Underground storage of fluids

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1 Introduction

The underground storage of fluids (gases and liquids) has three major aims:

- Storage of crude materials (natural gas and oil) or artificially produced fluids (e.g. LPG = liquefied petroleum gas)
- Energy storage (e.g. Ibrahim et al., 2008)
- Storage of liquid and gaseous residual products (e.g. CO_2 storage)

Two different options are available to store fluids underground:

- Cavern storage (for instance in leached salt caverns, excavated hard rock caverns or abandoned mines)
- Pore storage (for instance in aquifers or depleted oil and gas reservoirs)

Fig. 1.1 illustrates the potential use of the underground space for energy storage and production as well as extraction of raw materials. Compressed air storage (CAES) as a special form of energy storage in abandoned salt mines is discussed by Hausdorf et al. (2009). Fig. 1.2 and 1.4 illustrate capacity and discharge capabilities of different forms of subsurface energy storage.

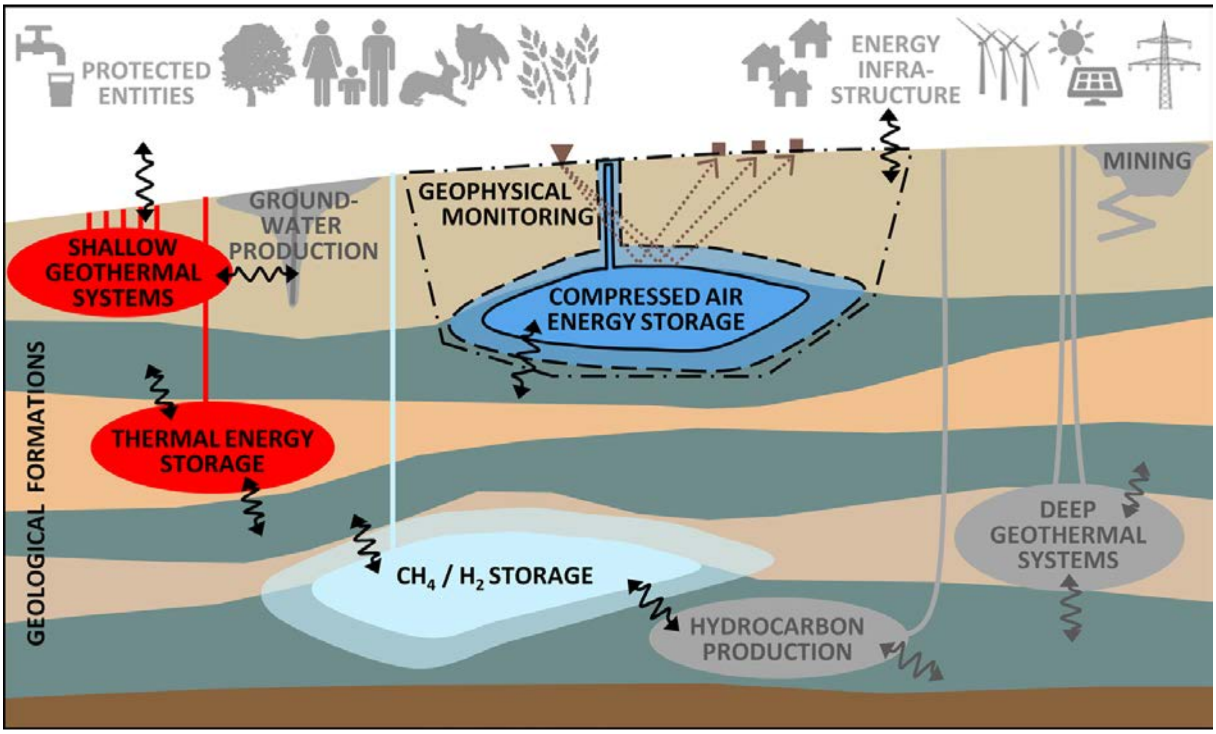

Fig. 1.1: Use of underground spaces for energy storage (Kabuth et al., 2017)

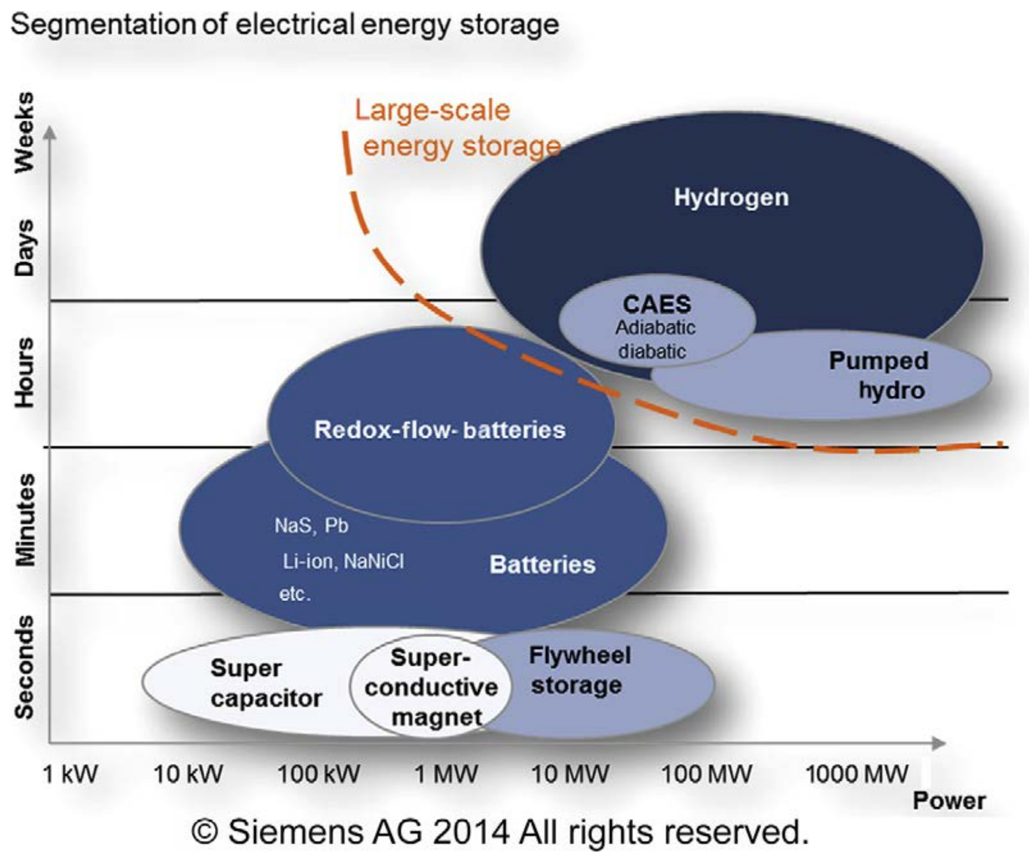

Fig. 1.2: Overview of energy storage technologies (Wolf, 2015)

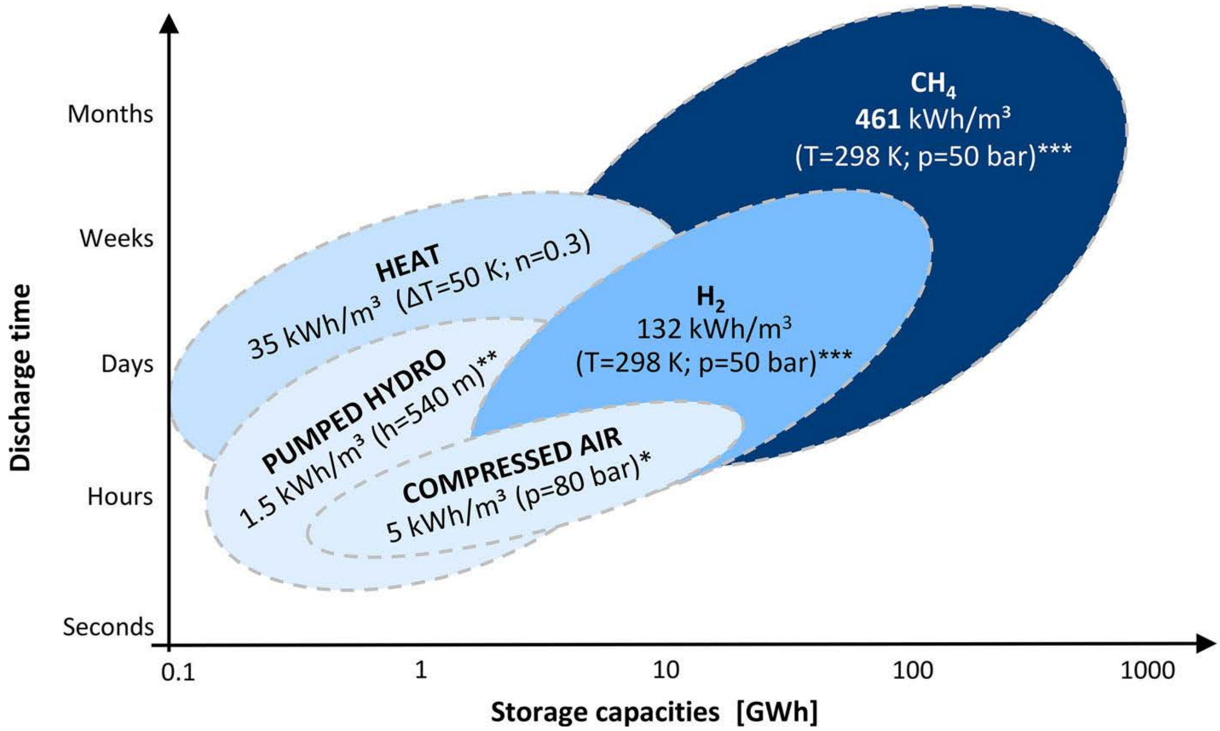

Fig. 1.3: Storage capacity and discharge time of different storage media (Kabuth et al., 2017)

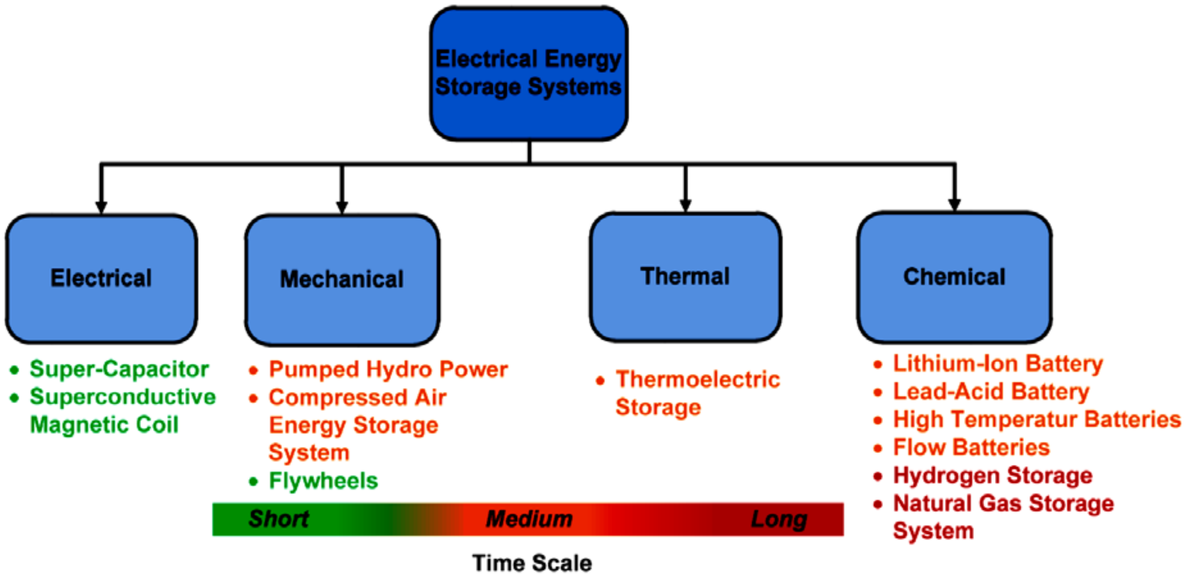

Fig. 1.4: Overview about Energy storage technologies (Fuchs et al., 2012)

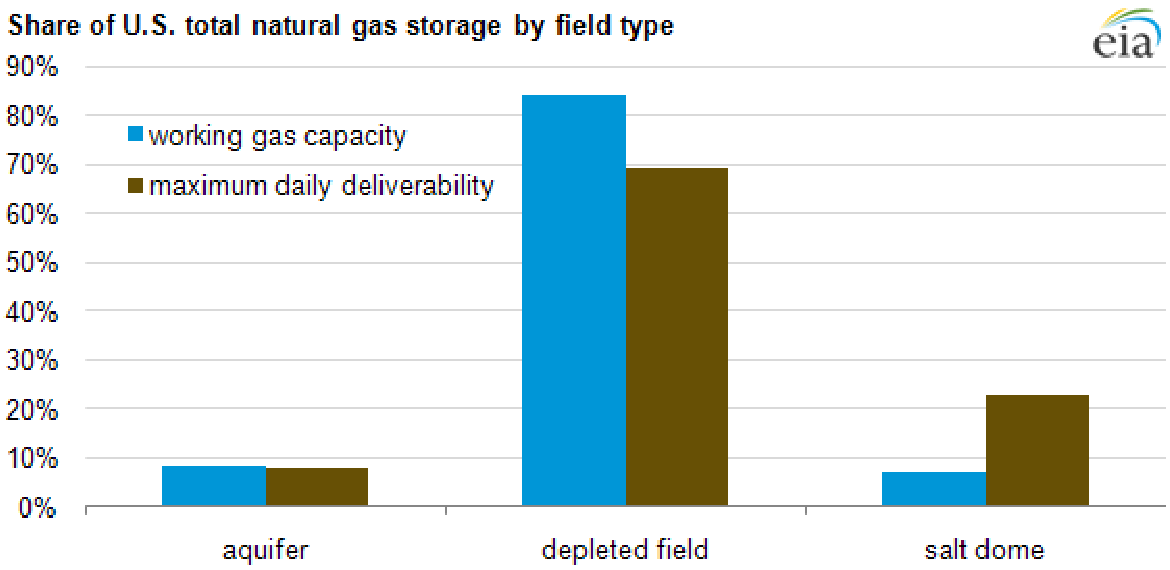

Fig. 1.5: Gas storage capacity and deliverability in the USA in 2011 (USEIA, 2011)

Exemplary, Fig. 1.5 shows the distribution of gas storage capacity in the USA in relation to the type of the storage facility and Fig. 1.6 shows the storage capacity of selected countries in Europe in relation to their yearly consumption. For gas storage one has to distinguish between working gas or volume (available for withdrawing during normal operation) and cushion gas or volume (permanently stored, not for withdrawing and necessary to stabilize the system due to the internal minimum gas pressure).

