Usage of underground space

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1 Introduction

For a long time, the mankind has used the underground space for different purposes, for instance for housing, storage facilities, water channels or for raw material extraction. Nowadays the underground space is used for:

- Extraction and storage of energy
- Extraction of raw materials
- Traffic routes (road and railway tunnels, metro lines etc.)
- Storage of raw materials (oil, gas etc.)
- Storage of waste (toxic, radioactive, construction waste etc.)
- Underground city infrastructure (car parks, office spaces, storage places, shops etc.)
- Urban supply infrastructure (telecommunication lines, electricity lines, water pipes, waste water systems, gas pipes, heating pipes etc.)
- Protected underground spaces (bunker) and military facilities
- Underground production and storage facilities
- Underground computer centres
- Underground research facilities (e.g. particle accelerators)
- Underground farming

Lack of surface space due to increasing population and the demand for better living conditions (especially better air and climate conditions) accelerate the activities to use the underground space to a larger extend, but especially in an environmentally friendly and innovative manner. The intensified use of the underground space can lead to energy and raw material savings and reduces the land use (reduction of soil sealing), which allows increasing vegetation, which contributes to a cleaner environment with better air conditions.

The increasing use of urban underground space contributes to achieving several of the sustainable development goals (SDG's) of the UN (Admiral & Cornaro, 2016):

- ensure availability and sustainable management of water and sanitation for all (SDG 6);
- ensure access to affordable, reliable, sustainable and modern energy for all (SDG 7)
- promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (SDG 8)
- build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation (SDG 9)
- make cities and human settlements inclusive, safe, resilient and sustainable (SDG 11)
- take urgent action to combat climate change and its impacts (SDG 13)

An intensive literature study up to the end of 2019 suggests (Volchko et al., 2020):

- The subsurface must be recognised not only by scientists but also by decision- and policy-makers and other stakeholders as a precious and multifunctional resource, which provides physical space, water, energy, materials, habitats for ecosystems, support to surface life and holds cultural heritage and geological archives. Careful planning and sensitive management of the subsurface needs to be stipulated.
- One underground resource (e.g. physical space) can provide several competing or coexisting subsurface functions – e.g. space for infrastructure and space for storage of gas, oil, carbon dioxide and waste which turn into services when utilised by humans.
- The subsurface comprises both man-made and natural assets and in this way creates actual or potential values to humans. Ignorance of these values can lead to incorrect or misleading assumptions about the subsurface in spatial planning processes, and as a result, opportunities can be lost in terms of various benefits that its responsible use might otherwise offer.
- Utilisation of the different subsurface functions to yield services requires not only careful planning but also a framework to support the decision-making process in achieving a balance between utilisation and preservation; where a decision is made to utilise fully rather than preserve the various subsurface functions a balance between the different usages should also be sought.
- To facilitate the change towards transdisciplinary work settings in the spatial planning processes and form a platform for knowledge exchange and capacity building, there is an urgent need for a common language, i.e. mutually understandable terminology, and a common understanding, i.e. an all-inclusive view on the subsurface as a complex multifunctional resource. Although not yet fully developed, geosystem services can be a key concept to achieve this.
- To overcome the “first-come-first-served” problem and thus enable fair inter- and intragenerational distribution of limited natural resources as well as sustainable development of cities, it is necessary to:
    - Shift the focus from man-made objects underground to subsurface functions;
    - Create the right conditions – mainly facilitated by making available timely, accessible and high-quality subsurface information – for bridging the communication gap between engineering geologists, civil engineers, architects, urban planners, urban designers and other stakeholders in spatial planning processes;
    - Investigate and map multiple subsurface potentials on a city scale to prevent lost opportunities at both city and project scales, including the potential to reuse already exploited space;
    - Balance development and resource perspectives on subsurface planning for prioritisation and optimisation of competing subsurface uses, and resolution of potential conflicts of interests;
    - Ensure through legislation that the precautionary principle is applied when allocating underground resources;

- Bring into focus the decision-making process itself (who, when, how) to support sustainable solutions on subsurface use, rather than the decision-support tools and methods themselves.

Von dem Tann et al. (2020) provide a comprehensive overview about different aspects for underground space planning and management based on analysing the corresponding history.

The bigger cities have already now specific plans for using the underground space, which is necessary to avoid conflicts between different types of use and to optimise the usage of the space. Exemplary, Fig. 1.2 shows the planning and already existing use of underground space for the city of Helsinki, Finland. The key factors, that have to be considered for underground work spaces are illustrated in Fig. 1.3.

