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Energy storage in deep salt formations: Geological and geomechanical conditions and potentials with a focus on Latin America

Almacenamiento de energía en formaciones salinas profundas: condiciones geológicas y geomecánicas con un enfoque en América Latina

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ABSTRACT

The storage of energy in the form of natural gas in deep, artificially created salt caverns is a proven technology. It balances potential imbalances between the supplier (supply and production of natural gas) and the customer (demand and consumption of natural gas), thus ensuring an optimal energy supply in times of crisis. From an engineering point of view, rock salt formations are particularly suitable for the storage of natural gas or oil due to their tightness against gases and liquids and the creep behavior of the material.

The goals of global climate policy and the associated reduction of carbon dioxide emissions into the atmosphere demand the sustainable use of artificial caverns for the storage of green hydrogen, which is currently being scientifically monitored in pilot projects. In order to achieve an economically viable and mechanically safe energy storage, the geological and geomechanical conditions of the salt rocks that support the caverns at great depth must be studied, which requires specialized work both at the laboratory scale and through pilot tests.

In this article, we present the main features required for some well-known salt formations and their potential for the underground storage of hydrogen and compressed air in caverns. To do this, geological and geomechanical boundary conditions for the potential analysis must be defined and, for the specific design and operation of a cavern, evaluated on a case-by-case basis. The storage capacity depends, among other things, on the maximum injection and withdrawal rate, as well as the minimum and maximum pressures to be respected, and the prevailing geological boundary conditions. Particular attention is paid to an overview of salt deposits in Latin America and especially Colombia. The salt deposits near Bogotá and on the Brazilian coast appear to be of interest for a more detailed analysis for underground gas storage in salt caverns. However, a conclusive assessment of the salt deposits requires precise knowledge of the existing geology and the storage needs and possibilities of the respective countries or regions.

Keywords: rock salt, storage potential, underground hydrogen storage, salt cavern design, Colombia, salt cavern operation.

RESUMEN

El almacenamiento de energía en forma de gas natural en profundas cavernas de sal creadas artificialmente es una tecnología probada. Equilibra los posibles desbalances entre el proveedor (suministro y producción de gas natural) y el cliente (demanda y consumo de gas natural), garantizando un suministro energético óptimo en tiempos de crisis. Desde el punto de vista de la ingeniería, las formaciones de sal gema son especialmente adecuadas para el almacenamiento de gas natural o petróleo debido a sus propiedades de impermeabilidad a los gases y líquidos y al comportamiento de fluencia del material.

Los objetivos de la política climática global y la consiguiente reducción de las emisiones de dióxido de carbono a la atmósfera exigen el uso sostenible de cavernas artificiales para el almacenamiento de hidrógeno verde, que actualmente se compruebe científicamente en proyectos piloto. Para lograr un almacenamiento de energía económicamente viable y mecánicamente seguro, es necesario estudiar las condiciones geológicas y geomecánicas de las rocas salinas que soportan las cavernas profundas, lo que requiere trabajos de laboratorio y proyectos piloto.

En este artículo presentamos las principales características requeridas para ciertas formaciones salinas conocidas y su potencial para el almacenamiento subterráneo de hidrógeno y aire comprimido en cavernas. A este respecto, deben definirse las condiciones geológicas y geomecánicas límite para el análisis del potencial y, caso por caso, evaluar el diseño y el funcionamiento específicos de una caverna. La capacidad de almacenamiento depende, entre otras cosas, de la tasa máxima de inyección y extracción, así como de las presiones mínima y máxima que deben observarse, y de las condiciones geológicas límites imperantes. Se presta especial atención a una visión general de los depósitos de sal en América Latina y especialmente en Colombia. Las formaciones salinas cerca de Bogotá y en la costa brasileña parecen interesantes para un análisis más detallado del almacenamiento subterráneo de gas en cavernas de sal. Sin embargo, una evaluación concluyente de los depósitos de sal requiere un conocimiento preciso de la geología existente y de las necesidades y posibilidades de almacenamiento de los respectivos países o regiones.

Palabras clave: sal gema, potencial de almacenamiento, almacenamiento subterráneo de hidrógeno, diseño de cavernas de sal, Colombia, operación de cavernas de sal.

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1. INTRODUCTION

Storing gas and oil under high pressure in large artificial underground cavities in salt rock is a storage technology that has proven itself over decades. Underground storage makes it possible to save space above ground while at the same time safely storing large amounts of energy. Rock salt, which is characterized by its advantageous creep properties and very low permeability to gases and liquids, has proven to be a suitable host rock. The existing underground gas storage caverns serve to balance out unbalanced supply and demand on the market or as a backup during energy-critical periods. Other potential underground storage sites could be aquifers, depleted gas and oil fields, abandoned mines and rock caverns (Małachowska et al., 2022), but these are not the focus of this study.

In Germany, the maximum usable working gas in artificial underground natural gas caverns in rock salt on 31.12.2022 was 14,290 million m³ V_n (at T_n = 273.15 K and p_n = 101325 Pa), which corresponds to a total energy of 151.7 TWh (at 11 kWh/Nm³ (Nationaler Wasserstoffrat, 2021)) and 18 % of the total natural gas consumption in Germany in 2022 (Bundesnetzagentur, 2023). The total volume is spread across a total of 270 individual caverns, which can be found at various locations, but mainly in northern Germany (Landesamt für Bergbau, Energie und Geologie, 2023).

For the USA, the U. S. Energy Information Administration states an underground natural gas storage capacity of 20,051 million m³ (at p = 14.73 psi and T = 60 °F) for the year 2022. The storage capacity describes the maximum total operating capacity for all available salt cavern storage facilities. In 2022, there were 38 cavern fields with different numbers of individual caverns. The salt caverns for storing gas and other energy sources are located in the USA, particularly in the southern states. The storage capacity in salt caverns in the USA has more than doubled since 2008 (U. S. Energy Information Administration, 2024).