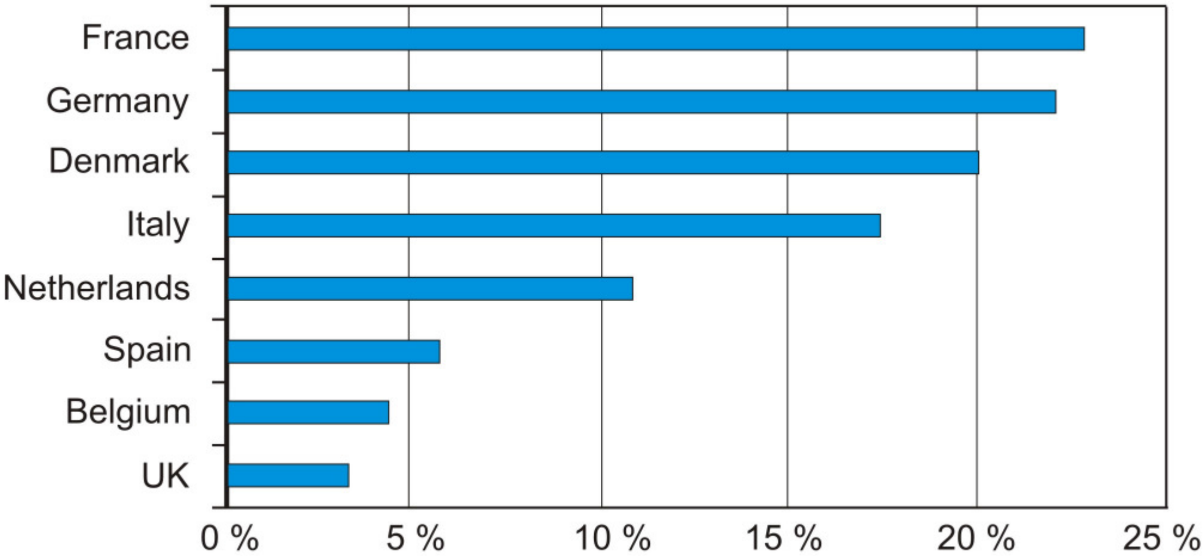

Fig. 1.6: Natural gas storage capacity in relation to yearly consumption (Gillhaus, 2007)

2 Cavern storage

Storage Technology	Siting Requirements	Security	Safety	Economy
Solution Mined salt caverns	Thick salt formations and water for leaching	E	E	E
Unlined Rock Caverns	Competent rock and stable ground water conditions	E	E	G
Underground Concrete tanks	Hard soil /weak rock and low ground water table	G	G	E
Conventional steel tanks	Large land requirements	A	A	A

Note: E - Excellent; G - Good; A - Average

Fig. 2.1: Underground cavern storage options (Nanda et al., 2015)

Typical storage options for caverns are shown in Fig. 2.1. By far most of the underground storage caverns are placed in salt formations. Caverns are typically located at depths between 500 and 2000 m below surface (see Fig. 2.2 and 2.3).Salt caverns can have quite different size and shape (see Fig. 2.4). The volume of salt caverns ranges from a few 10.000 to more than 1.000.000 m^3.On average salt caverns are about 300 m high with a diameter of about 60 m, which corresponds to volumes between 500.000 and 800.000 m^3. Caverns for gas storage in Europe are connected via a pipeline system (see Fig. 2.5). A comprehensive overview about salt caverns in Germany and worldwide is given by LBEG (2014, 2018).

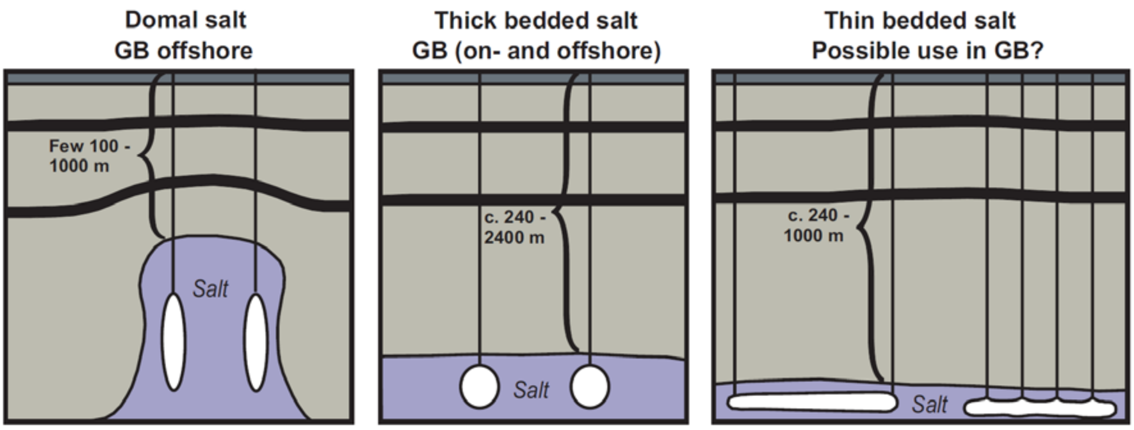

Fig. 2.2: Salt caverns in different types of salt deposits (BGS, 2008)

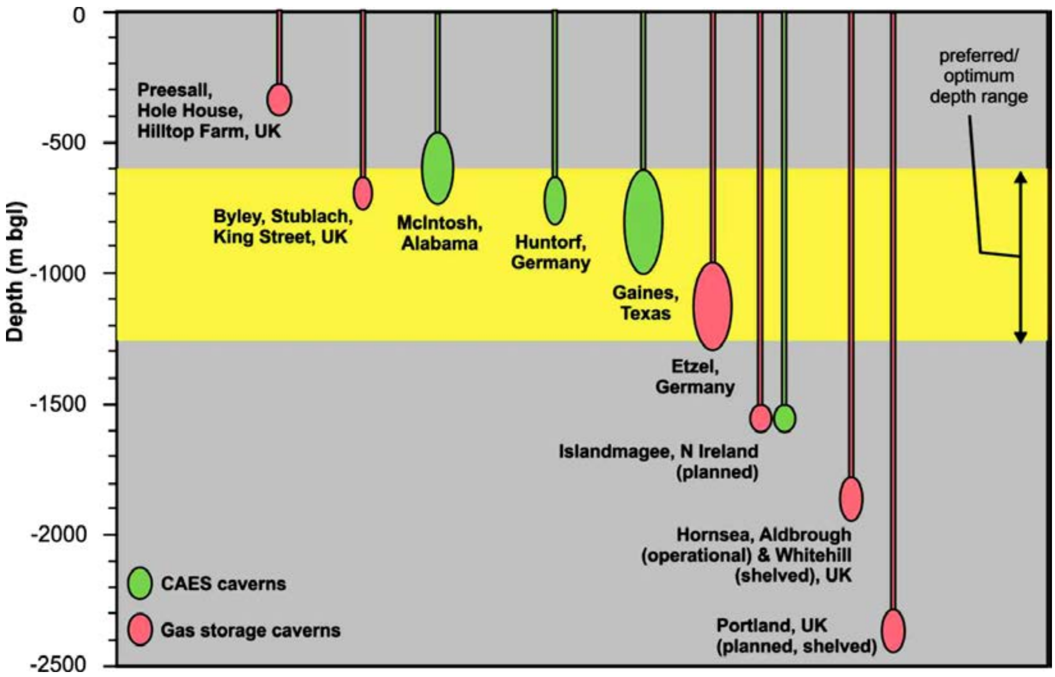

Fig. 2.3: Depth of operational and planned CAES and gas storage cavern (Kepplinger et al., 2011)

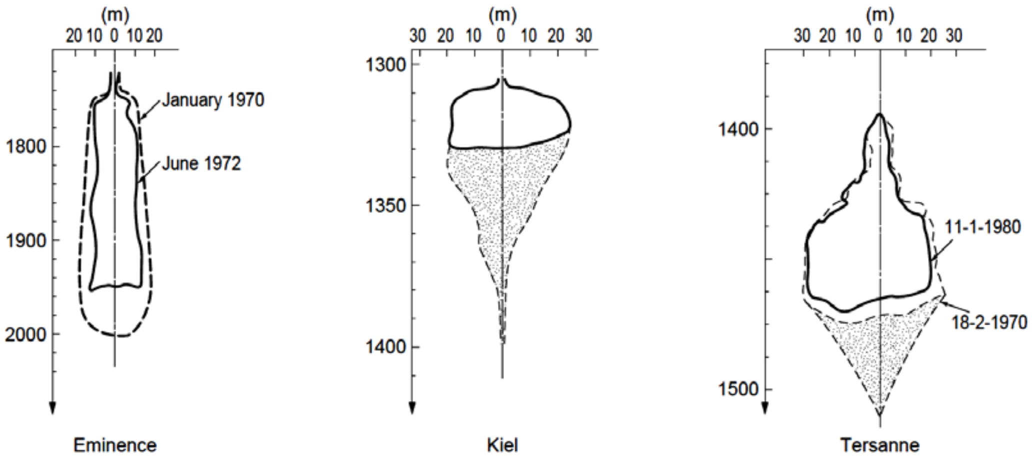

Fig. 2.4: Shape, size and depth range of selected caverns (Kepplinger et al., 2011)

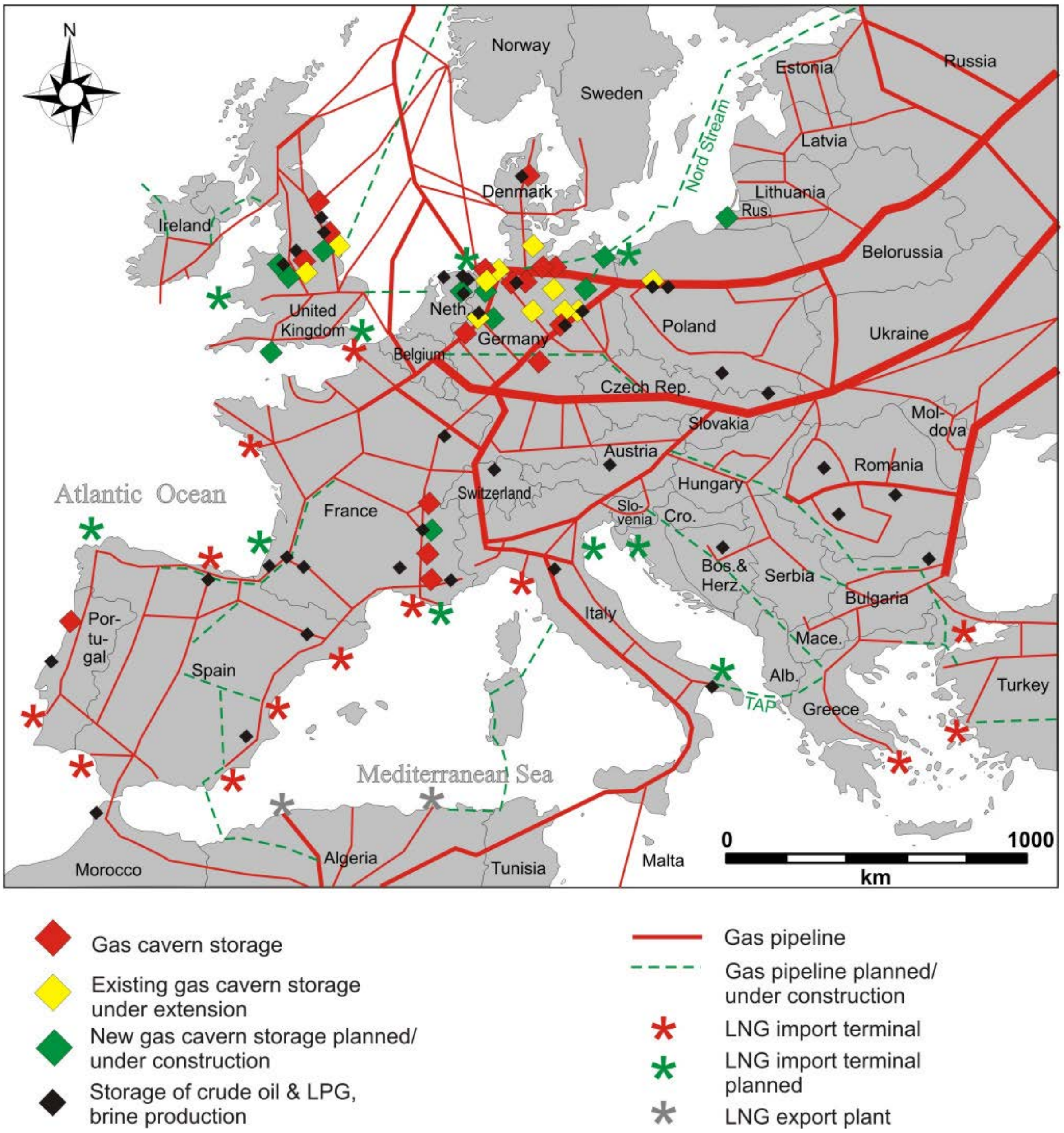

Fig. 2.5: Gas cavern storage system, piplines and LNG importterminals in Europe (Gillhaus, 2007)

Fig. 2.6 illustrates two in principle different methods to create storage caverns in salt. Figs 2.7 and 2.8 show the conventional leaching process, which can be subdivided into direct and indirect (reverse) circulation.