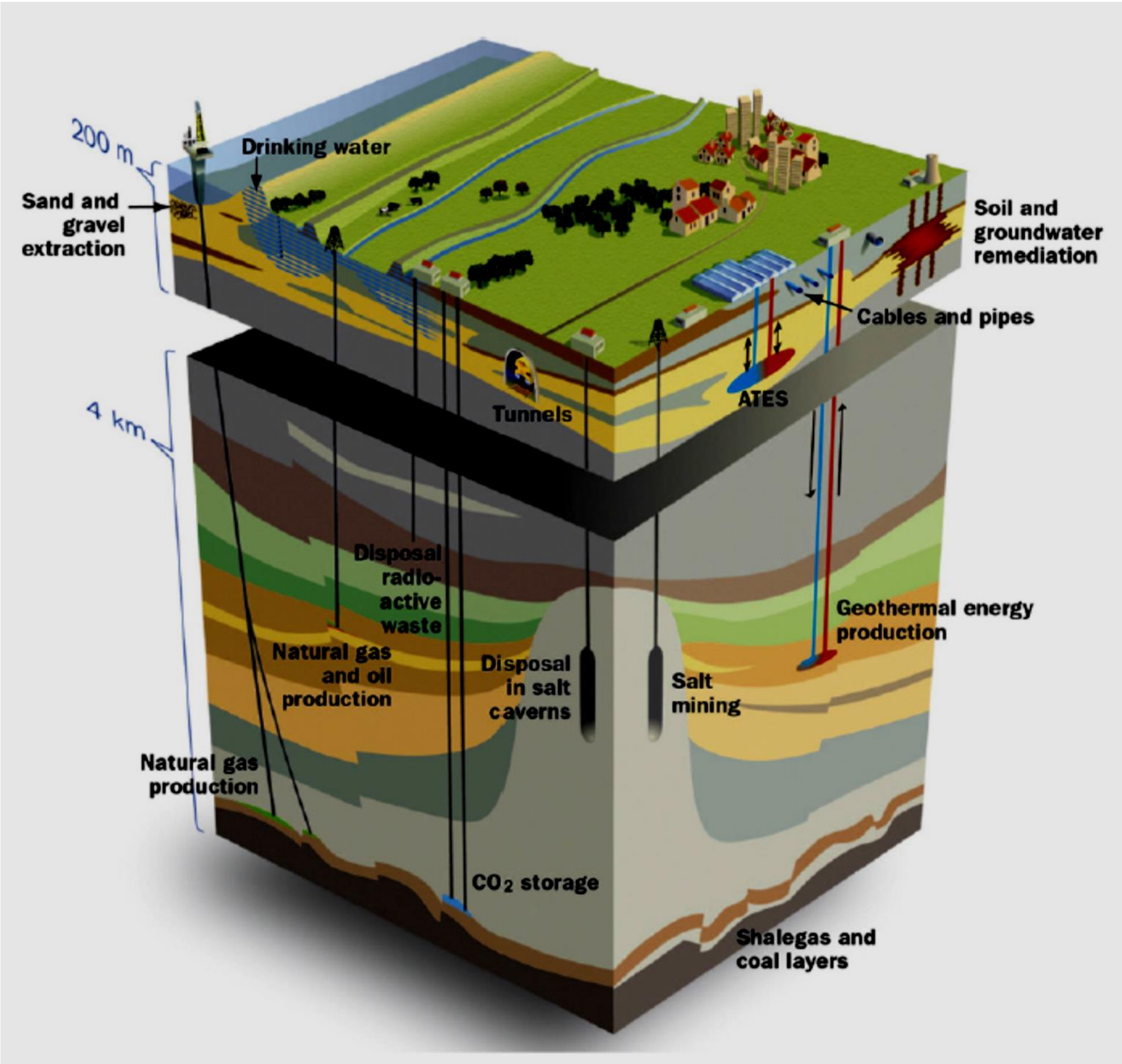


Fig. 1.1: Multiple usage of the subsurface (Griffioen et al., 2014)

Notes:

Dark grey	Existing underground spaces and tunnels
Grey =	Planned underground spaces and tunnels
Light grey =	Rock resources reserved for the construction of as yet unnamed underground facilities
Lightest grey	Rock surface less than 10 m below ground surface

(Courtesy Helsinki City Planning Department / Strategic Urban Planning Division)

Fig. 1.2: Existing and planned usage of underground space in the city centre of Helsinki (top) and planned used for underground constructions according to the master plan 2010 (bottom) for Helsinki (Vähäaho, 2011).

Tender et al. (2017) characterise the advantages of underground constructions according to the following three main criteria:

- Mobility
    - Improvement of accesses and traffic flow (decreasing travel time)
    - Reduction of risk of traffic collisions and accidents
- Quality of life
    - Increase of quality of life level
    - Infrastructure availability for everyone
    - Creation of free space at the surface for other (green) usage
- Economic and social sustainability
    - 3-dimensional freedom for design and planning
    - Surrounded by an excellent insulation level (temperature, noise, vibrations)
    - Low maintenance costs
    - Added value to real-estate and public space
    - Creation of new jobs and improved skills during construction
    - Fight against isolation of people and reduction of inequalities
    - Increase of population without extend of urban borders
    - Protection from terror attack, industrial accidents, heavy rainfall, erosion, earthquakes or other georisks

In terms of costs and financial balance the following has to be considered (Sterling & Godard, 2000):

- Constructions costs are high (big investment)

On the other hand:

- Costs for energy and maintenance are low,
- Lifetime is longer (replacement costs are low),
- Savings due to special design features (thermal isolation, noise protection etc.).

The use of underground space in urban regions (UUS) is of primary importance. Fig. 1.4 summarizes the benefits which can be obtained by UUSV.

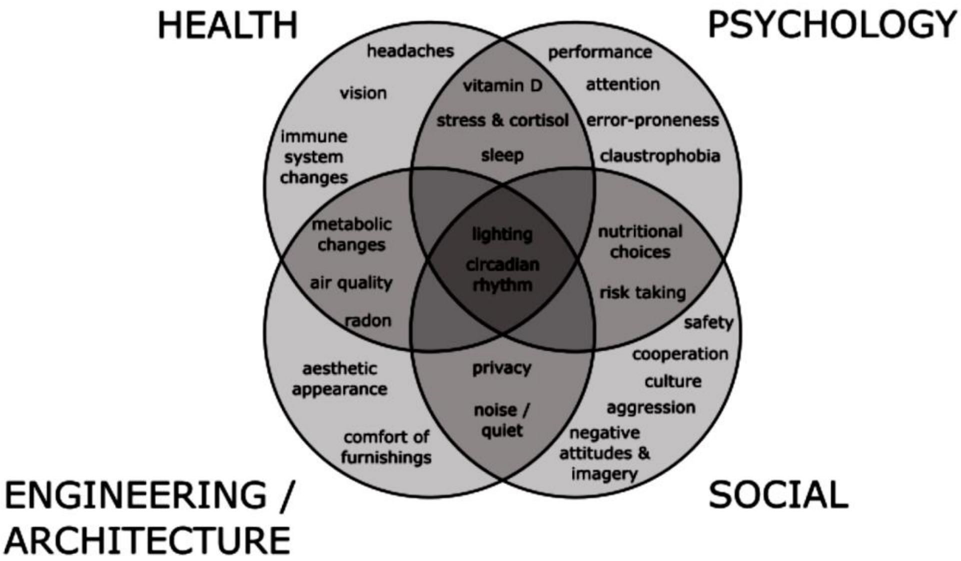


Fig. 1.3: Key factors associated with underground work spaces (Soh et al., 2016)