In order to meet the climate goals, set by the countries and alliances of nations (e.g. the European Union), hydrogen is to be used as a "climate-friendly" energy source, which may also be suitable for storage in underground gas storage caverns. The German government has set the goal of being greenhouse gas neutral by 2045 (Presse- und Informationsamt der Bundesregierung, 2021). To achieve this, the focus should be on energy sources that are based on renewable energies. A national strategy has therefore been developed for hydrogen, to support the development of a national market and scale up production, use and availability (Bundesministerium für Wirtschaft und Klimaschutz der Bundesrepublik Deutschland, 2020). Colombia's government also published a National Hydrogen Roadmap in 2021, which envisages the gradual reduction of greenhouse gas emissions by 2050, first in industry and then in the transport sector, among others. The use of underground gas storage facilities such as artificial salt caverns for storing hydrogen and CO_2 is also described (Ministerio de Minas y Energía, 2021). The International Energy Agency (Bermudez et al., 2023) states on its website that 32 governments had already developed a hydrogen strategy by the end of 2022. R&D projects in the field of hydrogen, including underground storage, are also being promoted by national and supranational governments and driven forward with the development of legal frameworks.

Subsequently, the operating parameters and the potential for underground storage of hydrogen are currently being discussed (Caglayan et al., 2020; Tackie-Otoo & Haq, 2024; Tarkowski et al., 2024; Warnecke & Röhling, 2021). Test caverns for the storage of hydrogen are also being created during research projects and their operation is simulated and investigated (EWE AG, 2023; STORAG ETZEL GmbH, 2024). There is no long-term, wide-ranging experience with the storage of hydrogen as there is with the storage of natural gas. The lower viscosity of hydrogen must be taken into account when designing the access wells and other steel parts and connections. Possible diffusion over a long period of time in these components can lead to failure, so research should pay special attention to this (Caglayan et al., 2020). In addition, the lower energy density of hydrogen compared to natural gas makes it necessary to consider the construction of further salt caverns with today's existing underground gas storage facilities if a complete conversion to hydrogen is to be expected.

A first step towards assessing the potential for the construction of salt caverns for the storage of renewable energies (in this case hydrogen and compressed air) was taken for Germany by Leibniz University Hannover, among others, in the federally funded InSpEE (Donadei et al., 2016) and InSpEE-DS projects (Donadei et al., 2020; Röhling et al., 2020; Zapf et al., 2020). In this project, together with the Federal Institute for Geosciences and Natural Resources (Germany) and DEEP.KBB, the state of knowledge available at that time on the geological conditions for Zechstein salt structures of great thicknesses in northern Germany (InSpEE) and double-saline and bedded salt layers in Germany (InSpEE-DS) was collected and categorized. The quantity and quality of information varied from area to area. The geological information was then integrated into the geomechanical calculation of various generic cavern models.

For the geomechanical dimensioning of the subsequent cavern operation, operating parameters have to be defined. These include the maximum fluid pressure that is permitted in the cavern, the minimum fluid pressure that must be given at least, and the maximum injection and withdrawal rates in order to reduce thermal stresses in the surrounding rock. Furthermore, geometric boundary conditions, for example in relation to the overburden and side rock, must be observed (Lux, 2009). The geomechanical evaluation of the salt caverns of different sizes and geometries with specific site-dependent geology subsequently enabled a location-dependent potential analysis for the storage of hydrogen and compressed air during InSpEE. The determined selection criteria and the potential assessment resulted in a GIS-based presentation of the information, which is publicly accessible (https://geoviewer.bgr.de/). In the InSpEE project (Donadei et al., 2016), a total energy storage potential of 4.5 TWh was calculated for the storage of electrical energy via compressed air and heat (CAES) and a total withdrawal energy potential of 1,614 TWh for hydrogen for the Zechstein salt structures of great thicknesses in northern Germany. During the InSpEE-DS project (Donadei et al., 2020), a storage potential for CAES of 2.6 TWh and for hydrogen of 1,712 TWh was determined for the double salinar and bedded salt structures.

In the recent years, several studies have been carried out on the storage potential of hydrogen and compressed air in salt caverns, primarily in Europe. Caglayan et al. (2020) worked out the technical potential for storing hydrogen in underground salt caverns for the European market. The technical potential is used to describe the possible amount of energy that can be stored, taking into account geomechanical and other technical limitations, but excluding possible social, environmental or economic restrictions. Based on the geological boundary conditions and the geomechanical calculations for generic cavern models, they determined a total energy storage capacity for the individual countries and areas (onshore and offshore). The total storage potential for Europe was calculated at 84.8 PWh (H_2), with Germany accounting for a relatively large share of 42 %.

Tarkowski et al. (2024) compared the calculated hydrogen demand with the possible storage potential in underground salt caverns for Poland. They assumed a maximum storage demand for hydrogen of 35-38 TWh for Poland. The minimum and maximum number of caverns and structures required for the existing bedded salt deposits, salt domes and for deep aquifers were determined for the corresponding low or high calculated demand. For this purpose, the required number of caverns or storage structures for the region (salt deposits) or for cavern fields (salt domes) was determined, taking into account the geological boundary conditions and the geometric and geomechanical requirements for cavern dimensioning, such as a minimum salt thickness above the cavern or a necessary distance between two individual caverns.

There are significantly fewer underground storage facilities in Latin America than in the European countries and the USA. Confort (2018) summarized the projects and the associated legal situation in the respective countries for eight different Latin American nations. He only identified projects for the underground storage of natural gas in depleted gas fields in Argentina, Brazil and Mexico. Nevertheless, he emphasized that the legal framework for the implementation of underground energy storage is generally in place. He saw the greatest need for an intensification of underground gas storage projects in Argentina, Mexico and Colombia. The existing pipeline density, gas consumption, the proportion of gas imports and the countries' own production all played a role in the assessment.

The compilation of known salt deposits and salt cavern fields worldwide by Horváth et al. (2018) also indicates only a small number of industrial activities in this area in Latin America. In southern Mexico, there is a cavern field in which liquid hydrocarbon is stored in one cavern and three other caverns are used for brine production. Furthermore, crude oil has been stored in 12 caverns in a salt dome in Tuzandepetl, Mexico since 1992. In Brazil, 30 caverns are being used for solution mining near Salvador in the state of Bahia. In Colombia, for example the Upín mine in the Department of Meta and the Zipaquirá mine in the Department of Cundinamarca are used for solution mining.