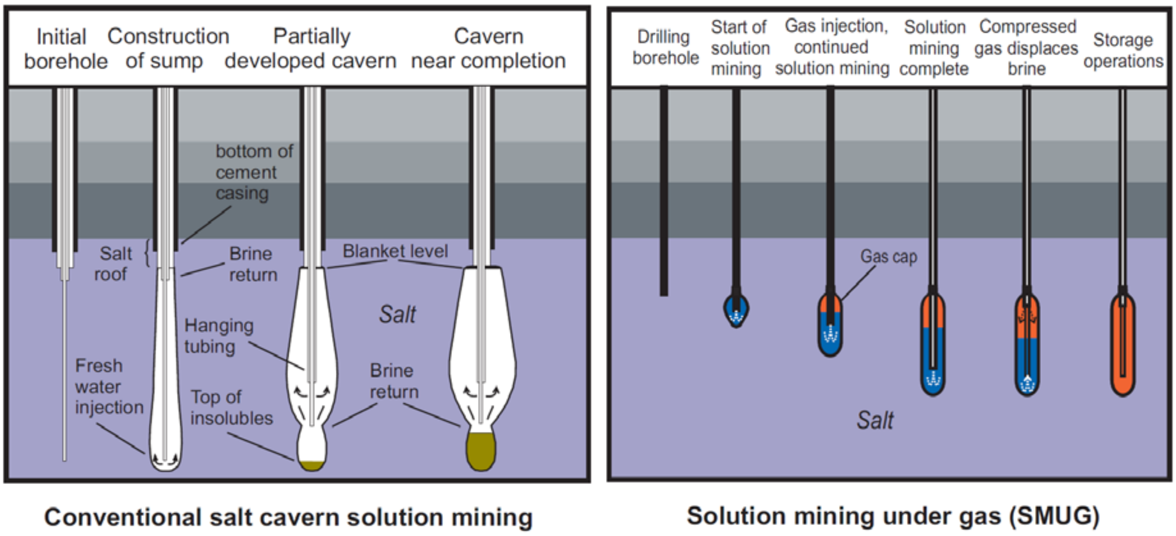

Fig. 2.6: Conventional versus SMUG solution process (BGS, 2008)

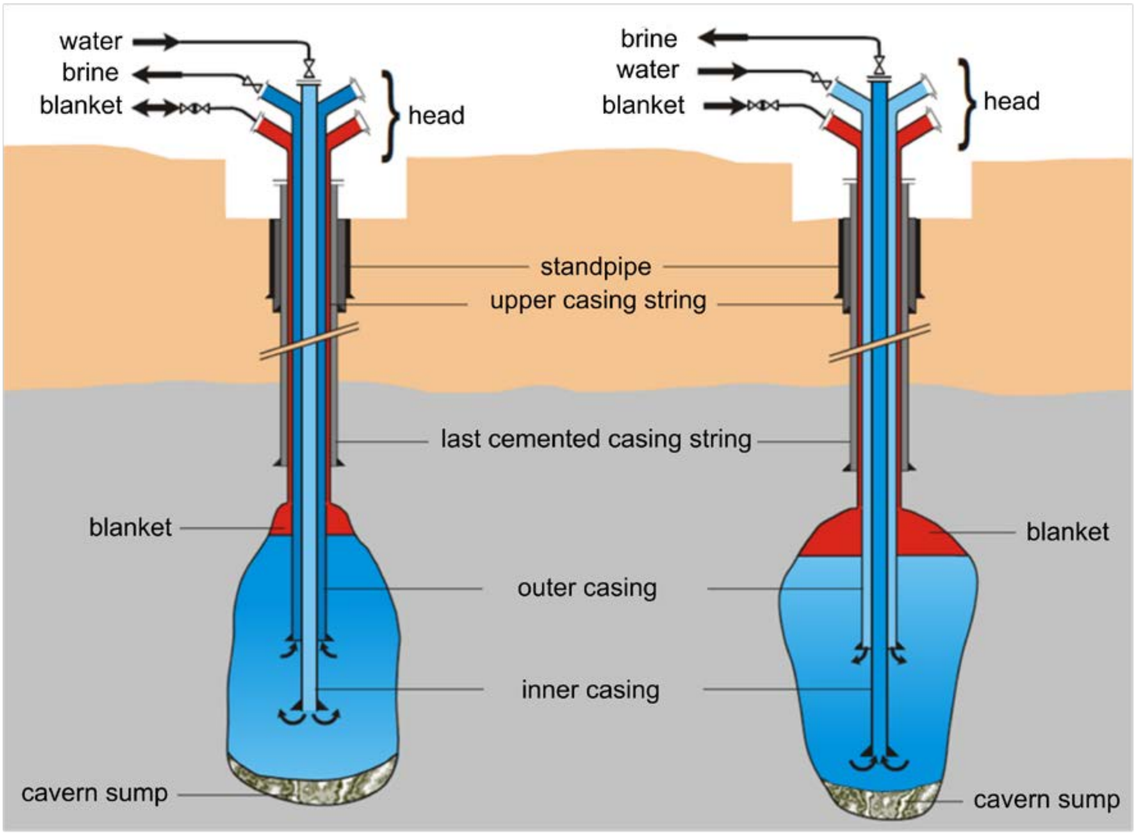

Fig. 2.7: Principles of direct (left) and revers (right) circulation to create salt caverns (Modified after KBB, 2007)

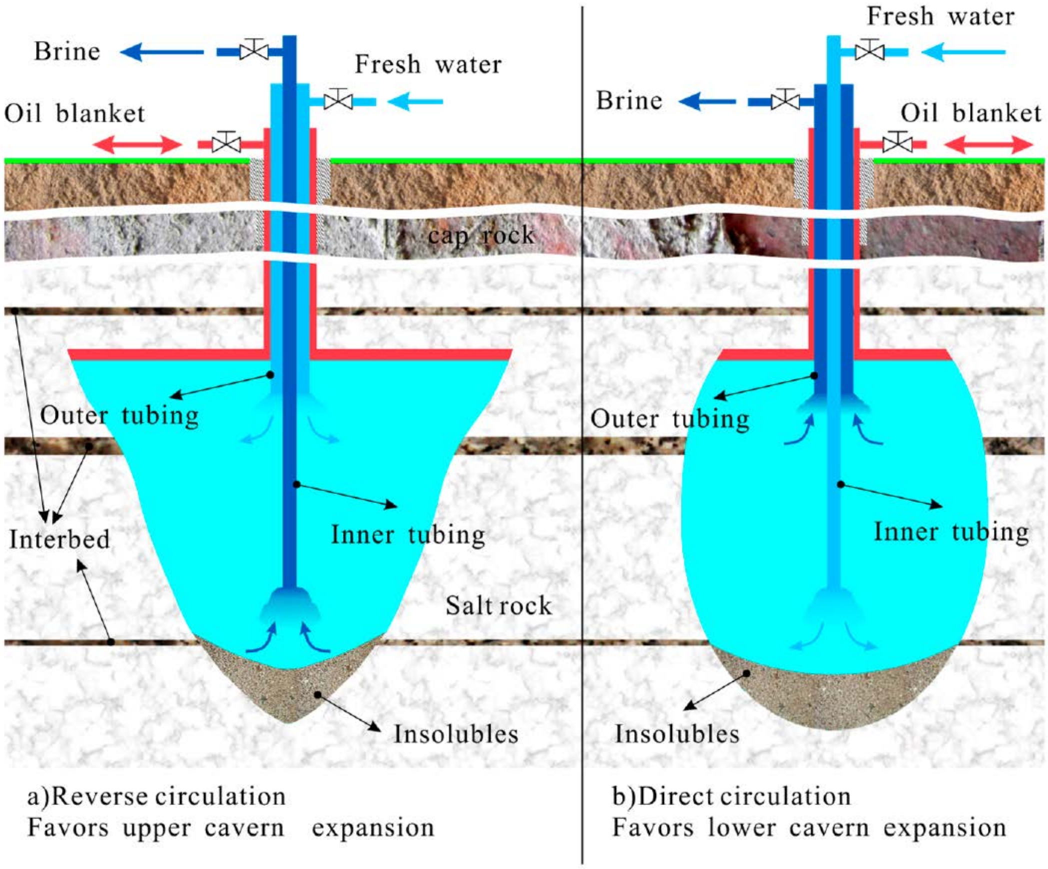

Fig. 2.8: Principles of direct and revers circulation to create salt caverns (Ge et al., 2019)

Fig. 2.9 illustrates the process of salt cavern leaching and subsequent usage from the point of view of stresses:

a) Virgin stress state prior to the leaching process
b) Leaching process
c) Extraction of brine and injection of storage product
d) First filling and cyclic operation

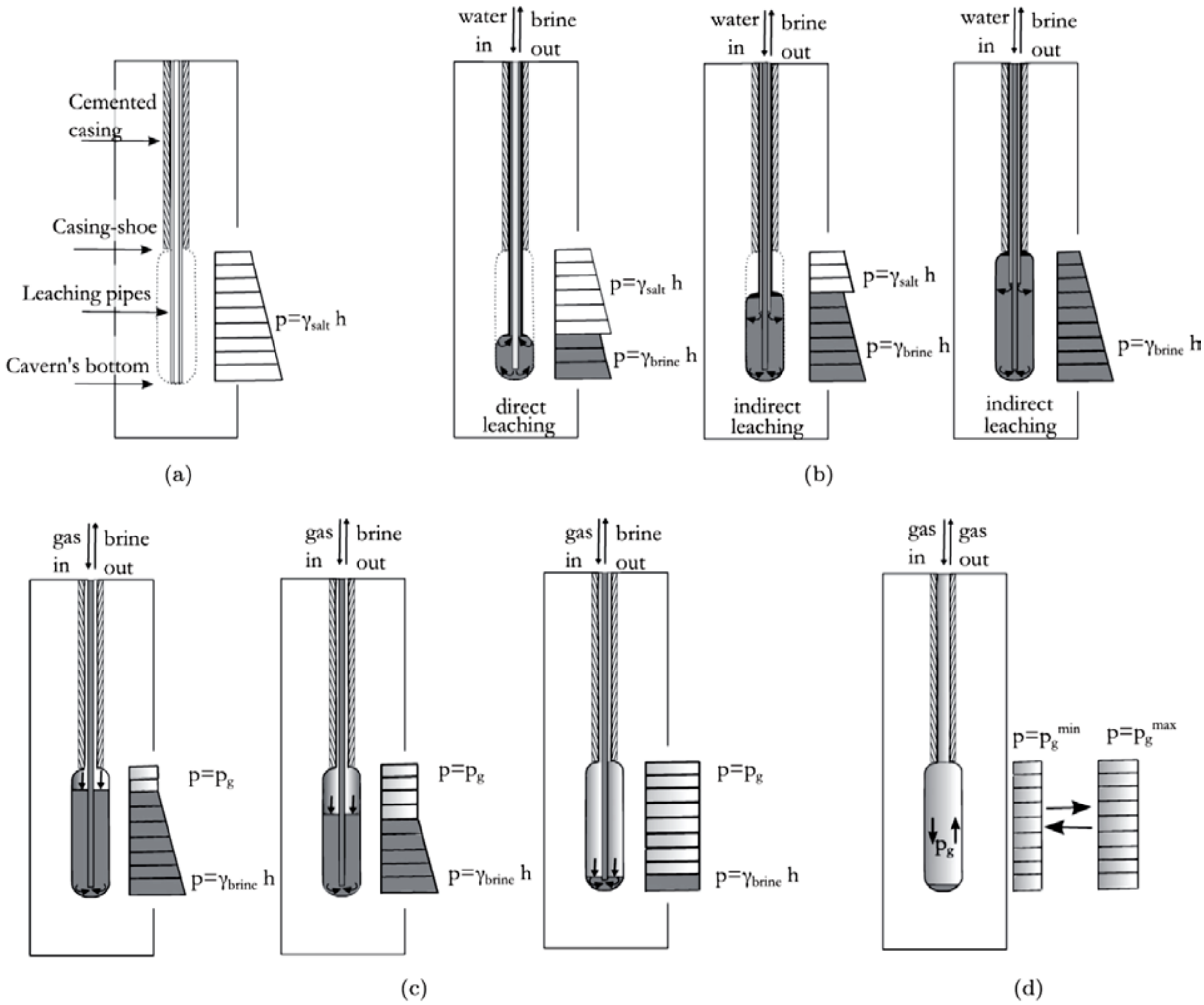

Fig. 2.9: Schematic representation of salt cavern leaching processand subsequent use of cavern under special consideration of acting stresses. a) Virgin stress state prior to the leaching process; b) Leaching process; c) Extraction of brine and injection of storage product; d) First filling and cyclic operation (Khaledi et al., 2016)