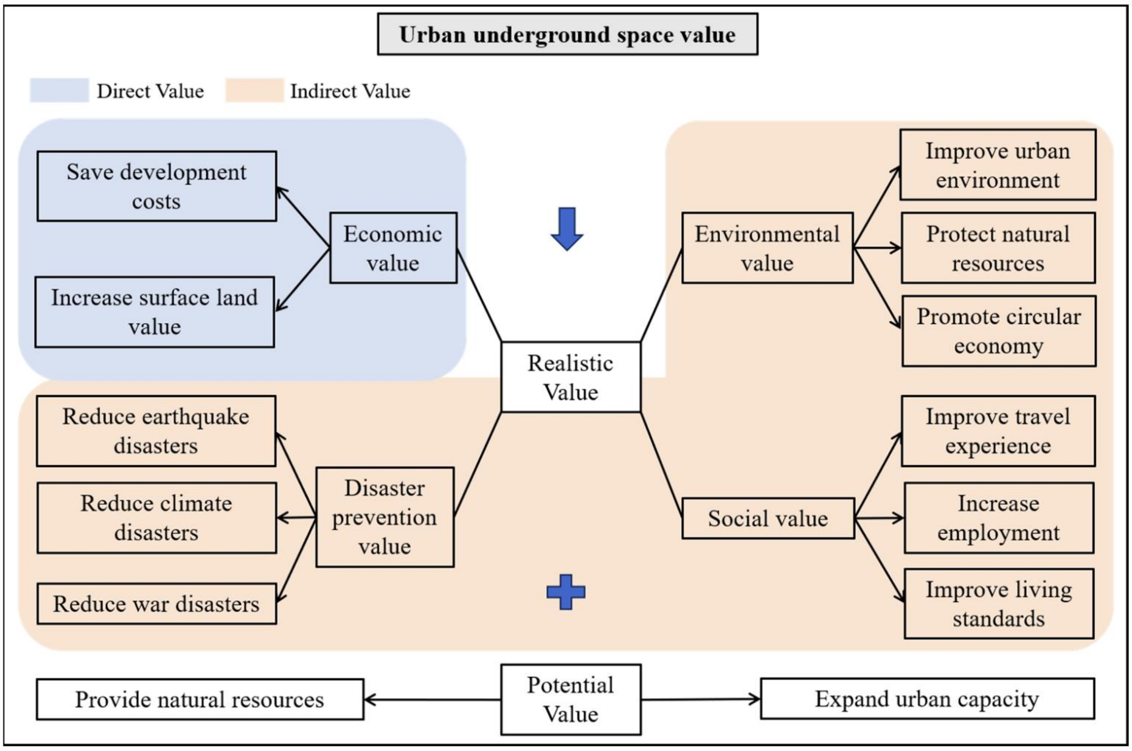


Fig. 1.4: Types of urban underground space values (Wu et al., 2024)

2 Underground energy storage

Fig. 2.1 provides an overview about possibilities in principle to store energy. Among these possibilities several can use the underground space, for instance pumped hydroelectric, hydrogen storage, compressed air storage as well as any kind of heat storage.

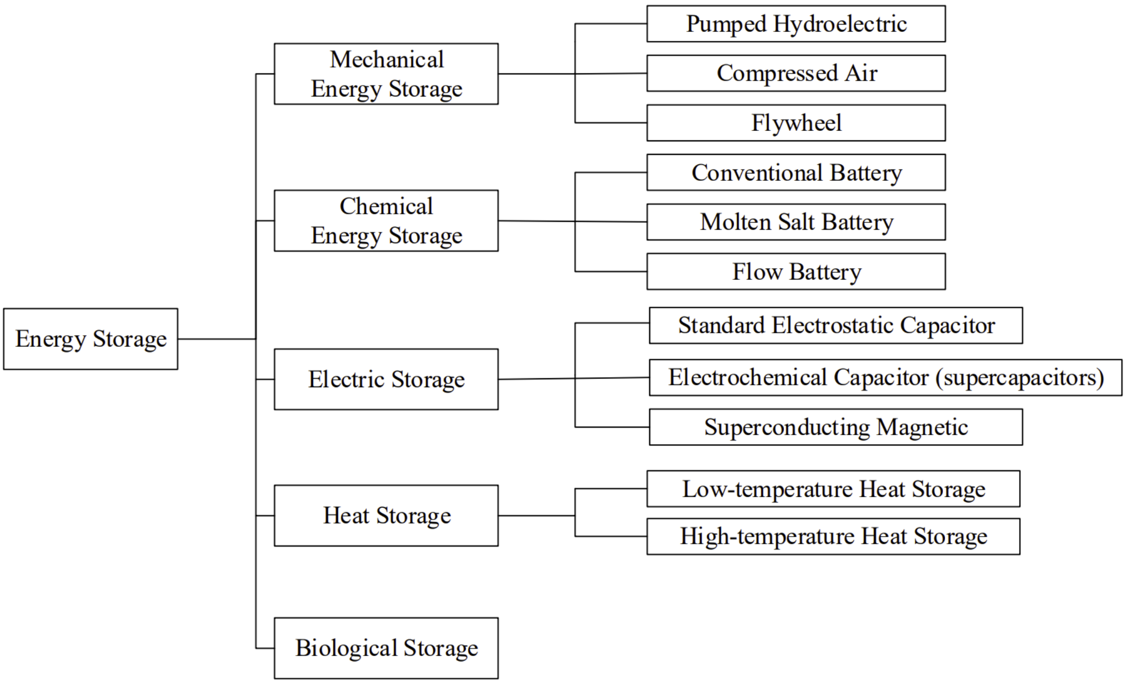


Fig. 2.1: Possibilities in principle to store energy (Li et al. 2018)

Big underground openings (e.g. abandoned mines or salt-leached caverns) can be used to store energy as well as large porous formations with tight cap rock (e.g. exhausted oil or gas reservoirs). Most popular idea are:

- storage of compressed air (CAES) in large underground openings (e.g. Schmidt et al. 2020, Schmidt et al. 2024, Wan et al. 2024)
- Storage of H_2 and CH_4 for power-to-gas-technology in porous rock masses
- underground pump-storage hydropower plants (UPSH) (e.g. Menendez et al. 2019, 2020)
- Hydropower stations (HPS)

Fig. 2.2 illustrates the general set-up and operation of a salt-cavern based CAES. Besides this technology also pore-space-based as well as lined rock caverns are suitable.