Nevertheless, underground salt structures can be found in various Latin American countries that offer potential for the underground storage of energy sources. This unused potential can compensate for irregularities in the supply of energy, but can also provide security over a certain period of time during energy-critical times. However, in order to estimate the potential, the geological conditions must be further specified with regard to the geomechanical design of cavern storage facilities in rock salt.

2. METHODOLOGY AND APPROACH

The aim of this article is to describe examples of potential analyses for underground gas storage in rock salt, the necessary geological and geomechanical boundary conditions, and to provide corresponding evaluation criteria for underground storage in salt caverns in Colombia and Latin America.

To identify the evaluation criteria, we will first look at examples of geological salt formations that are suitable for underground storage of gas in rock salt. We will then describe the basic rules for the geomechanical dimensioning of an underground gas storage in rock salt. Based on the findings of recent studies evaluating the potential for underground storage of energy carriers from renewable energy sources, important evaluation criteria for a potential site in Colombia and Latin America are described.

3. GEOLOGICAL AND GEOMECHANICAL BACKGROUND

The existing geology is the basis for the construction and operation of artificially created salt caverns, which must be geomechanically designed in advance to ensure operational safety and stability over the entire life cycle. These are presented in the corresponding chapter.

A review of potential analyses already carried out for the underground storage of energy sources in salt caverns will provide information on the boundary conditions and parameters that need to be taken into account when calculating the maximum underground storage capacity in salt caverns and the resulting storable energy.

3.1 Geological framework

In the InSpEE project (Donadei et al., 2016), the partners worked out the geological conditions of the salt formations that are available in the North German basin for the underground storage of hydrogen and compressed air. The North German Basin is particularly suitable for the construction and operation of salt caverns, as salt diapirs formed from originally shallow salt formations.

The general location of the salt formations in Germany is known, but there was a need to describe the depth extent of the salt formations in particular. For this purpose, level section maps for four different depths were developed on the basis of existing literature and maps. Furthermore, the degree of exploration of the salt structures was evaluated and classified. This showed that only 9 % of the 697 salt structures in the North German Basin could be described as well explored. 66 % were classified as poorly explored, i.e., only geophysical exploration methods were used or boreholes were drilled, but these provided no information on the salt structure. The salt formations were rated as "good" if mining activities had already been carried out in this structure or if exploratory drilling had been performed.

Moreover, a preliminary analysis based on the existing 697 salt structures in northern Germany was carried out to identify the potentially suitable salt structures. This was to ensure that the focus of the main work was placed on suitable salt structures. The maximum depth of the salt structure surface, the salt quality, the minimum thickness of the host rock and the minimum area in the region of the preferred depths for hydrogen and compressed air were evaluated in descending order.

Within the project, the authors limited the cap rock depth to a maximum of 1000 m for the storage of hydrogen and compressed air based on the project-specific geomechanical model calculations, since no reference cavern with a greater cap rock depth was modelled. Donadei et al. (2016) point out that this is a conservative assumption for determining potential and that there already exist caverns with greater cap rock depth. This criterion already ruled out 39 % of the possible salt structures. Furthermore, 2 % were not considered in the further investigation due to the salt quality, 5 % due to the minimum area and 1 % due to the minimum thickness.

For the salt structures classified as suitable, the internal structure of the formation must be described for the quantitative assessment of the potential for underground storage. To do so, a total of 5 different types of internal structure were derived in the InSpEE project, which can be classified by the stage of development of the respective salt formations (Pollok et al., 2015). A distinction is made between a salt pillow, in which there is little to no internal folding.

In this case, the usable area in the Zechstein z2 (Staßfurt formation) for cavern construction increases with increasing depth. Internal structure type 2 is subject to tectonic deformation and shows complex interfolding between Zechstein z2 and younger salt formations. This also limits the usable area, especially in the upper part. Diapirs (internal structure type 3) are generally characterized by steep folds at the edge of the Zechstein z2. This means that the usable area is constant over the depth. Internal structure type 4 describes compressively overprinted diapirs, here complex folding occurs and therefore the usable area for cavern construction can also be severely restricted. So-called double salinars are characterized by the involvement of the Upper Rotliegend salinar in the salt formation. The five specific types of internals are shown in the Figure 1.

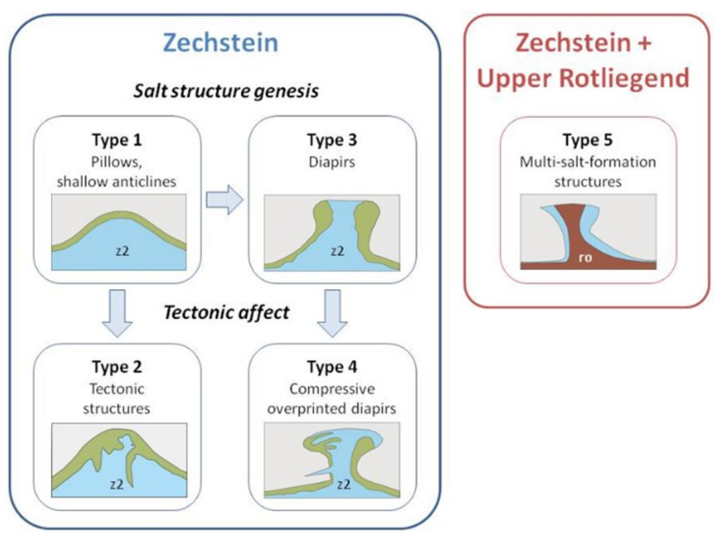

Figure 1. Generalized internal structure types of the salt formations in the North German Basin (adapted from Pollok et al., 2015)

Depending on the internal structure type of the salt structure, there is a respective area share for the individual salinars and a usable area on average for the production of salt caverns. Deep drilling and other investigation methods must be used if a salt cavern should be planned and constructed. This can result in suitable salt structures being classified as unsuitable after exploration. The opposite applies to structures that are initially classified as geologically unsuitable, for example those that have been poorly explored to date (Donadei et al., 2016).

Summarizing the joint projects InSpEE and InSpEE-DS, the existing salt domes as well as the double-saline and bedded salt layers were investigated for Germany and evaluated for the usability of underground storage of energy carriers from renewable energy sources in salt caverns. Some salt structures could not be conclusively evaluated due to an uncertain or insufficient data situation.