The design of caverns depends on the following geomechanical aspects:

- Depth of cavern
- Geometry of cavern
- Distance between caverns in case of a cavern field
- Distance of cavern to neighbouring geological units (especially the barrier)
- Pressure regimes during storage operation
- Constitutive behaviour of host rock (short and long term)

Fig. 2.10 illustrates the cavern design procedure in general, which consists of the following principal steps:

- Set-up of geological model
- Set-up of geomechanical model
- Transfer of geomechanical model into a numerical model

- Numerical simulation of storage operation, consideration of extreme scenarios (e.g. blow-out) as well as safety analysis of barrier system and long-term behaviour

In most cases several storage caverns are arranged in a field layout (see Fig. 2.11 to 2.13). In this case the distance between the caverns has to be considered and optimized.

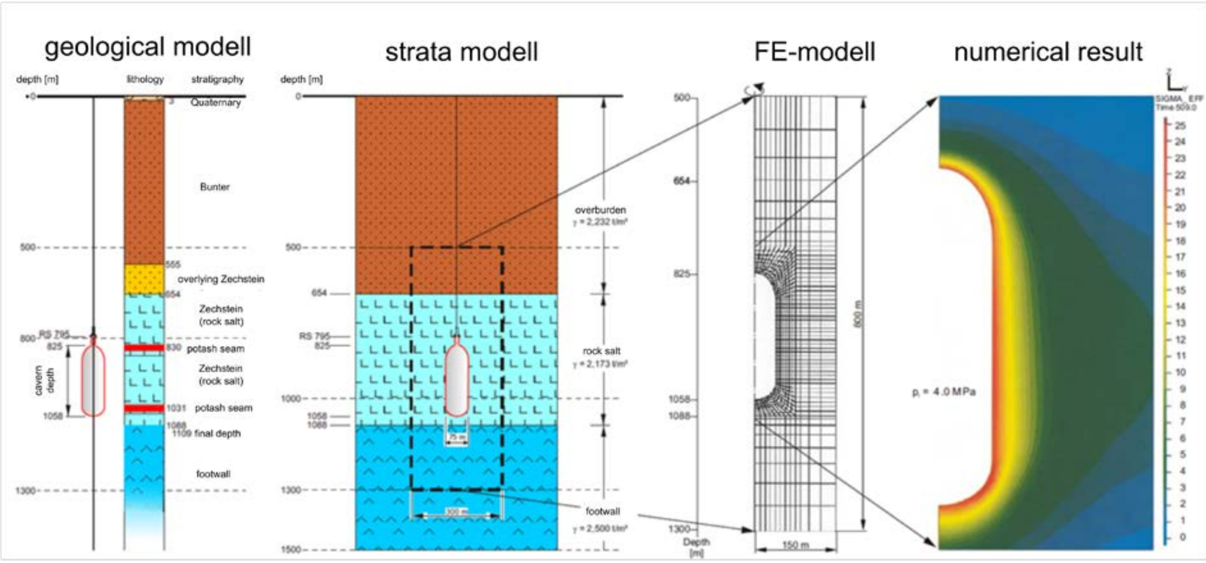

Fig. 2.10: Procedure for rockmechanical cavern dimensioning (Modified after KBB et al., 2007)

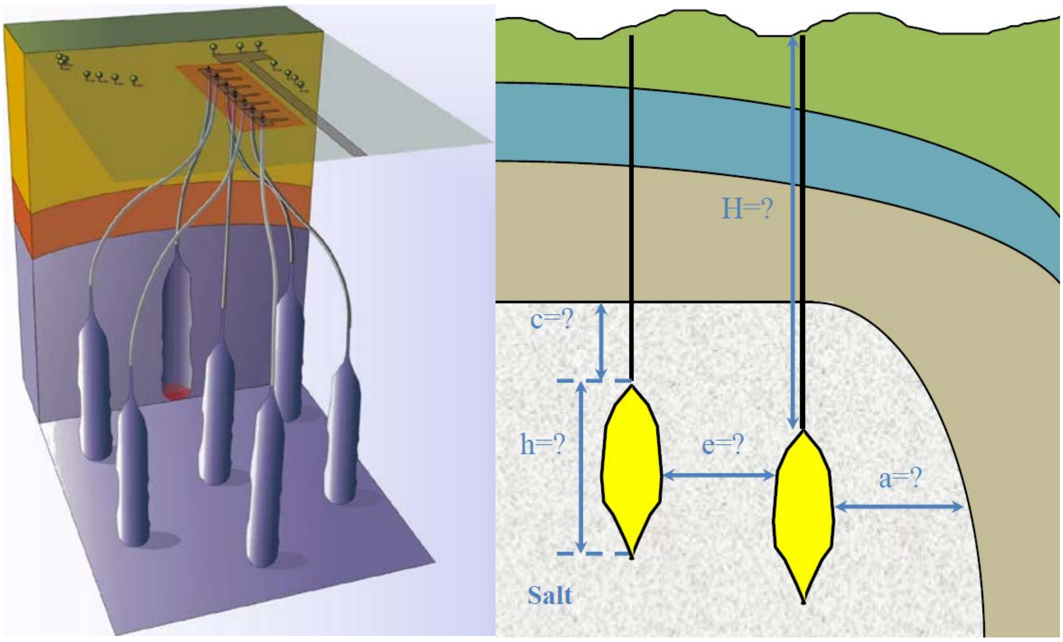

Fig. 2.11: Illustration of a cavern field (company material: KBB) and key geometrical parameters for salt caverns (Hevin, 2019)

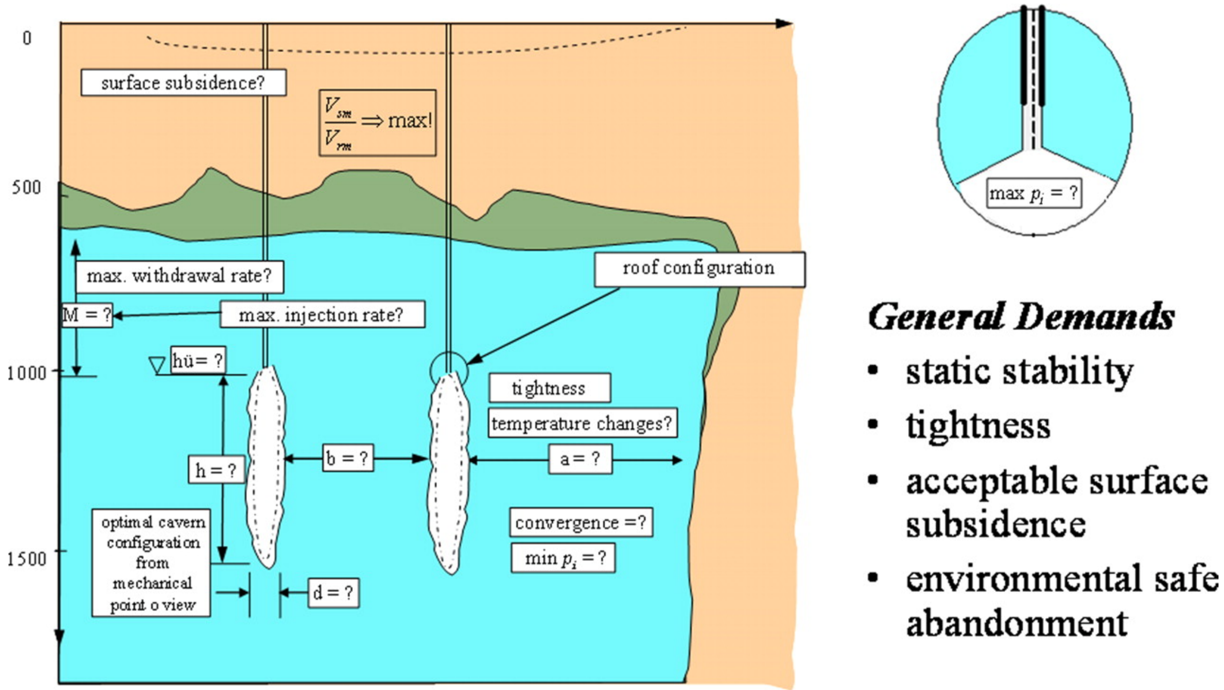

Fig. 2.12: Illustration of key geomechanical problems associated with salt caverns (Lux, 2009)

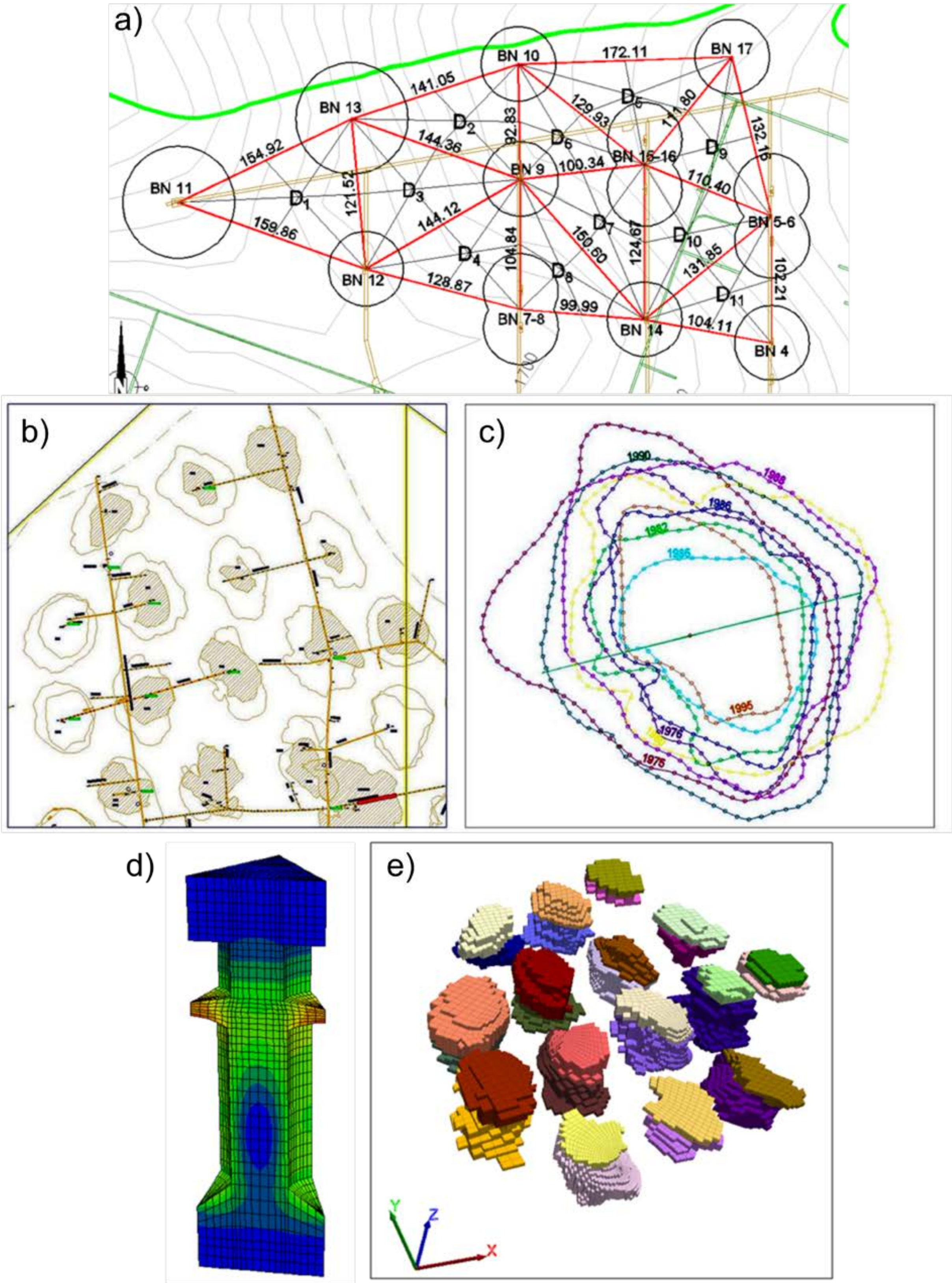

Fig. 2.13: Numerical simulation of a cavern fiel. a) idealized sketch of cavern field; b) real cavern field;c) contour of one single cavern for several depth values; d) numerical model for single pillar in idealized cavern field; e) complex 3D model for cavern field with realistic geometries (Modified after Huber et al., 2012)

