_report_graphically_designed_DE.pdf, zuletzt geprüft am 18.02.2023.