Tarkowski and Czapowski (2018) investigated the existing salt domes for the potential storage of hydrogen in underground gas caverns in Poland. They evaluated the geological usability of the 27 existing salt domes using five selected criteria: The size or area of the corresponding salt dome, the depth of salt mirror, the complexity of the salt dome, as well as the degree of exploration and the quantity and quality of the available geological reports. The analysis of the existing salt domes revealed seven salt domes in Poland to be favored for the underground storage of hydrogen in salt caverns.

Lankof and Tarkowski (2020) also analyzed the bedded rock salt deposits in south-western Poland for the underground storage of hydrogen in salt caverns. To do this, they evaluated existing data and defined minimum conditions for the necessary geological conditions. The salt layer should have a minimum thickness of 150 m and the maximum depth of the salt top should not be more than 1800 m below ground level, which is based on the deepest existing storage caverns in Europe. It should be noted that although deeper salt caverns can also be used as gas storage, it is fundamentally necessary to demonstrate the geomechanical stability and operational safety on a cavern-specific basis. The economic factor also plays a decisive role. For the Werra rock salt formation (z1), heat maps for the salt thickness and maximum depth of the salt top were created on the basis of the existing geological data (see Figure 2) and then used for the potential analysis, taking into account geomechanical and operational conditions.

3.2 Geomechanical design of underground gas storage caverns

The cavern is constructed by solution mining of the corresponding area of salt rock. Before the actual cavern borehole is created, test boreholes are first drilled to determine the best possible cavern location. A borehole is then made at the appropriate location to the bottom part of the planned cavern and the borehole is lined with cemented casing between the ground surface and the salt top. Two further pipe strings, the external and central leaching tubing, are then inserted into the borehole. At the beginning of the solution process, fresh water is introduced via the central leaching tube to dissolve the salt. Furthermore, a blanket that is inert with salt, lighter than water and not mixable with brine nor water, is added to protect the cavern roof from being flushed out (Charnavel, 2022). The main solution process takes place using the indirect leaching, whereby the fresh water is led into the cavern via the external leaching tubing and the heavier brine is removed via the central leaching tubing. After 2 to 3 years the indirect leaching process and thus the cavern construction is completed (Pischner & Edler, 2012).

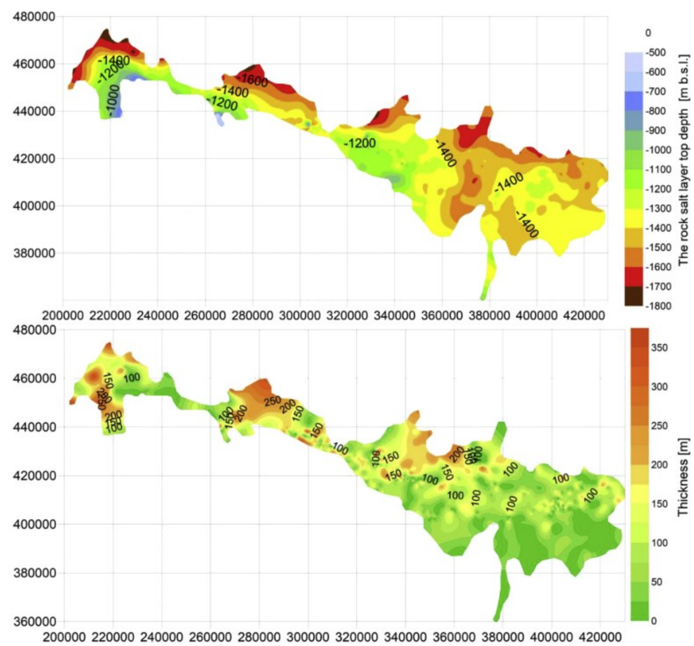

Figure 2: Representation of the distribution of salt tops (in meter below sea level) and salt thicknesses (in meter) of the Zechstein z1 formation for SW Poland as a heat map (from Lankof & Tarkowski, 2020)

A very important part of the creation and operation of salt caverns is their geomechanical design and the consideration of the thermodynamic behavior of the fluid to be stored with high pressures. The storage of natural gas was initially based on seasonal storage to serve the above-mentioned cases. Nowadays, a greater flexibility in demand can be seen in natural gas storage, and this can also be expected for the storage of hydrogen and other environmentally friendly energy carriers. The different operating scenarios for each energy source influence the level of rock stresses and temperatures over the operating period (Schlichtenmayer & Bannach, 2015) and must be taken into account accordingly (Donadei et al., 2016). Therefore, the dimensioning of underground storage facilities in rock salt has to meet requirements to ensure stable, reliable and economical operation.

Consequently, the location-specific material behavior of the rock salt must be determined for the dimensioning of an underground storage cavern. Empirical values from previous dimensioning of nearby caverns can be used, nevertheless it is very important to carry out laboratory tests on rock salt test specimens from the specific location to determine the strength as well as the elastic and creep parameters of the material. The time-, stress- and temperature-dependent creep behavior can then be modelled using the "Lubby2" material law for rock salt developed at the Institute of Geotechnical Engineering at Leibniz University Hannover, which is shown in Equation (1) and based on the rheological Burgers model with temperature, stress and time dependent material parameters. Further creep laws to describe the different creep stages and other material properties can be found in Hampel et al. (2016), which were studied in the course of a material law comparison on the thermo-mechanical behavior and healing of rock salt.

$$\dot{\varepsilon}^{eq}(t) = \left(\frac{1}{\overline{\eta}_k(\sigma)}\exp\left(-\frac{\overline{G}_k(\sigma)}{\overline{\eta}_k(\sigma)}\cdot t\right) + \frac{1}{\overline{\eta}_M(\sigma)}\right)\cdot \sigma_{eq} \qquad (1)$$

with equivalent strain rate $\dot{\varepsilon}^{eq}$, equivalent stress σ_{eq}, Maxwell viscosity $\overline{\eta}_M$, Kelvin shear modulus $\overline{G}_k$ and Kelvin viscosity $\overline{\eta}_k$.

The operation of an underground storage cavern in rock salt is regulated by a maximum and minimum internal cavern pressure and a maximum injection and withdrawal rate (Zapf et al., 2024). This first requires the calculation of a mechanical and thermal primary stress state of the rock mass and the geomechanical consideration of the leaching phase.