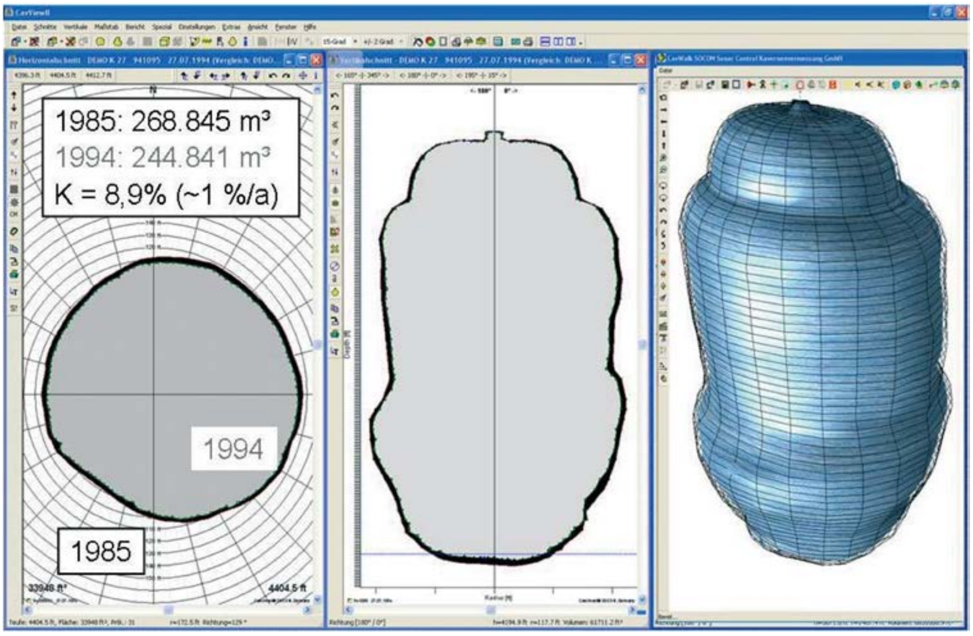

Fig. 2.14: Results of sonar measurement of a salt cavern (Reitze et al., 2010)

The geomechanical monitoring of caverns contains the following elements:

- Sonar measurements of the cavern contour (Fig. 2.14)
- Surface movement monitoring (geodetic, satellite etc.)
- Pressure monitoring
- Flow and volume balance monitoring
- Microseismic monitoring

The major geomechanical problems related to gas storage in salt caverns are:

- Potential of hydraulic fracturing and percolation (e.g. Knauth, 2018)
- Damage of the cavern contour
- Thermo-mechanical damage incl. cyclic fatigue
- Damage in the area of the casing shoe

The main geomechanical design parameters (see also Fig. 2.12) are:

- Minimum and maximum gas pressure in the cavern
- Service life at low gas pressure
- Maximum supply and discharge rates

Besides storage in rock salt caverns, also lined or unlined caverns in crystalline and metamorphic rocks are common (e.g. Morfeldt, 1983; Nanda et al. 2015; Naithani, 2012; Grøv, 2007). Unlined rock caverns are large underground excavations in rock formations. Typically, a cavern is 20 m wide, 30 m high and its length varies depending upon the storage capacity from 300 to 1000 m (see Fig. 2.15 and 2.16). Lined caverns are normally smaller.

Water curtain boreholes or tunnels and grouting may be necessary for cavern in hard rock due to the existence of fractures (see Fig. 2.15 to 2.17).

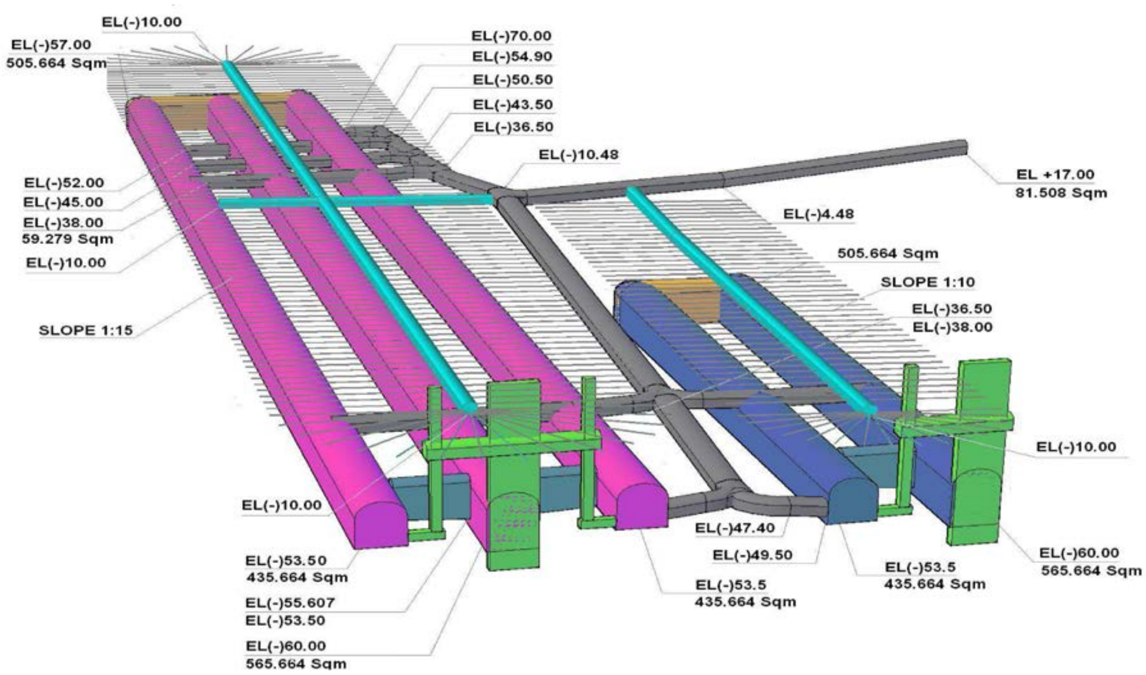

Fig. 2.15: Unlined cavern system in hardrock in India with water curtain boreholes (Höfer-Öllinger et al., 2014)

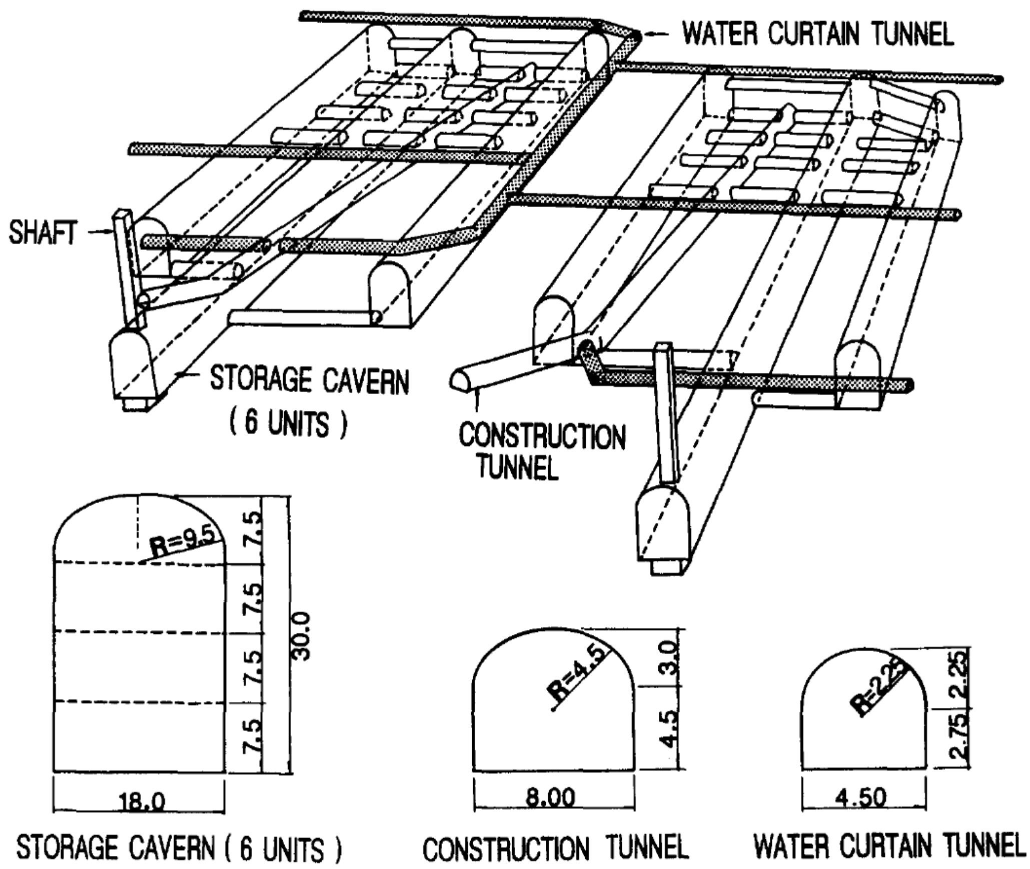

Fig. 2.16: Unlined cavern system in hard rock in South Korea with water curtain tunnels (Lee et al., 1996)

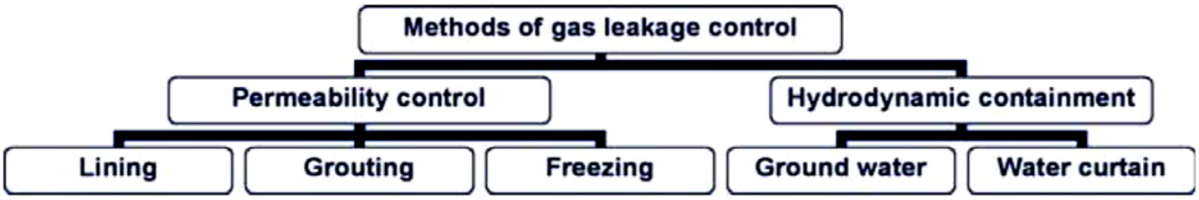

Fig. 2.17: Methods to control gas leakage from pressurised underground storage facilities (Grøv, 2007)

In terms of usage of renewable energy hydrogen will play an important role in the future and storage of hydrogen becomes an important task. Storage of hydrogen in large salt caverns (volume between about 500.000 to 750.000 m^3) is an interesting option. Caglayan et al. (2020) have investigated the corresponding potential in Europe. The underlying cavern scheme is illustrated in Fig. 2.18. Please note, that authors have considered onshore and offshore potentials, but they also cancelled regions where storage caverns would possibly not be accepted by the population due to several safety risks and ecological considerations. Fig. 2.19 documents the potential energy storage capacity for different countries in Europe.