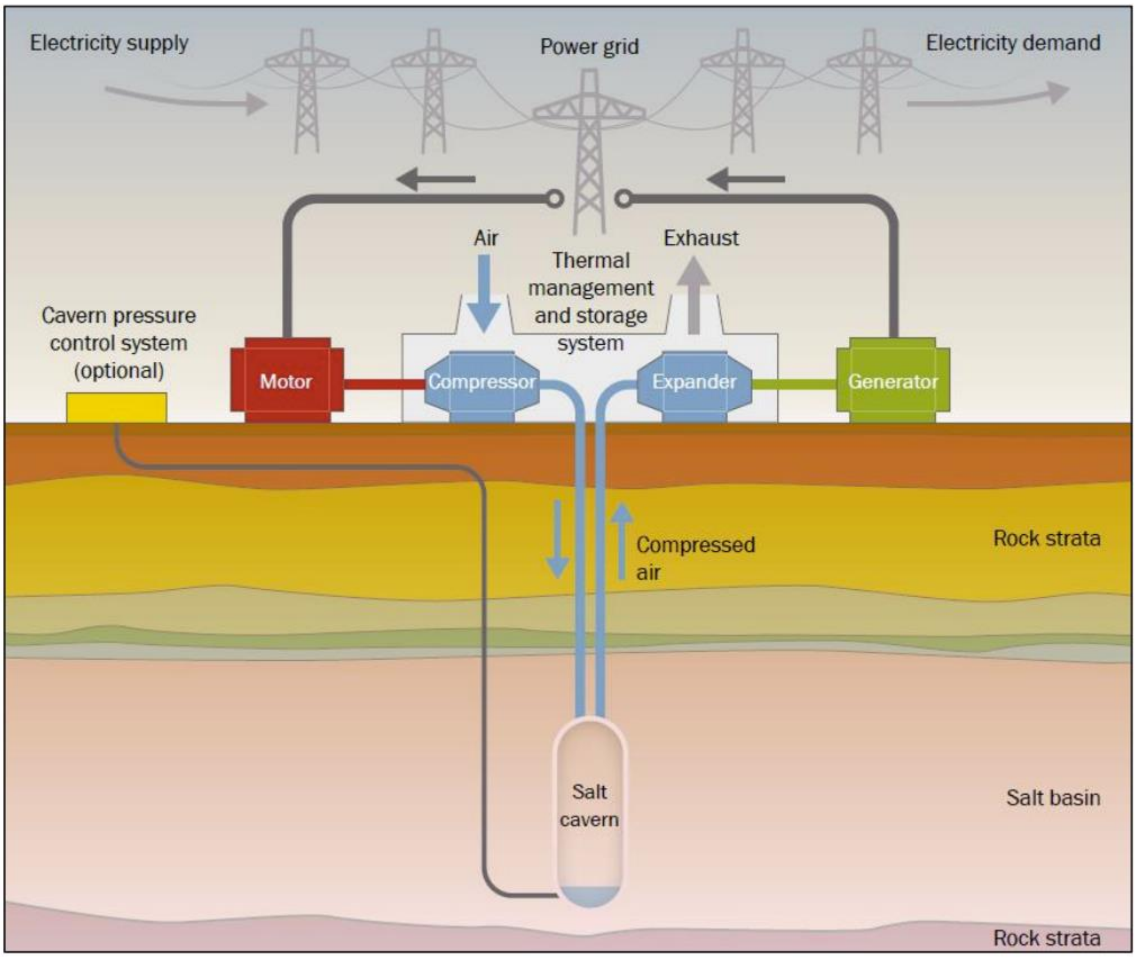


Fig. 2.2: Principle scheme of salt-cavern based CAES (TNO Report R12006, 2020)

As documented by Fig. 2.3 and Fig. 2.4 CAES can be quite cost-effective and shows a good performance in respect to the energetic cycle efficiency compared with other potential energy storage systems.

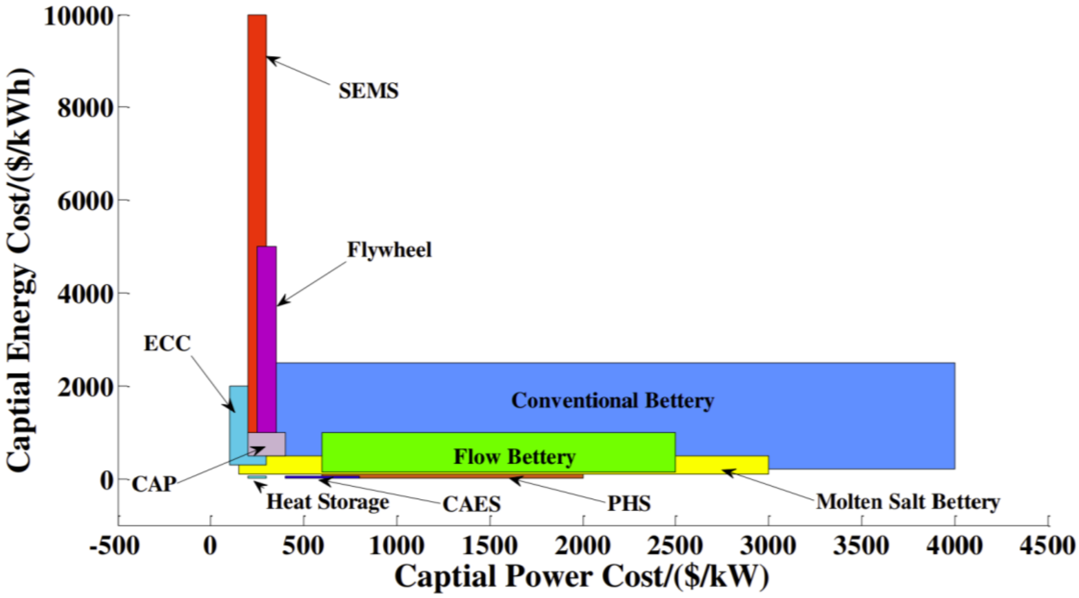


Fig. 2.3: Capital energy costs vs. capital power costs (Chen et al., 2009)

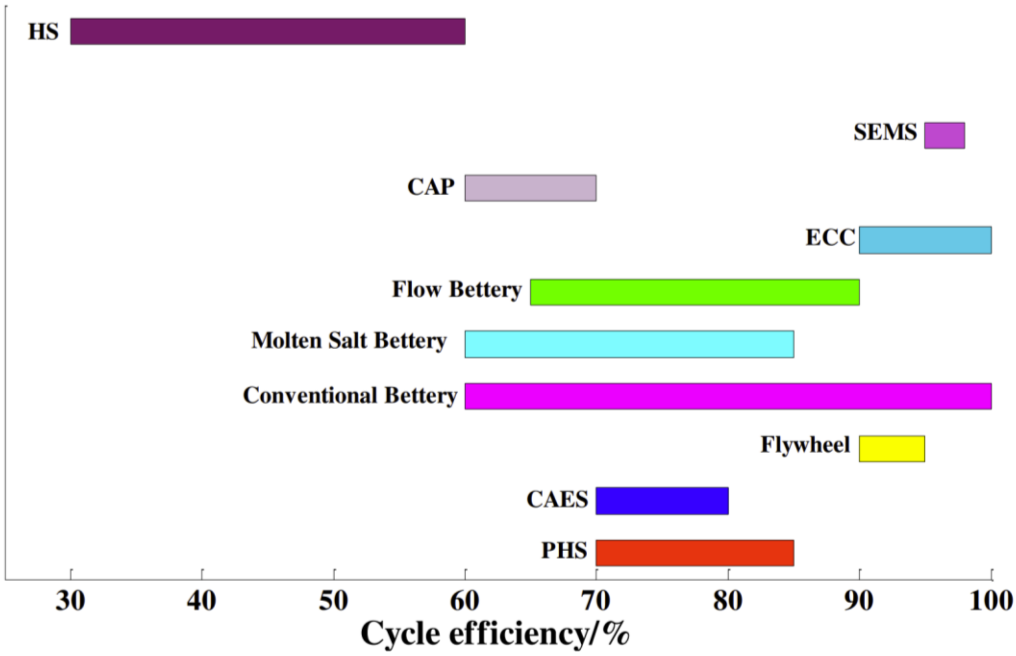


Fig. 2.4: Cycle efficiency of CAES (Ibrahim et al., 2008)

Fig. 2.5 and 2.6 illustrate exemplary the above-mentioned technologies and Fig. 2.7 shows potential conflicts between the biosphere and the usage of the underground space for energy storage, which have to be considered by environmental impact studies.