A minimum pressure in the operating phase of the cavern is necessary to maintain the stability of the cavern if the internal pressure is too low, thus preventing the cavern cavity wall from spalling due to too high deviatoric stresses. The limitation of the maximum internal pressure prevents the loss of local and global tightness of the rock due to a possible internal pressure that is greater than the rock pressure. This scenario could increase the permeability at critical locations and lead to the exceeding of the effective tensile strength of the rock. It is designed based on the calculated pressure at the level of the last cemented casing shoe and ensures that there is a sufficiently large safety zone around the cavern in which a certain compressive stress value is not exceeded by the gas pressure. Typically, the maximum pressure is limited to 80 % to 85 % of the vertical primary stress state in the rock at the level of the casing shoe (Bérest et al., 2020). In order to estimate the required minimum internal cavern pressure, the stress intensity index η must be considered, which can be calculated from the stress state of the rock and its strength values determined in the laboratory. It represents a utilization level of the rock mass. Staudtmeister and Rokahr (1997) provide the following equation for the stress intensity index η:

$$\eta = \frac{\sqrt{2J_2^D}}{\beta^D} \qquad (2)$$

Where J_2^D is the second invariant of the deviatoric stress tensor and β^D the failure strength of the rock.

As a guidance value, a minimum pressure of 30 % of the vertical primary stress state can be assumed (Ozarslan, 2012).

Also, the injection and withdrawal rate must be limited to a maximum in order to limit the development of thermally induced and pressure-driven infiltration fractures. Particularly during the withdrawal phase, the temperature of the gas is reduced, which also reduces the temperature of the rock salt in the vicinity of the cavern wall. This results in a reduction of the rock stresses, which can lead to a gas pressure that is greater than the rock stresses (Bérest et al., 2013; Yildirim et al., 2020) and therefore to the effective tensile strength of the material being exceeded.

Geometric boundary conditions must also be taken into account when designing a cavern. Figure 3 shows the geometric distances to be observed from the surrounding rock or overburden and other caverns in the salt formation. The geometry of a single cavern is defined in simplified terms with a total height h and a diameter d (Lux, 2009). For storage caverns created in a salt dome, the aim is to achieve an elongated, cylindrical shape, with a diameter of 50 to 80 m and a height of several hundred meters. The storage caverns in bedded rock salt have a lower height-to-diameter ratio due to the lower thickness of the rock salt formation (Cyran, 2020).

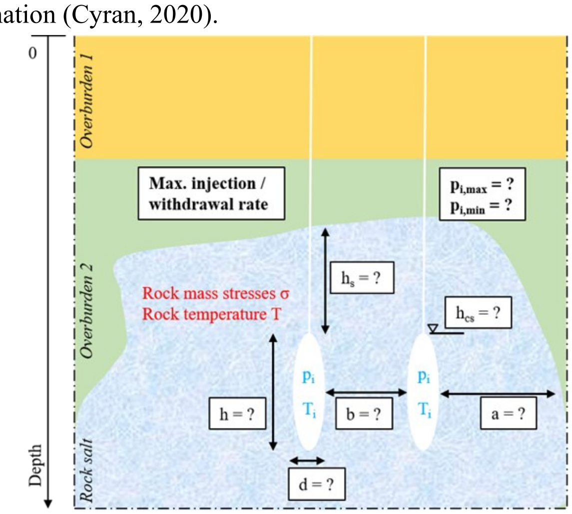

Figure 3: Operating parameters, geometric boundary conditions and thermo-mechanical parameter in the geomechanical design of gas storage caverns (adapted from Lux, 2009)

Furthermore, a distance b between two individual caverns, a distance h_s from the last cemented pipe shoe to the overburden and a distance a to the side rock must be taken into consideration. In addition, the ratio of the cavern diameter to the depth of the cavern should be less than 2/3 in order to avoid cratering (Karimi-Jafari et al., 2008). Thus, a sufficient depth is necessary for reasons of stability. The geometrical design is based on the operation-related stress and temperature behavior of the rock mass (Lux, 2009).

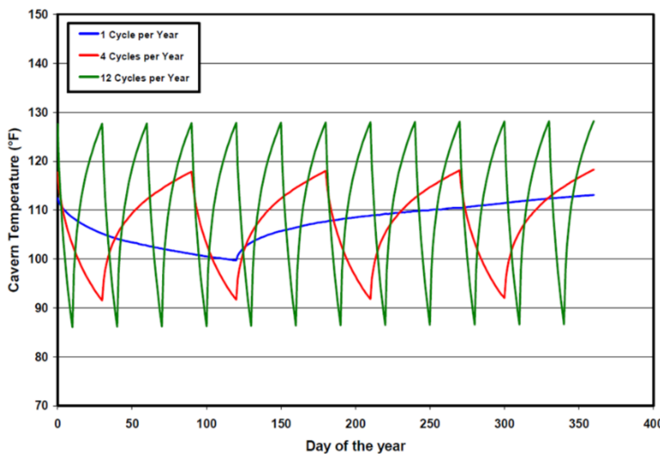

Figure 4: Temperature development in a cavern under different operating scenarios for hydrogen storage (Nieland, 2008)

Returning to the aforementioned influence of the operating scenario, the following Figure 4 shows the effects of different operating modes on the temperature curve of the stored energy carrier, in this case hydrogen. Seasonal injection and withdrawal (1 cycle per year) shows a smaller temperature change over the period than the other two scenarios (4 cycles per year and 12 cyles per year). The cooling of the hydrogen during withdrawal from the cavern is balanced out by the warmer temperature from the rock over the long withdrawal period; the same applies in the case of injection. Here, the rock temperature is lower than the gas temperature at one point in time and ensures that the hydrogen heats up more slowly. With 4 and 12 cycles per year, the temperature equalization by the rock cannot influence the hydrogen temperature in the cavern quickly enough due to the rapid changes, so that the range of temperature changes is greater. The standing phases, for example at minimum pressure or maximum pressure level, also have an influence on the thermal interaction between the cavern and the rock and must also be critically evaluated when dimensioning a salt cavern.