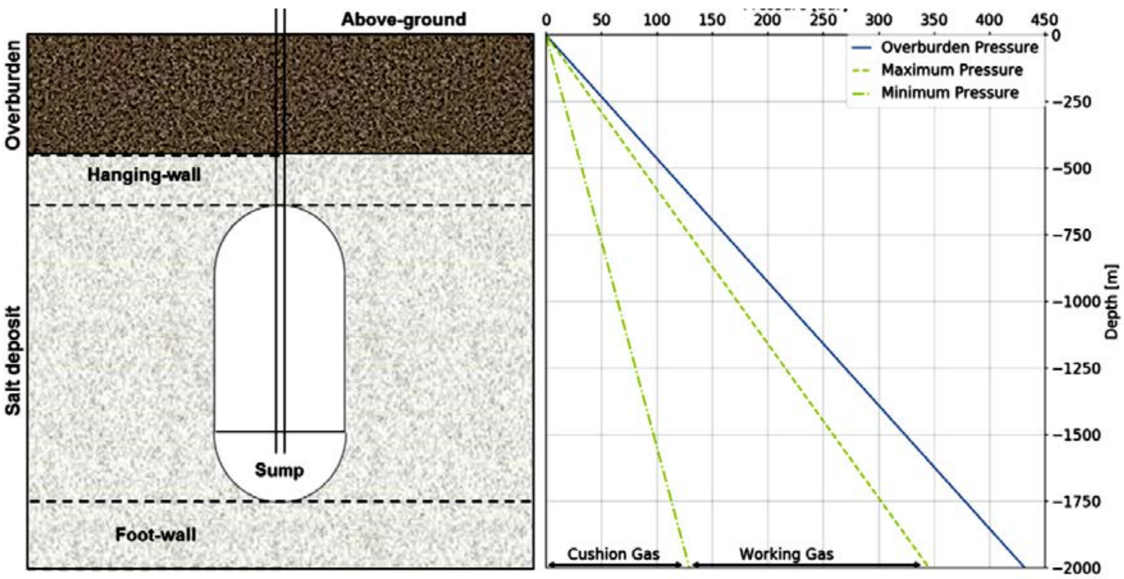

Fig. 2.18: Ilustration of general cavern layout and pressure regime used to estimate the hydrogen storage potential (Caglayan et al., 2020)

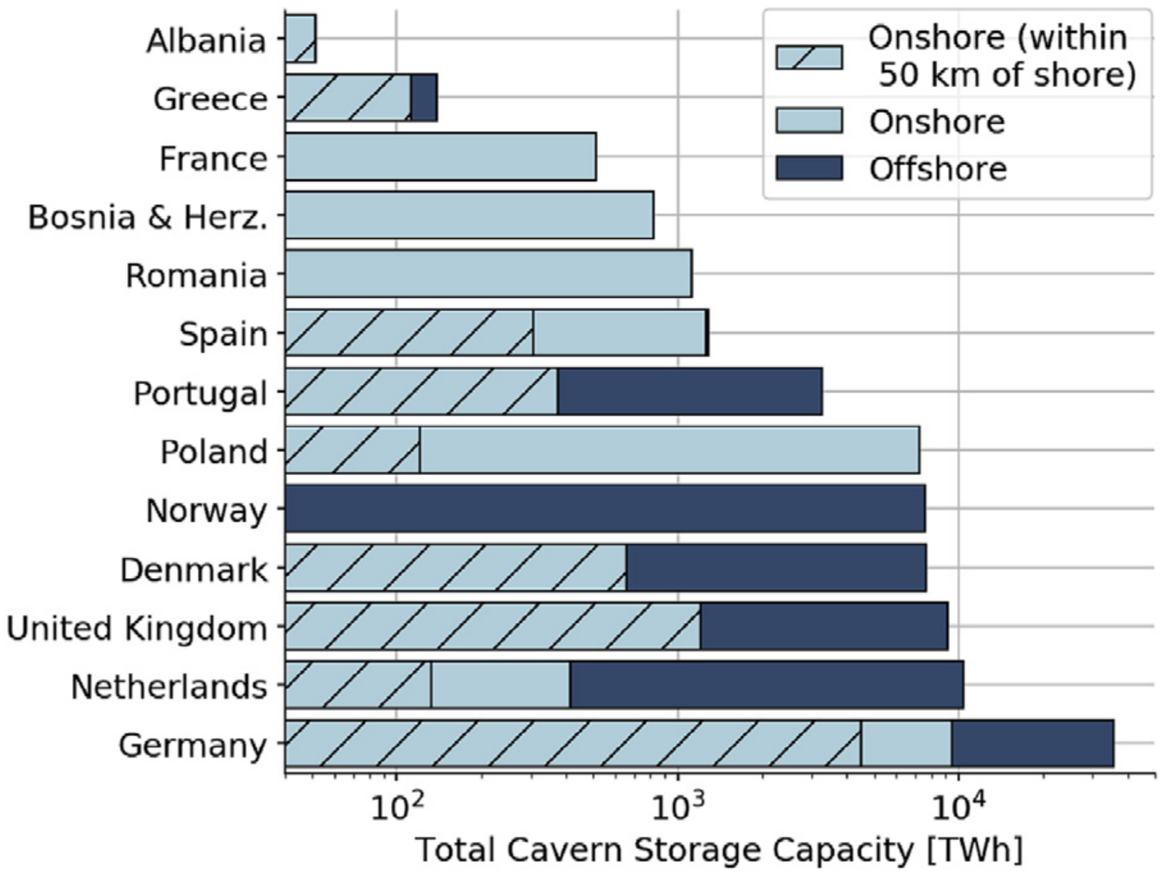

Fig. 2.19: Total hydrogen storage potential in Europe onshore and offshore within a distance of 50 km of shore (Caglayan et al., 2020)

The dimensioning of gas storage caverns are often based on the determination of a so-called utilization factor, which compares the current stress state in the near field of the cavern or the pillars between caverns with a critical value. Typical utilization factors which allow safe and long-term operations of gas caverns are in the order of 0.5. More details about the determination of utilization factors are given in the e-book “Factor-of-safety calculations in geomechanics”.

3 Pore storage

The concept of pore storage is illustrated in Fig. 3.1. Pore storage is a multi-phase problem, which needs the consideration of the following elements:

- Solid component (rock matrix)
- Gaseous phase
- Natural water phase
- Liquid phase

Pore storage can be performed under the following pre-requisites:

- upward curving structure (strata) that is closed off from all sides
- porous and permeable storage horizon
- impermeable cap rock
- an edge water reservoir that can accommodate the displaced water during the gas injection

Teatini et al. (2011) describe the geomechanical response of the operation of gas storage in a depleted reservoir, especially in terms of ground surface movement and fluid pore pressures. Fig. 3.2 shows a typical storage cycle for a gas storage reservoir. Please note, that a certain cushion gas pressure has always to be maintained in the reservoir. Fig. 3.3 illustrates the contacts between different phases. Depending on the actual situation (injection or extraction of gas) these phase boundaries will move.

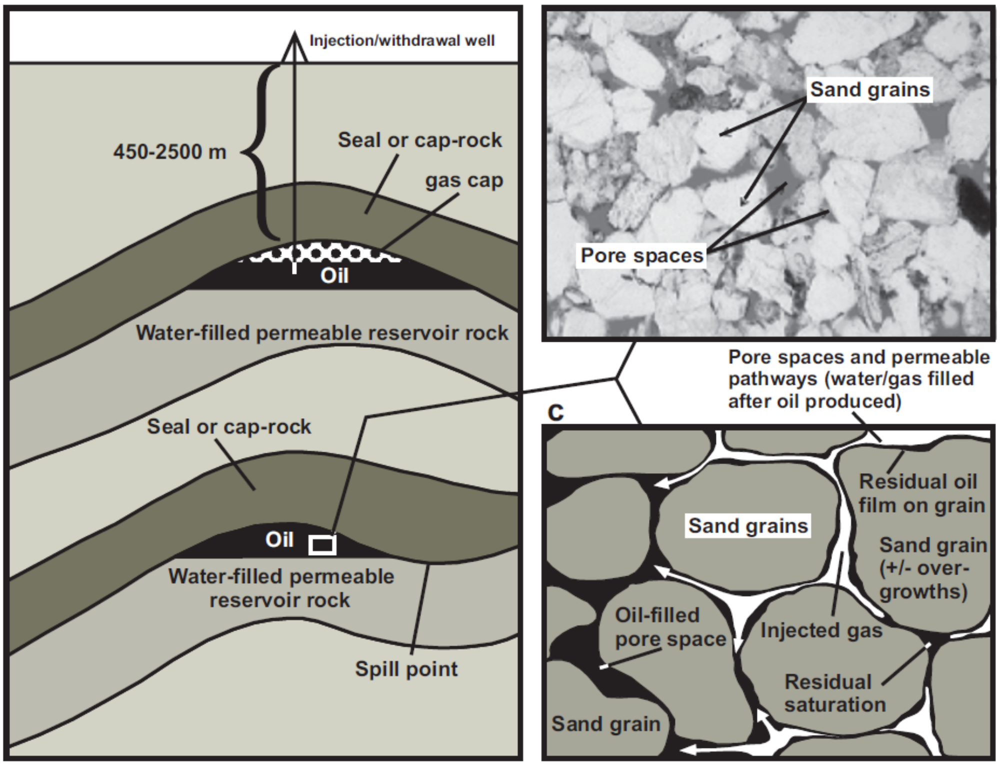

Fig. 3.1: Concept of pore storage (BGS, 2008)

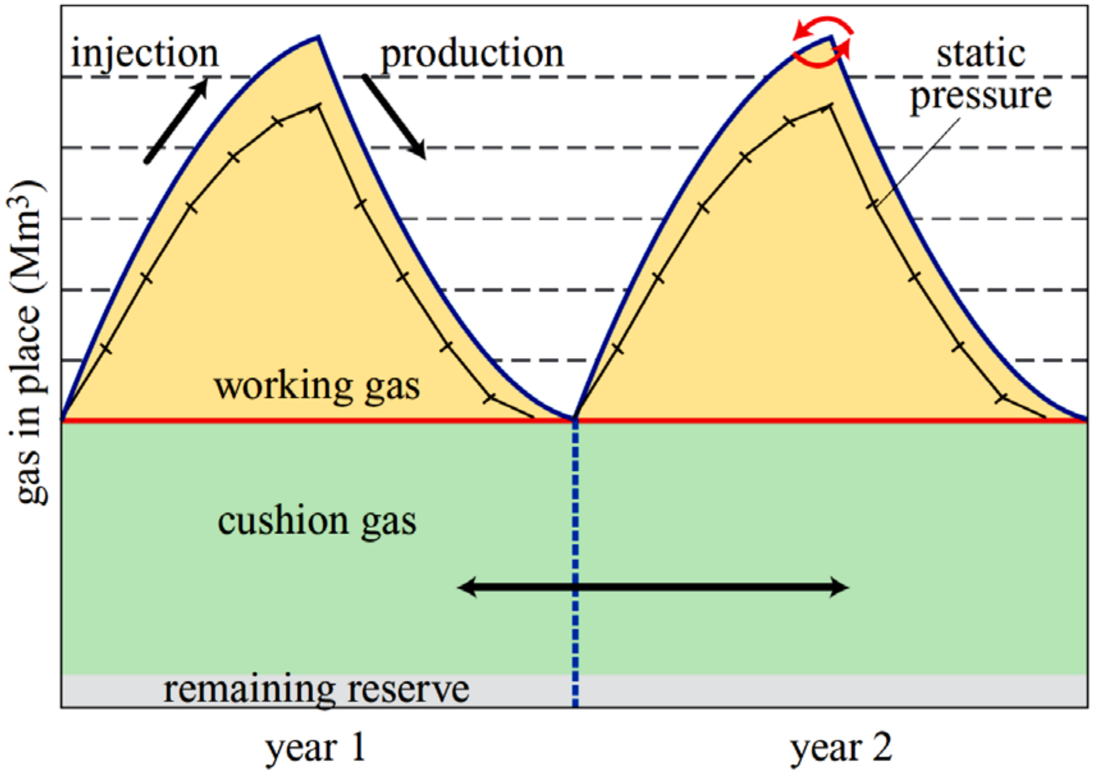

Fig. 3.2: Storage cycle (ENI, 2005)

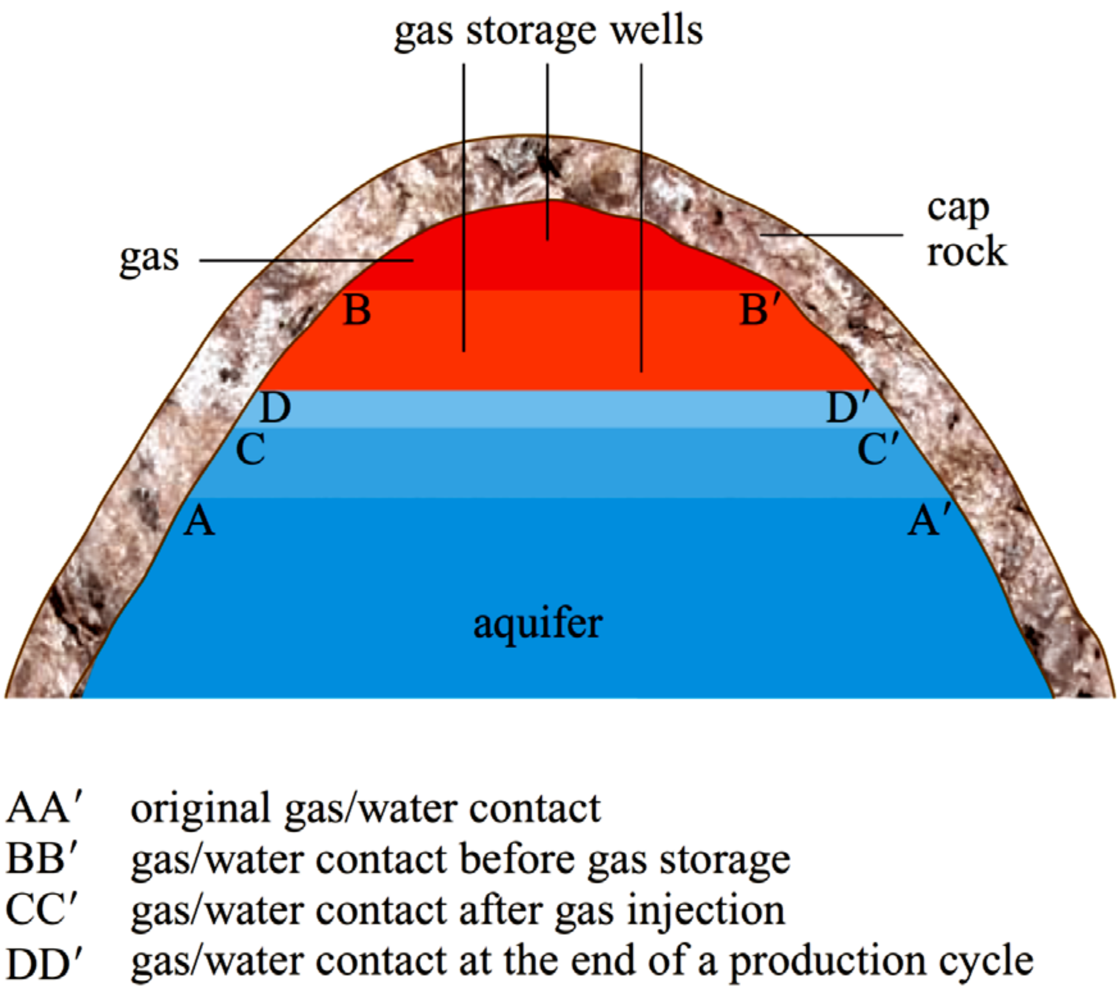

Fig. 3.3: Sketch for movement of gas-water contact for underground gas storage in a depleted reservior (ENI, 2005)