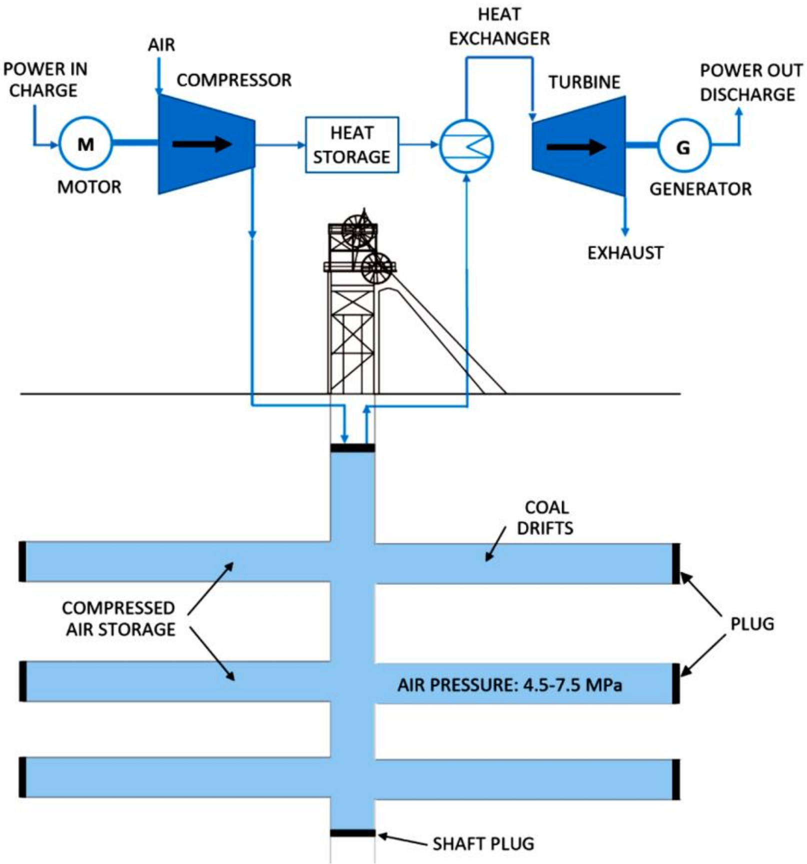


Fig. 2.5: Simplified scheme of an CAES (Schmidt et al., 2020)

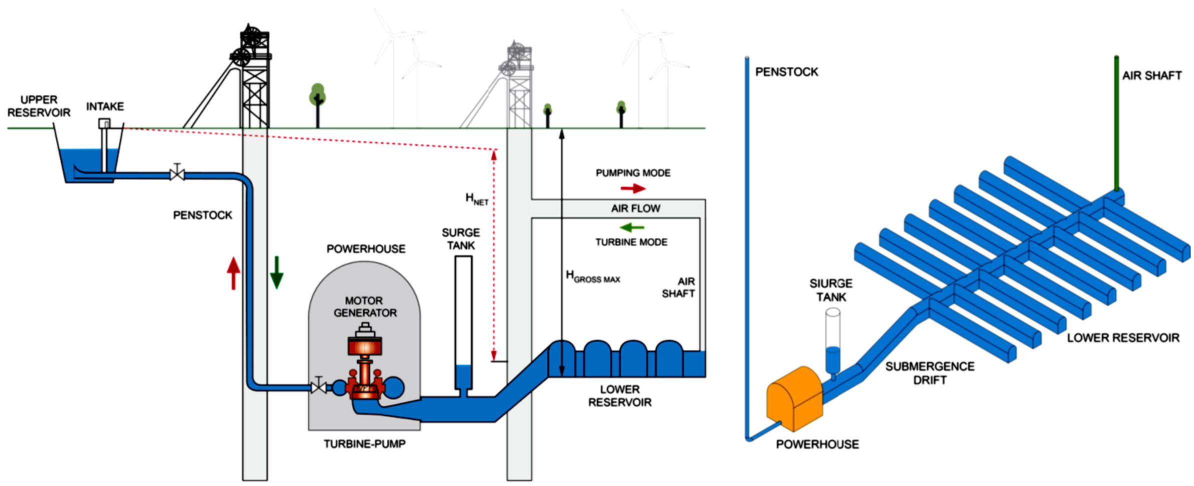


Fig. 2.6: Simplified scheme of an UPSH (Menendez et al., 2019)