The pressure and temperature development of the stored energy carrier in the operating scenario depends on several factors. Firstly, the chemical composition, which determines the thermodynamic behavior of the fluid, plays a role. Moreover, the ratio of the geometric volume to the effective cavern surface is decisive for the calculation of the thermodynamic load case. The primary stress state, the depth of the cavern and the geometry must also be taken into account when dimensioning the load case. Caverns at greater depths require a larger amount of fluid, which must be held as a cushion gas in order to maintain the minimum pressure. However, a greater depth usually also means that a higher maximum pressure can be approached. Depending on the location-specific material creep behavior of the rock salt, the higher rock temperatures at greater depths lead to a higher creep rate and thus also a higher convergence rate of the rock salt. The resulting reduced geometric volume of the cavern consequently reduces the storage capacity over time. The creep behavior is also influenced by the operating mode (Donadei et al., 2016). Sonar measurement of the cavern (Wippich et al., 2022) or observation of the surface subsidence (Babaryka & Benndorf, 2023; Misa et al., 2023) allows conclusions about the volume convergence of the cavern to be drawn.

Donadei et al. (2016) list the following characteristics that are necessary for an assessment of the storage capacity: the volume of a cavern, the depth, the thickness of the salt formation, the distance between caverns in a cavern field and the associated operating scenario, which can be better described via a permissible maximum and minimum pressure and the permitted withdrawal and injection rates. Their investigation was carried out for different depths, cavern volumes and different pressure regimes. For the daily injection and withdrawal of compressed air, it was found that the thermodynamic behavior only produces a significant difference in temperature at a higher-pressure level. A lower temperature difference means a more favorable thermodynamic behavior, as the reduction of the rock stresses due to temperature effects is lower. This advantage can also be seen in the subsequent thermomechanical calculation, where a higher-pressure level also has a particularly favorable effect on the rock stresses. One advantage of bigger caverns with the same pressure regime is the larger amount of compressed air that can be injected and withdrawn. The influence of the cavern size and depth on the stress distribution of the rock mass in the edge region is not significant.

The thermodynamic behavior during the storage of hydrogen was analyzed by Donadei et al. (2016) based on seasonal storage. It was found that the temperature difference is lower for bigger caverns and also for more slender caverns. The thermomechanical calculations for the storage of hydrogen show that higher withdrawal rates with a subsequent longer standing time in particular have a negative effect on the rock stress. The vertical and circumferential rock stresses at the edge of the cavity fall into the effective tensile stress range during the standing phase and into the absolute tensile stress range during the withdrawal phase, which can lead to (effective) tensile fracturing. The authors summarize that for hydrogen storage, a bigger cavern with a greater depth is thermodynamically more favorable.

3.3 Evaluation criteria and potential assessment for underground gas storage caverns

In the InSpEE project (Donadei et al., 2016), evaluation criteria were defined for a subsequent assessment of the potential for underground storage of compressed air and hydrogen in salt caverns on the basis of geological and geomechanical investigations. It should be noted that only the salt structures of the Zechstein salt z2 and the Rotliegend salt were investigated. No consideration was given to the salt structures that can be found offshore in Germany.

The geological extent was considered in a rough increment of 500 m, whereby a minimum thickness of at least two neighboring 500 m increments was required for consideration. The maximum depth of the cap rock top was conservatively defined as 1000 m above sea level. This already excluded 99 structures for the potential assessment that could be technically feasible. Furthermore, a minimum area was defined based on a calculated minimum cavern. If the cavern pool was arranged in a chain of three, a rectangular area of 500 x 1100 m was required per cavern. If the cavern pool was arranged in a triangular shape, a circular area with a minimum diameter of 840 m was required. Salt quality also played a role for brining and operation and was taken into account in the potential analysis using empirical values. Any existing competing uses (e.g., mining) of the salt dome were taken into account based on available data. The difficulties of brine disposal and further processing, barriers due to nature and environmental protection, measures to reduce possible ground subsidence above the cavern and a too large distance to the transport infrastructure and the energy consumer are mentioned as further factors to be considered when planning a salt cavern, but were not considered further in the potential analysis. Finally, a storage potential in salt caverns of 4.5 TWh for the storage of electrical energy via compressed air and heat, and of 1.6 PWh for the storage of hydrogen is determined for the northern German region.

Juez-Larré et al. (2019) carried out an analysis of the potential for underground storage of energy sources in depleted fields and salt caverns for natural gas, hydrogen and CAES (Compressed Air Energy Storage) for the Netherlands. They used a volume of 600,000 m³ to estimate the potential storage volume in salt caverns. The distance between the cavern and the adjacent rock mass was 100 m and 150 m from the overburden. A distance of between 160 to 210 m was assumed between the individual caverns. Furthermore, a conservative calculation was made with 50 % of the theoretically possible caverns. The ratio between the working gas and the remaining cushion gas was also 1:1 with an assumed maximum pressure of 180 bar. This resulted in a storage volume of 53 million m³ for natural gas in a single cavern. A conversion factor of 0.85 was applied for hydrogen. Thus, the potential analysis for the storage of natural gas and hydrogen in salt caverns for the Netherlands resulted in a storage potential of 17 billion m³ (184 TWh) for natural gas and 14.5 billion m³ (43 TWh) for hydrogen. For the storage potential of CAES in salt caverns, the maximum and minimum pressure was reduced, as the energy consumption for air compression is very high. It is therefore also necessary to reduce the depth of the cavern. Finally, the authors show a potential for storing compressed air of 0.58 TWh in 321 possible salt caverns.

As already mentioned, Caglayan et al. (2020) determined the potential for hydrogen storage in salt caverns for Europe. They also defined geometric and geomechanical boundary conditions in order to estimate the storage potential. The buffer distance between the salt formation edge and the planned caverns is defined with 500 m for salt domes and 2000 m for bedded salt to address the uncertainty of geological boundary conditions.

They chose a different cavern volume and a different geometry for evaluation, depending on whether the cavern is located in a bedded salt deposit or in a salt dome. Furthermore, they set the height for caverns in bedded salt deposits at 120 m and for a salt dome at 300 m, and the diameter at 84 m and 58 m respectively. The distances to the bottom of the overburden and the necessary thickness below the cavern are described by the authors in relation to the cavern diameter. The distance between the top of the cavern and the overburden should be at least 75 % of the cavern diameter and at least 20 % of the cavern diameter should be present as salt rock below the cavern. The salt thickness of the possible deposit should be at least 200 m and the maximum depth should be between 500 m and 2000 m. For the potential analysis, the distance between the caverns should also be four times the diameter.