Tab. 3.1: Comparison between cavern and pore storage

Cavern storage	Pore storage
▪ small to medium volume	▪ large volume
▪ fast injection and discharge	▪ slow injection and discharge
▪ relatively small amount of cush-ion gas necessary	▪ relatively large amount of cushion gas necessary
▪ reaction with host rock minimized	▪ reaction with host rock possible

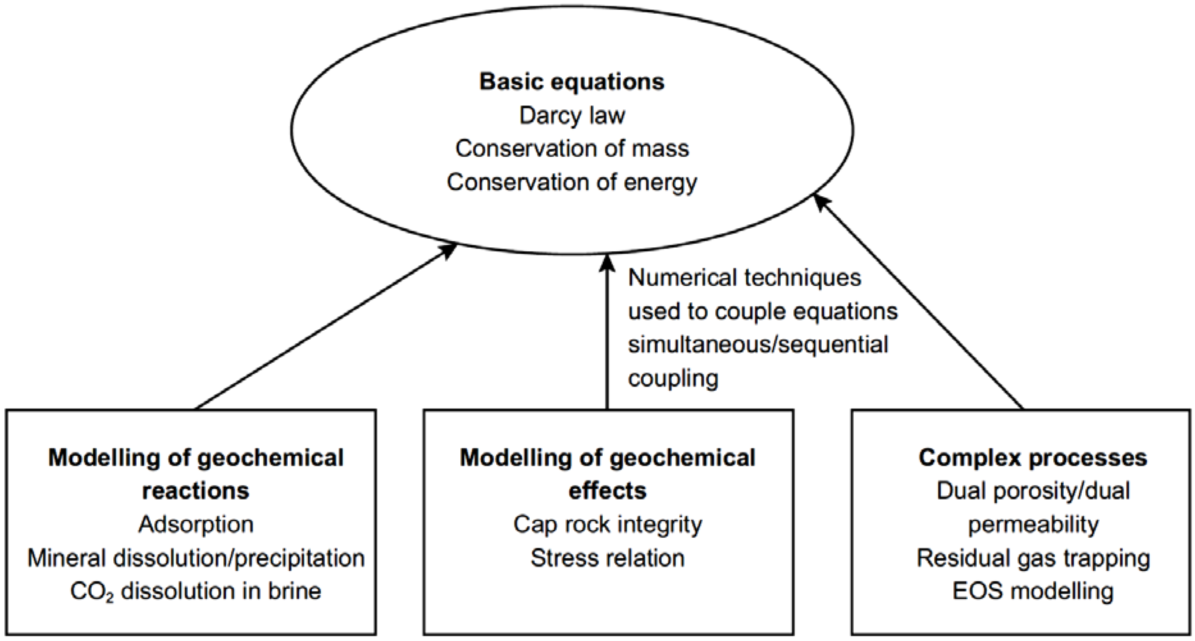

Fig. 3.4: Workflow of CO2 modeling (Ajayl et al., 2019)

Tab. 3.1 compares caverns and pore storage in terms of the main characteristics (main advantages/disadvantages). Pore storage is also used for CO_2-sequestration (e.g. Ajayl et al., 2019). The CO_2 storage can be realised by physical or chemical trapping (see also Fig. 3, which illustrates the modelling work flow under the hydro-chemical aspect). The following options are under discussion and usage, respectively:

- storage in saline aquifer formations
- storage in depleted oil or gas reservoirs
- storage in deep not recoverable coal beds after methane extraction
- storage during enhanced oil recovery

4 Underground pumped storage

An interesting option is the use of underground space for pumped-storage power plants (UPSH). Classical pumped-storage power plants as shown in Fig. 4.1 are already used worldwide. However, two aspects restrict a very broad application:

- It needs a certain topography (mountain area)
- It demands significant land use for upper and lower water reservoir (potential conflicts with environmental protection and nature conservation)

The use of underground space avoids the above-mentioned conflicts. Two different schemes are possible:

- Both water reservoirs are underground
- One water reservoir at the surface, the other underground (see Fig. 4.2)

Three major problems have to be considered for UPSH:

- Tightness of reservoirs, especially the underground ones
- Influence of underground water reservoir with groundwater regime (e.g. Pujades et al., 2016)
- Stability of underground infrastructure in respect to water pressure impact (e.g. Menéndez et at., 2019)

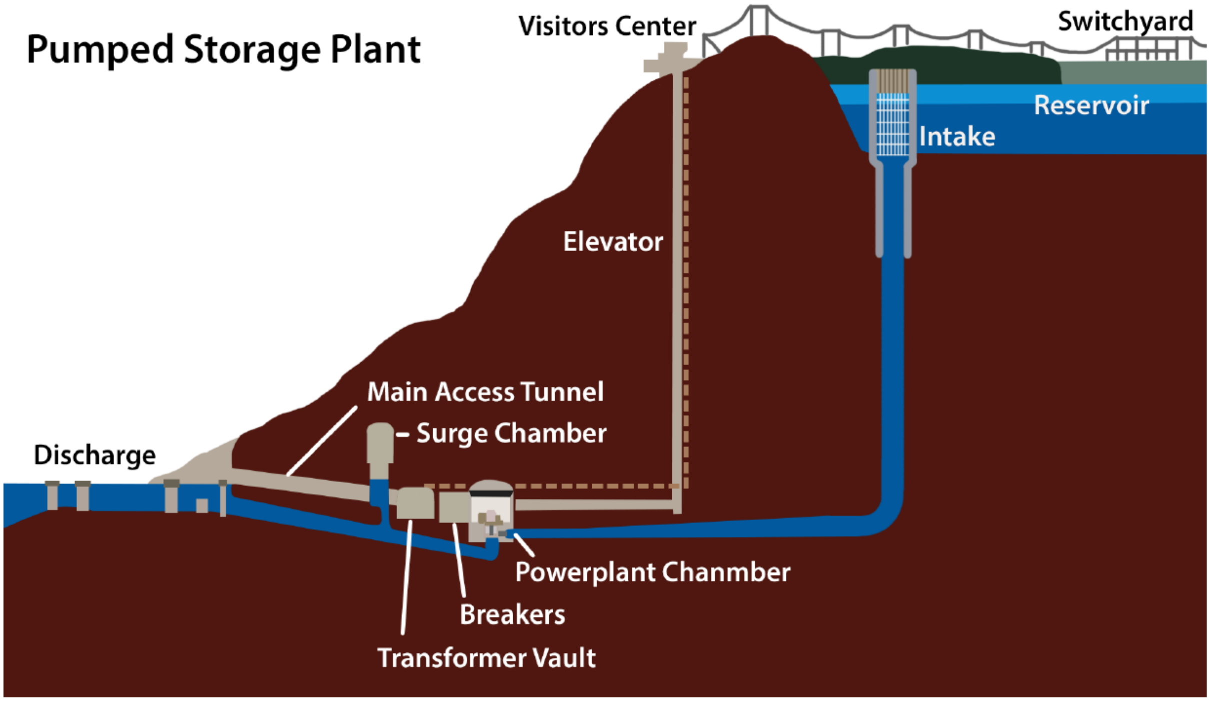

Fig. 4.1: Classical hydroelectric pumped-storage system (REA, 2016)

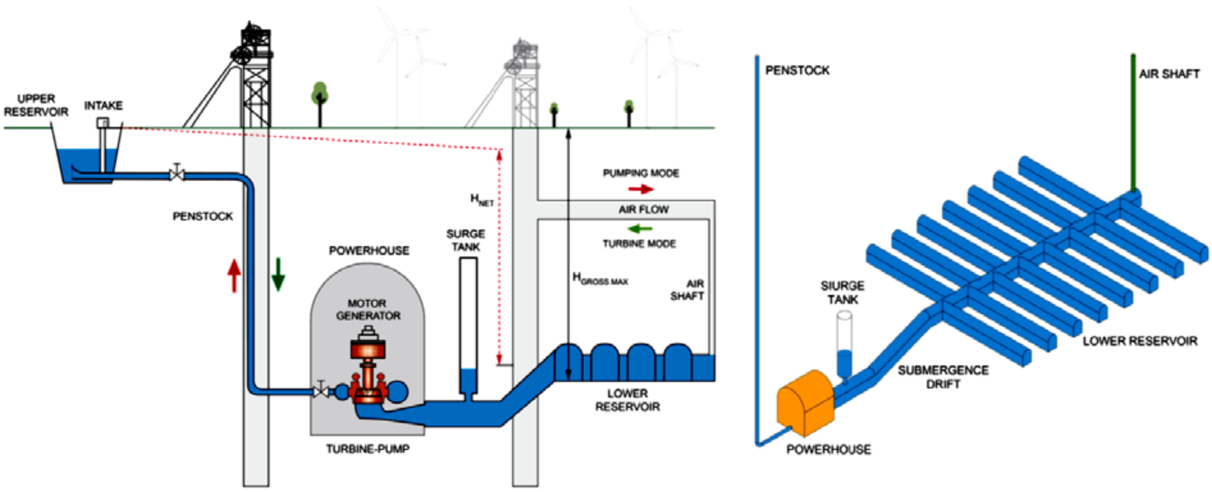

Fig. 4.2: Scheme for underground-pumped-storage system in a abondaned mine (Menéndez et al., 2019)

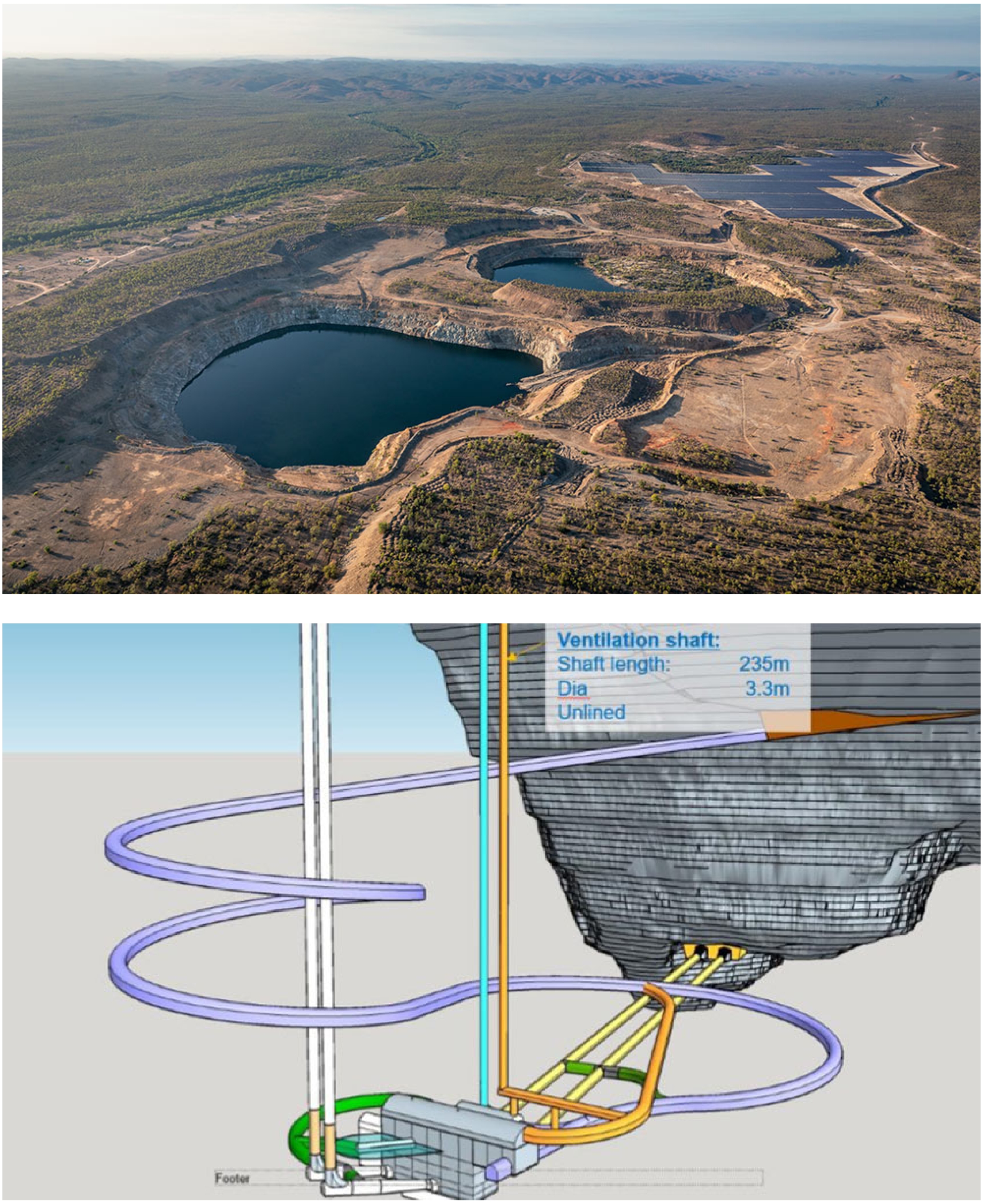

Fig. 4.3: Scheme for underground pumped-storage system in a abandoned mine: The Kidston project in Australia (Reynolds, 2020)