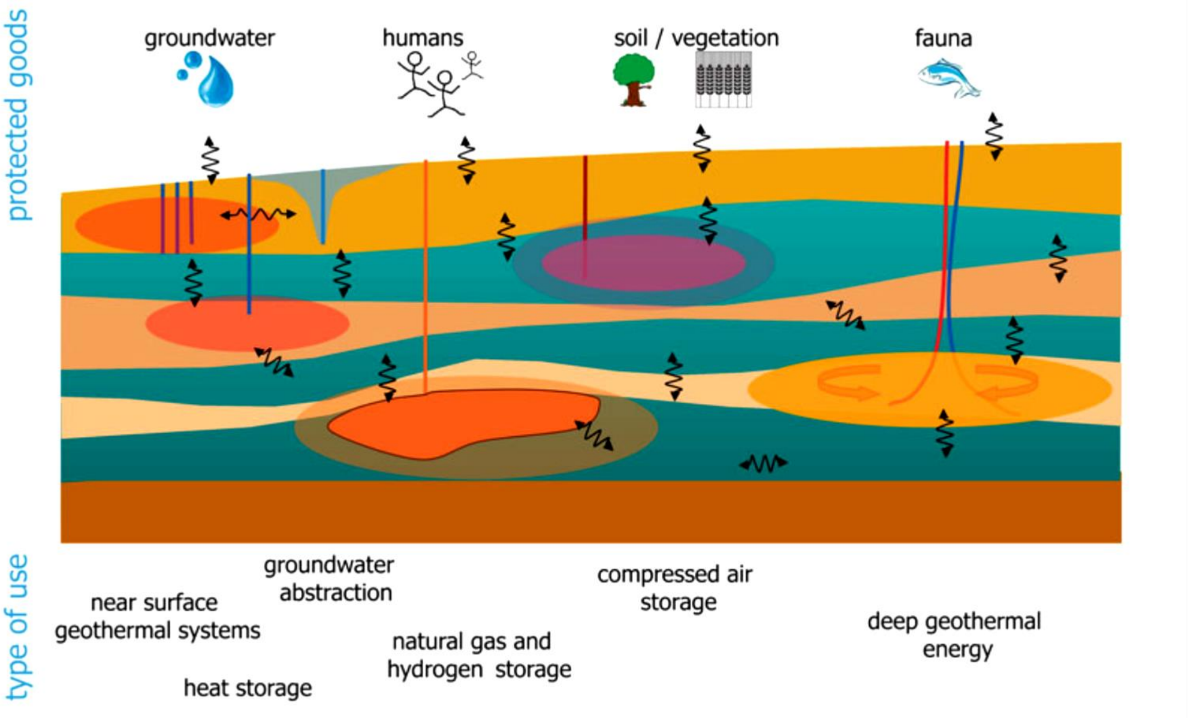


Fig. 2.7: Interactions between underground energy projects and the biosphere (Bauer et al., 2013)

The major rock mechanical and geoengineering problems related to the energy storage in rock masses are:

- tightness of the heat storage volume and the cap rock, respectively
- environmental impacts (e.g. induced seismicity, water pollution, surface deformations etc.)
- long-term behaviour of the system
- hydraulic properties of the reservoir
- geothermal efficiency

The island Madeira (Portugal) was used the set-up two remarkably engineered water systems used for energy production as well as irrigation. The first one (Multi-Purpose Socorridos System: MPSS) consists of the 5.2 km long Covao tunnel, which represents the upper water reservoir; a gallery for storage of water with a total capacity of 40,000 m^3 and a cavern pumping station. The working scheme of the system (see Fig. 2.8 and 2.9) is described by Sousa (2015) as follows:

> *"In dry seasons, during the day, water stored between the Encumeada (1) and Canal do Norte (2) tunnels, and in Covao (3) loading chamber and tunnel can be turbined at St. Quiteria (4) and Socorridos (5) to generate electricity. At St. Quiteria, all of the water that is turbined is used for public supply after going through a water treatment station. At Covao, part of the water is diverted for irrigation and water treatment plants for public supply. Likewise, at Campanario (6), part of the water is diverted for irrigation. All of the water that is turbined during peak periods at Socorridos hydroelectric power station (5) is stored in the Socorridos storage gallery (7). At night water is pumped back (8) to the Covao tunnel (3) so that it can be used again the next day, completing the cycle"*

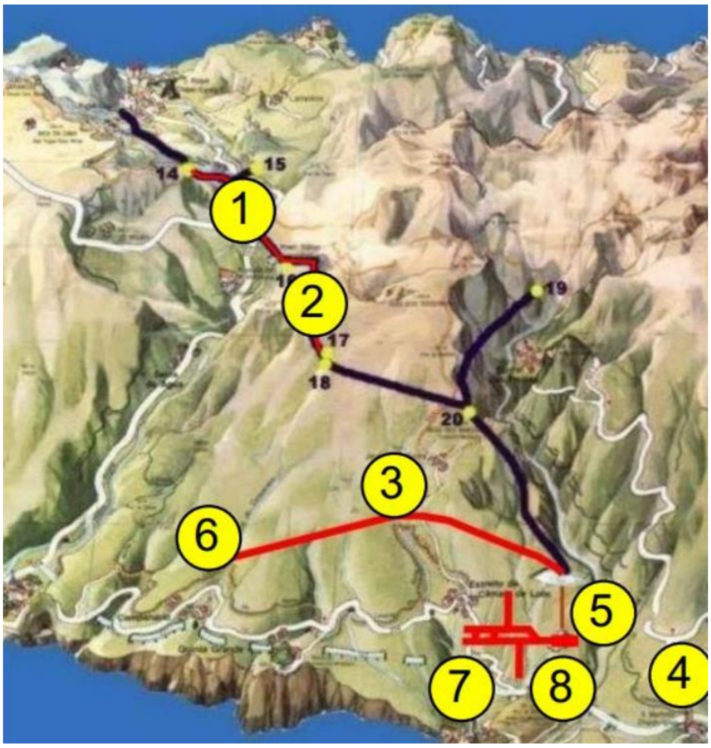


Fig. 2.8: Scheme of Multi-Purpose Socorro's System (Sousa, 2015), numbers are explained in the text.

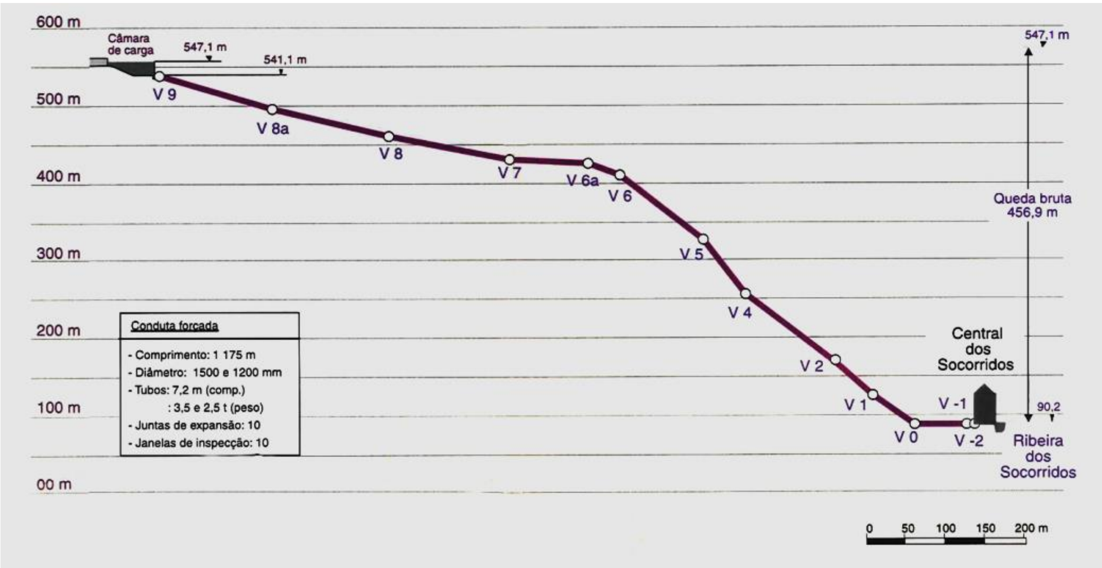


Fig. 2.9: Penstock connecting Covao reservoir to the Socorridos power plant (Sousa, 2015)