The minimum and maximum pressure in the operating phase is limited to 24 % respectively 80 % of the lithostatic pressure at the top of the cavern. The location-specific storage capacity is then calculated using the product of the mass of the working gas, the minimum heating value of hydrogen and a safety factor of 0.7. Overall, Germany has the greatest potential for the underground storage of hydrogen with 35.6 PWh.

The Netherlands and the UK follow in second and third place with 10.4 and 9 PWh respectively. The authors further subdivide the potential into onshore (with a maximum distance of 50 m of shore) and offshore storage. The greatest potential for storing hydrogen offshore in underground salt caverns is in Norway with

7.5 PWh, whereas there is no potential onshore. It should be noted that in this study the technical potential was considered; the economic and ecological factors were not taken into account.

4. THOUGHTS ON DETERMINING THE STORAGE POTENTIAL OF UNDERGROUND SALT CAVERNS IN LATIN AMERICA, WITH AN EMPHASIS ON COLOMBIA

After the studies presented in the previous chapters, we now look at a possible procedure for determining the storage potential in the salt deposits in Colombia and Latin America. As shown in the studies presented, knowledge of the geology is crucial for this. Furthermore, proof of geomechanical stability and operational safety must be provided.

In their compilation on the world's known salt deposits and salt cavern fields, Horváth et al. (2018) drew attention also to Latin America. In particular, there are large underground salt deposits in the form of domal and bedded salt structures in the northeast and southeast of Mexico. There are also bedded salt deposits in Argentina that lie 1030 m above the sea level.

The salt deposits have layers of anhydrite, which also contain gypsum and clay. More than 30 domal salt structures are reported for Peru, which are located in the eastern Cordillera. Rock salt deposits in Chile are located in the San Pedro de Atacama formation; they contain parts of gypsum, anhydrite and halite and occur in layers 0.5 to 1.0 m thick. There are also large salt deposits in Brazil, where various salt structures can be found in the Amazon region and in the coastal region. Also, domal salt structures have been identified underwater on the south-eastern Brazilian coast in the Santos and Campos Basin. Figure 5 is a map of the known Latin American salt deposits (left side) from Horváth et al. (2018), with a closer view of Colombia's salt deposits on the right side.

For Colombia, Horváth et al. (2018) list salt structures in the departments of Cundinamarca and Meta. In the Upin Mine near Villavicencio in the Meta Department, salt layers with a low to high proportion of clay can be found. The layers are located close to the surface to depths of more than 5000 meters. For example, a salt layer of 120 m at a depth of 1633 m to 1752 m was explored for a borehole drilled in this area (Parravano et al., 2015). North of Bogotá, near Zipaquirá, Cundinamarca, there are salt deposits described as salt domes.

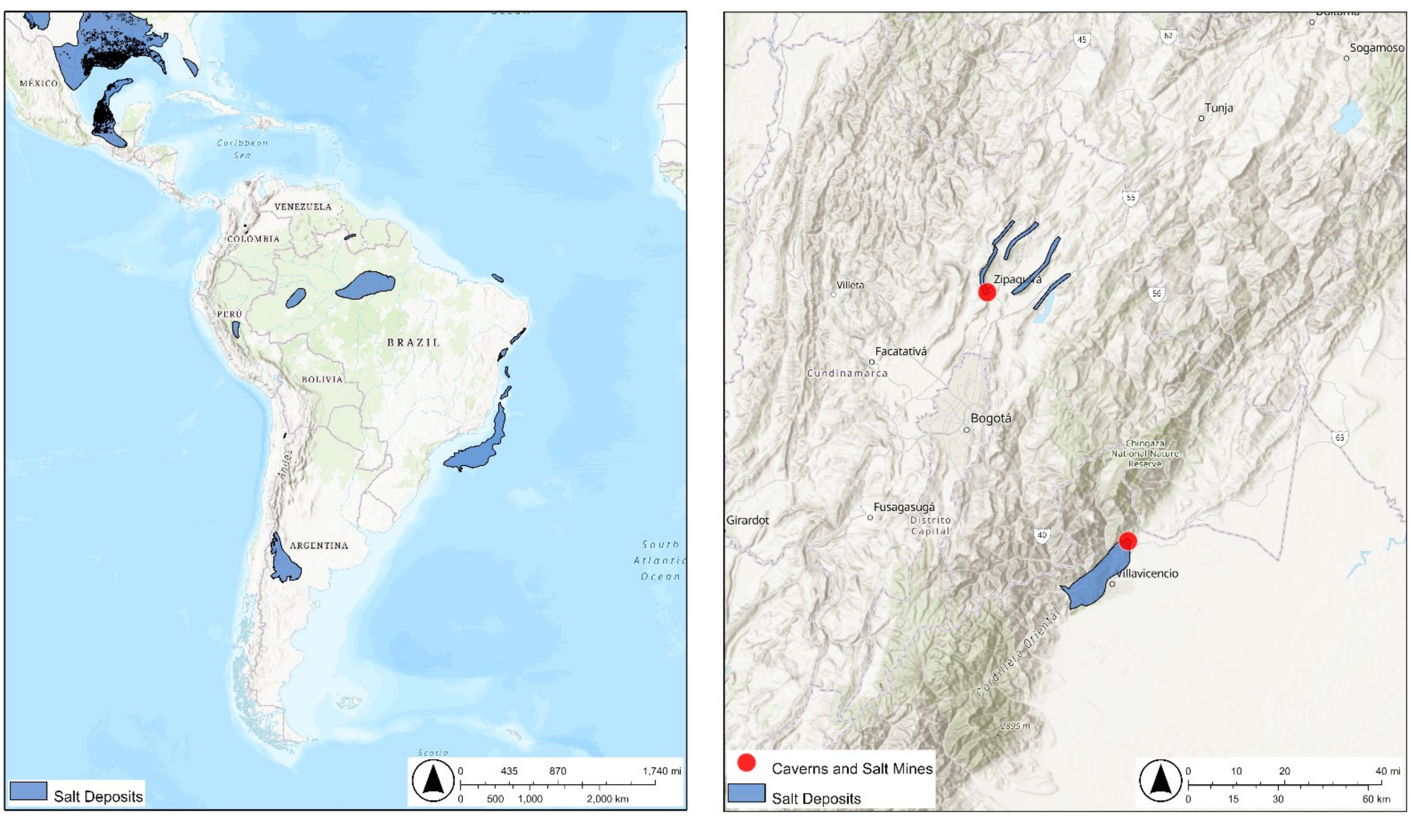

Figure 5: (left) Salt deposits with Salt domes (black areas in blue areas) in Latin America and (right) Salt deposits plus caverns and salt mines near Bogota, Colombia. Data from Horváth et al., 2018.