An interesting project is currently under construction in Australia. The planned pumped storage system in an exhausted open pit mine in Australia (Reynolds, 2020) is characterized by the following data (see Fig. 4.3):

- The power cavern complex has two caverns: the main powerhouse is 82.2 m long, 17.5 m wide and 44 m high and the transformer cavern is 31.8 m long, 10 m wide and 10 m high.
- The 1.5 km long access tunnel is 6.5 m wide and 6.6 m high.
- The intake shaft is 240 m deep and has a diameter of 4.8 m; the cable shaft is 250 m deep and has a diameter of 3.3 m; the ventilation shaft is 235 m deep and has a diameter of 3.3 m.
- The two tailrace tunnels are each 160 m long, 6 m wide and 6 m high

5 Environmental impact

Underground surface facilities have certain impact on the environment (e.g. Bauer et al. (2013) and Bruns (2015)), which have to be considered by planning and maintenance of such facilities. Fig. 5.1 lists some of the most important impact factors. Most important potential negative impacts in case of underground storage of liquids are ground surface movements above certain thresholds, induced seismicity and escape of fluids due to leakages and damage of the geological barrier. Exemplary, Fig. 5.2 shows the correlation between storage activity and induced seismicity for a pore storage field in Italy. Figs 5.3 and 5.4 show the ground surface movement above a pore storage field in northern Italy. There are several regulations and recommendations for safe, economic and environmentally friendly operation of underground storage facilities like Ground water protection council and Interstate oil and gas compact Commission (2017).

- typically no effect
x site specific assessment
X typically effect

	large scale pressure change	brine movement	liquid phase movement	induced seismicity	land subsidence	temperature changes	chemical and microbial reactions
groundwater production	x	-	-	-	x	-	x
near surface geothermal energy	-	-	-	-	-	X	X
hydrocarbon production	X	x	X	x	x	x	x
salt production	x	X	-	-	x	-	X
mining	X	x	-	X	X	x	x
deep geothermal energy	X	X	-	X	-	X	X
natural gas storage	x	X	X	x	X	x	x
heat storage	-	-	x	x	x	X	X
compressed air storage	-	-	-	x	X	X	x
storage of synthetic methane	X	X	X	x	X	x	x
storage of hydrogen	X	X	X	x	X	x	x
brine / liquid waste disposal	X	X	-	X	x	x	X
CO_2 disposal	X	X	X	X	x	x	X

Fig. 5.1: Potential environmental impact in case of use of geological subsurface for energy and liquid storage (Bauer et al., 2013)

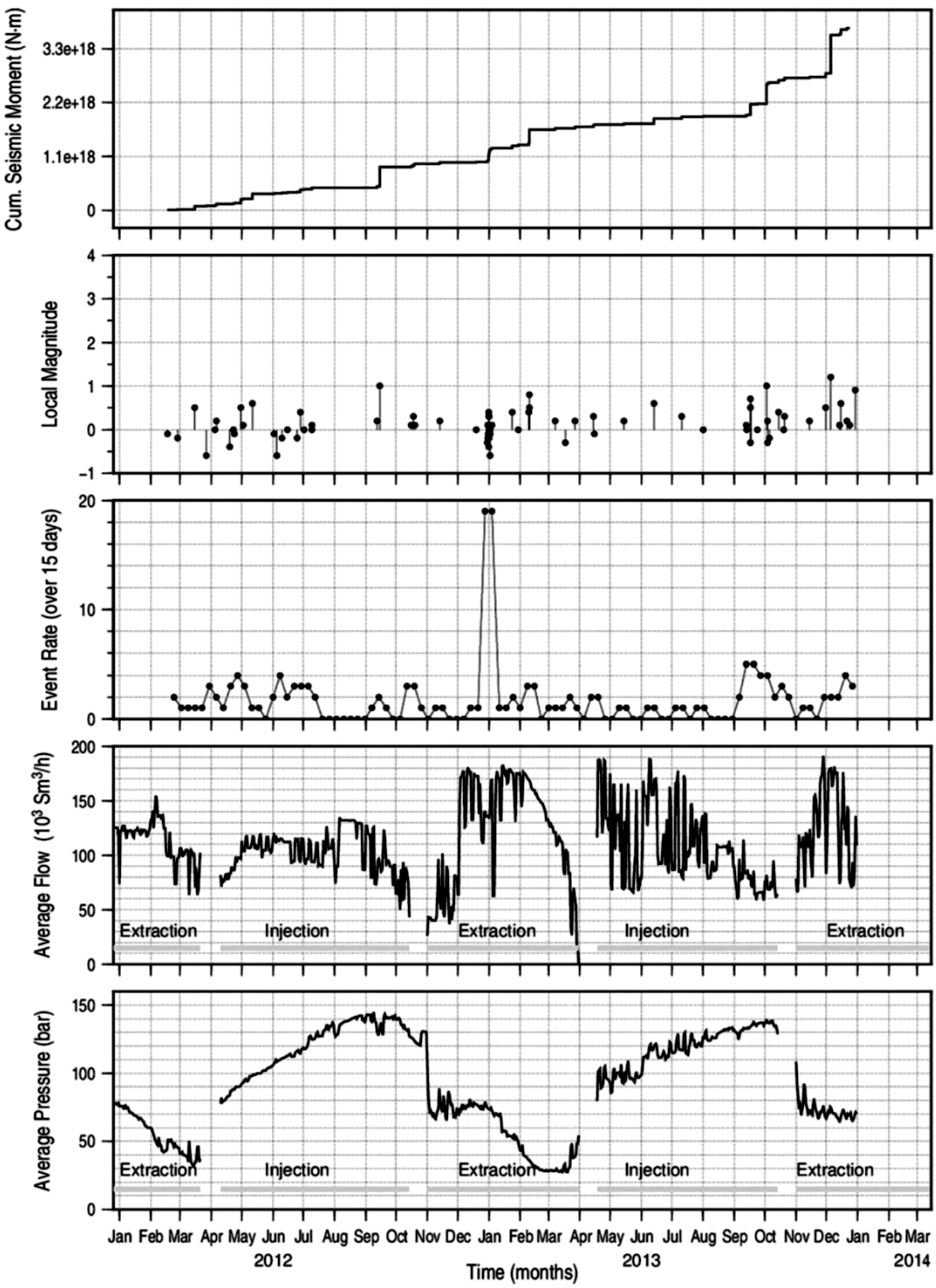

Fig. 5.2: Comparison between seismicity and gas storage activity of the Collalto Stoccaggio field (Priolo et al., 2015)

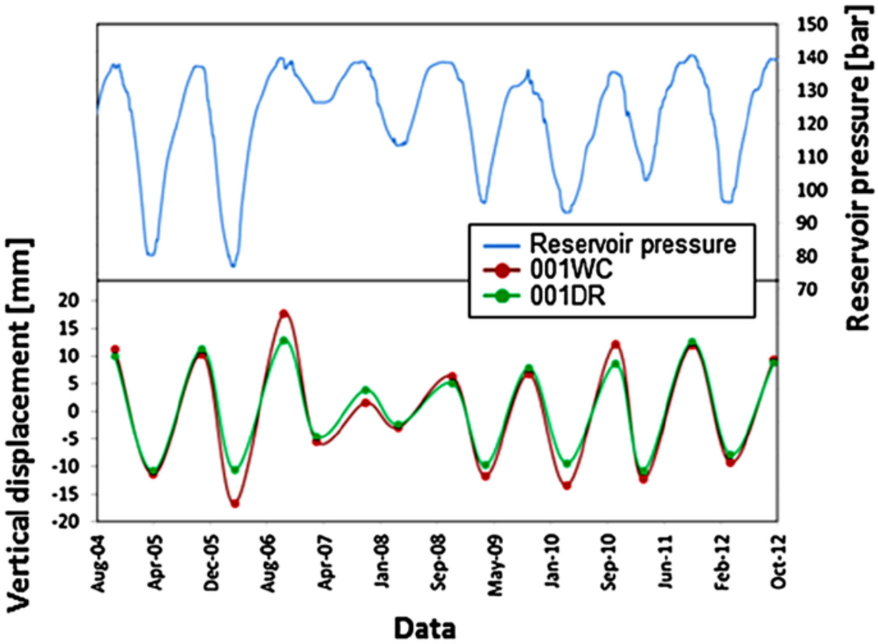

Fig. 5.3: Average reservoir pressureand vertical movement of two measurement points above the storage area (Codegone et al., 2016)

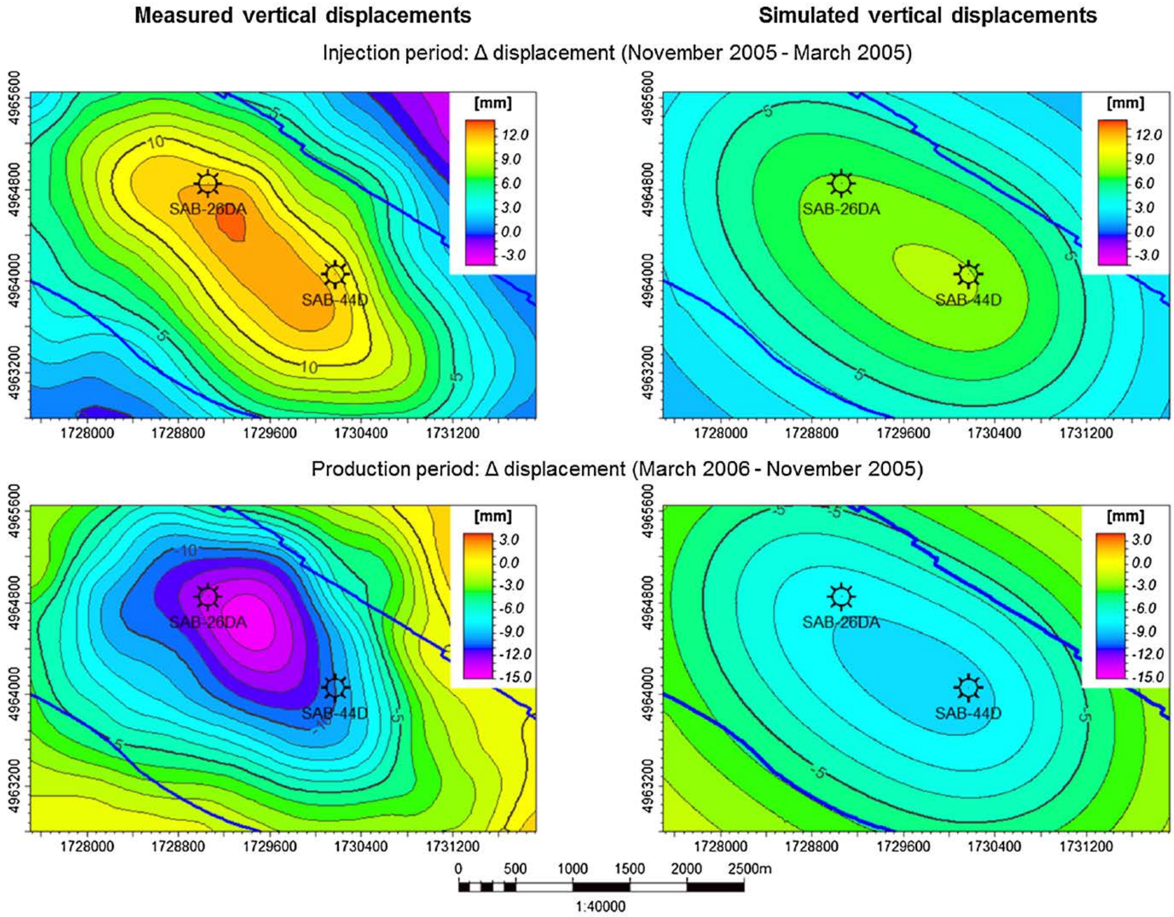

Fig. 5.4: Measured and simulated ground surface displacements above the storage area (Codegone et al., 2016)

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