The second one is the Calheta III Hydroelectric System (see Fig. 2.10), which consists of the following parts (Sousa, 2015):

- Pico da Urze Dam (31 m height and 1 Mio m^3 of storage capacity
- Calheta Dam (34.5 m height with 73,750 m^3 total storage volume for the retention of the water turbinated in Calheta III, for subsequent pumping to Pico da Urze's reservoir with flooded area of 6,360 m^2)

- Calheta III Hydroelectric power plant and Calheta pumping station (2 generators with 15 MW each and 3 pumps for Calheta pumping station, each one with 4.9 MW)
- Penstocks (1500 mm steel tubing, 3,460 m length from Calheta and Paul stations to Pico da Urze's bayou)
- Water Pumping Station of Paul (2 x 150 kW electric pumps to pump the collected water by Paul I water channel (Levada do Paul I), below the Pico da Urze dam, and also by Paul II water channel (Levada do Paul II), both to Pico da Urze bayou)
- Paul II Water Channel (Levada do Paul) Expansion (10.6 km length between the Juncal stream (Ribeira do Juncal) and the forebay of Paul, by raising the side walls to increase transport capacity)
- Paul Old Water Channel (Levada Velha do Paul) Expansion (main source of supply to Pico da Urze's bayou with 1,600 m length between the Lajeado stream (Ribeira do Lajeado - where it takes in the water) and the Alecrim stream (where it gives back the intake water)
- Lombo Salão Water Channel (Levada do Lombo do Salão) Renewal (1,690 m long, located between Calheta I Hydroelectric Power Plant and Lombo do Salao forebay, aims at reducing water flow losses during its path, in order to improve the water delivery to irrigation and adduction to Calheta II Hydroelectric Power Plant (Central de Inverno da Calheta - Calheta II)

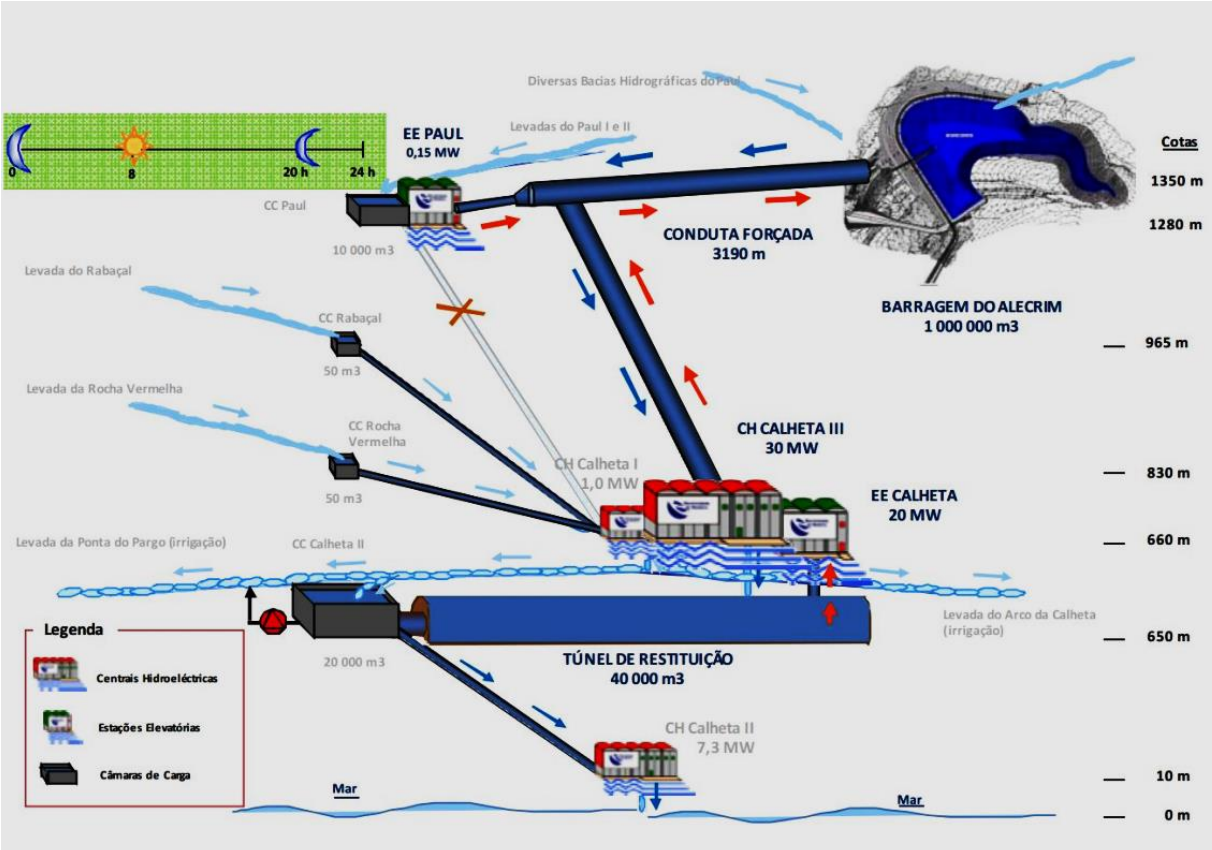


Fig. 2.10: Scheme of Calheta III Hydroelectric System (Sousa, 2015)

Kitsikoudis et al. (2020) present the idea to use an abandoned slate mine as lower water reservoir of a UPSH (see Fig. 2.11). There are 9 chambers (rectangular cuboid shape of 15 x 45 m with its top side at -40 m, distance between the chambers is 10 m, the height of the caverns varies between 70 m and 110 m). Total volume of all chambers is 550,000 m^3.