The salt and black shale dome in Zipaquirá, for example, has a diameter of almost 2 km and a height of 250 meters. Salt layers exist here at depths of up to 2000 m (Garcia & Jimenez, 2016). The known salt formations described in Colombia are shown in Figure 5 (right), and the caverns and salt mine sites described by Horváth et al. (2018) are also indicated. In addition, the Nemocón Mine in Department Cundinamarca and the salt flats of Galerazamba, Bolivar, are used for solution mining.

The information in the literature shows that there are already industrial activities in various salt deposits in different countries in Latin America, but the number of deposits also implies possible potential for underground storage of energy sources in rock salt formations. This requires a better understanding of the geological structures. It is necessary to examine the drilling material obtained and identify the location-specific material properties to subsequently carry out a geomechanical site assessment for possible cavern construction. The technical evaluation of a cavern site requires the cooperation of various specialists such as geologists, physicochemists, civil engineers and mechanical engineers.

Economic and ecological aspects always accompany the technical aspects of a cavern site assessment or potential analysis (Caglayan et al., 2020). Acceptance by the local population and the involvement and support of politicians and decision-makers also play an important role. Also, the legal framework for the underground storage of gas and other energy sources must be defined.

In addition to the geological, geomechanical and technical boundary conditions, further technical and operational constraints must be taken into account throughout the entire life cycle of a cavern.

The construction of the artificial cavern produces a very large amount of salt water, which must be disposed of or reused. In the case of the salt caverns, which are located near the North Sea in Europe, the resulting salt water is discharged into the sea (Eradus, 2022). In the Toz Golu project in Turkey, the brine was transported to a lake 40 km away (Ozarslan, 2012). However, the brine can also be processed in the chemical industry, as for example in the case of the Vauvert salt cavern in France (Furst et al., 2021).

In addition, the supply of the energy source to be injected as well as a suitable gas pipeline infrastructure for transporting the gas must be provided. Another aspect when operating a cavern is maintaining a minimum pressure inside the cavern to ensure stability and operation. In order to preserve this minimum pressure, a large amount of gas is required, which remains permanently in the cavern during operation and cannot be used for the intended purpose.

To summarize, the following basic technical constraints need to be considered when estimating the storage potential in salt caverns in Colombia and Latin America:

1) Existing and possibly new salt deposits must be further investigated geologically.

2) In the case of geological suitability, the corresponding rock layers must be characterized geomechanically. Mechanical material behavior must be determined in laboratory tests.

3) The stability and operational safety of the salt cavern must be demonstrated by the location-specific wellbore and geomechanical design of the salt cavern to be constructed prior to construction and operation. The rock mass behavior has to be monitored during operation.

4) Injection and withdrawal of the gaseous energy source has to be ensured by a transportation infrastructure to the supplier/consumer. The necessary cushion gas of the cavern must be taken into account.

5. SUMMARY AND CONCLUSIONS

The storage of energy sources such as gas and oil in artificially created underground caverns in rock salt formations is being realized worldwide under suitable geological conditions. A large number of underground storage caverns can be found in northern Europe and the USA in particular. The climate goals set by various governments and organizations to reduce CO_2 emissions bring the storage of hydrogen (ideally green hydrogen) into the focus of current scientific studies. In this context, it is an aim to assess the potential of underground storage of such an energy carrier in caverns worldwide.

The studies described in this article show the potential in various countries and draw attention to the importance of considering the geological and geomechanical boundary conditions. They determine different storage potentials for individual countries based on different boundary conditions, defined geological constraints and geomechanical approaches. It shows how important a site-specific geological investigation and geomechanical dimensioning of a salt cavern is, in order to determine the real storage capacity.

For example, a minimum thickness and distance of the salt layer to the overburden and surrounding rock is necessary. Additionally, a sufficient depth of the salt formation is geomechanically and economically advantageous in order to meet the operating parameters (minimum pressure, maximum pressure, maximum injection and withdrawal rate) of a cavern operation. Furthermore, it becomes clear that not only the technical framework conditions for the construction and operation of a cavern, but also the legal, economic and ecological conditions at the respective potential cavern location play an important role for stakeholders.

There are salt deposits (domes and layers) in various regions of Latin America. In Colombia, salt structures and industrial activities in rock salt are known near Bogotá, which may be suitable for gas and hydrogen storage. The exact geological conditions of the salt formations around Bogotá and, in particular, the dimensions of the salt dome at Zipaquirá, should be described in detail for the purpose of underground gas storage in salt caverns. Based on the information currently available, the pre-salt areas on the Brazilian coast (Santos and Campos basins) are also favorable for Latin America, which have already been discussed for the storage of hydrogen (Dias et al., 2023). The salt deposits in Colombia and Brazil mentioned appear to be the favorites for further investigation, but do not rule out the other locations mentioned. The geological and geomechanical approach for the European countries has shown that an intensive and detailed analysis of the individual salt structures is necessary.

Due to the geological conditions in Colombia and on the east coast of Brazil, the sites should be thoroughly investigated and geologically and geomechanically evaluated with regard to underground gas storage. The existing geological conditions must be examined in detail and basic potential analyses can reveal initial possibilities for underground gas storage in salt caverns, e.g., of hydrogen. Underground gas storage in artificially created salt caverns is a proven method for storing large quantities of energy and is becoming a focus for sustainable and flexible energy storage due to the climate policy goals of many governments, including Colombia.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that the article does not present a conflict of interest.

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