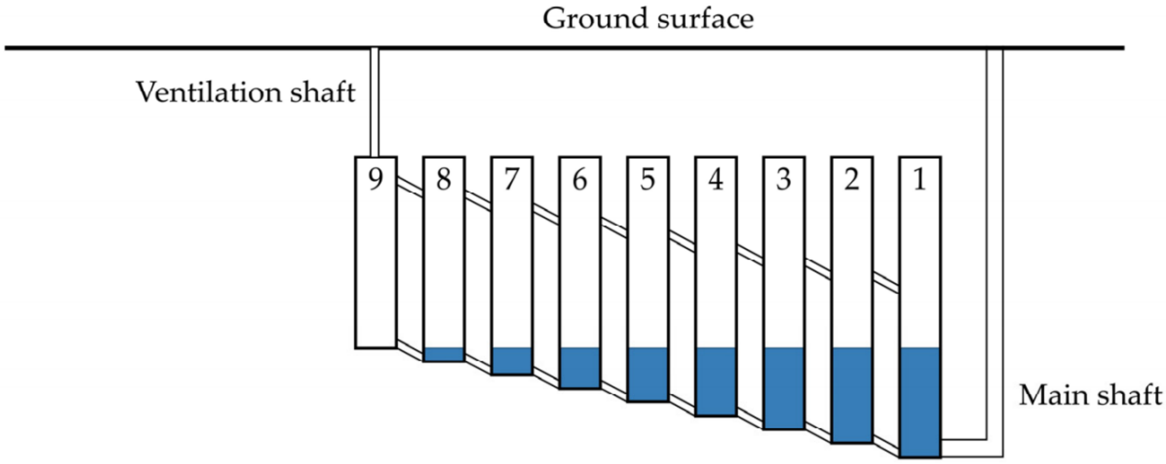


Fig. 2.11: Lower water reservoir at Martelange mine, Belgium (Kitsikoudis et al., 2020)

Besides the use of already existing openings like abandoned mines also new excavation systems are created to erect hydropower stations (HPS). Exemplary the HPS Nant de Drance in Switzerland, put into operation in 2020, is presented. This underground HPS with efficiency of 80% connects the two lakes Emosson and Vieux-Emosson (see Fig. 2.12 to 2.16).

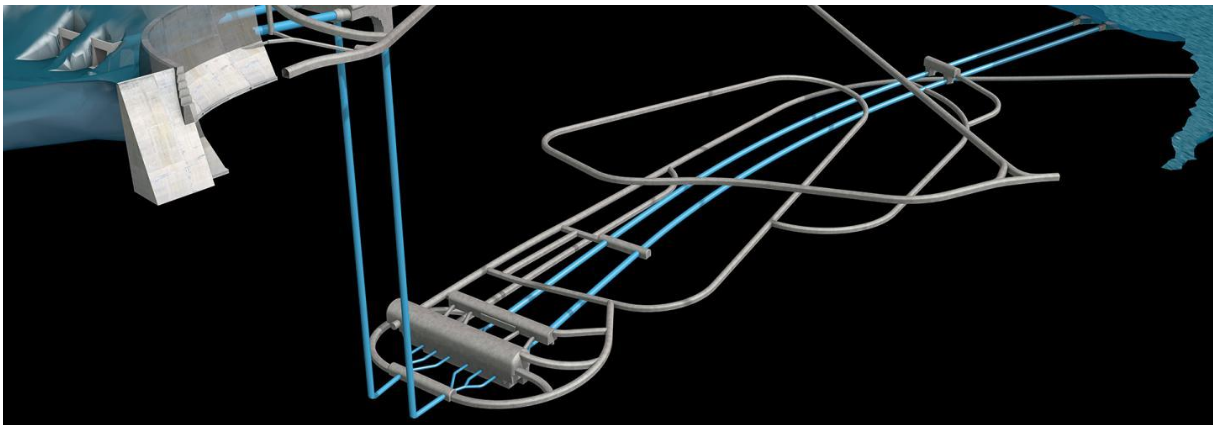


Fig. 2.12: Sketch of underground structures for HPS Nant de Drance (AF Pöyry, company material)

Some data about the HPS Nant de Drance:

- Power: 900 MW
- Cavern volume: 340 000 m^3
- Dimensions of machine cavern: 194 x 32 x 52 m
- Dimensions of transformer cavern: 130 x 15 x 19 m
- Total length of drifts: 13 km
- Length of supply tunnels : 2 x 1.694 km
- Vertical shafts : 2 x 440 m, 7 m diameter
- 6 Francis pump turbines each of 150 MW
- 4 connection drifts: length 30 m, cross section 20 m^2

Fig. 2.13: Arial photo showing the two lakes and the dam (Nant de Drance HPS, company material)

Fig. 2.14: Cavern during construction (Nant de Drance HPS, company material)

Fig. 2.15: Dam during construction (Nant de Drance HPS, company material)

Fig. 2.16: Dam during construction (Nant de Drance HPS, company material)

3 Underground heat storage

To reduce the carbon footprint and the collect energy from fluctuating renewable energy sources for heating and cooling purposes, geothermal heat storage systems become attractive (e.g. Bauer et al., 2013, 2015; Schüppler et al., 2019; Bott et al., 2019, Todorov et al. 2020; Stricker et al. 2020). In terms of the timespans one can distinguish:

- long-term (seasonal) systems
- short-term (daily, weekly) systems.

From the technical point of view the following systems can be distinguished:

- Aquifer storage
- Borehole storage
- Cavern storage
- Pit storage
- Tank storage

The general principle of seasonal heat storage is illustrated in Fig. 3.1. The heat storage medium is pure water in most cases, but in interaction with the surrounding medium (rock or soil or even artificial materials like concrete, sealing or isolation materials). Water is well suited because it is available in huge amount, is easy to move and has a high heat store capacity (see Tab. 3.1)

Tab. 3.1: Heat storage capacity of different media in a temperature range between 0°C and 100°C (Bott et al., 2020)

Material	**Heat storage capacity** **kWh/(m³K)**	**Heat storage capacity** **MJ/(m³K)**
water	1.16	4.18
soil / rock	0.69	2.50
high porous gravel bed	0.33	1.20

Within a temperature range between 35°C and 60°C the storage capacity for soil or rock is about 15 – 30 kWh/m³, but for water about 60 – 80 kWh/m³ for water (Bott et al., 2020). Most effective are large storage volumes of nearly spherical shape. Besides low temperature systems also high-temperature systems (temperature close to 100 degree or even higher) are under planning like the DeepStor project (Fig. 3.2) in Germany, where a depleted oil field at greater depth is used as storage area. Simulations for selected depleted oil fields in the Upper Rhine Graben (Germany) indicate, that assuming a doublet system with seasonal injection and production cycles is applied, injection at 140°C in a typical 70°C reservoir leads to an annual storage capacity of up to 12 GWh and significant recovery efficiencies increasing up to 82% after ten years of operation (see Fig. 3.3).

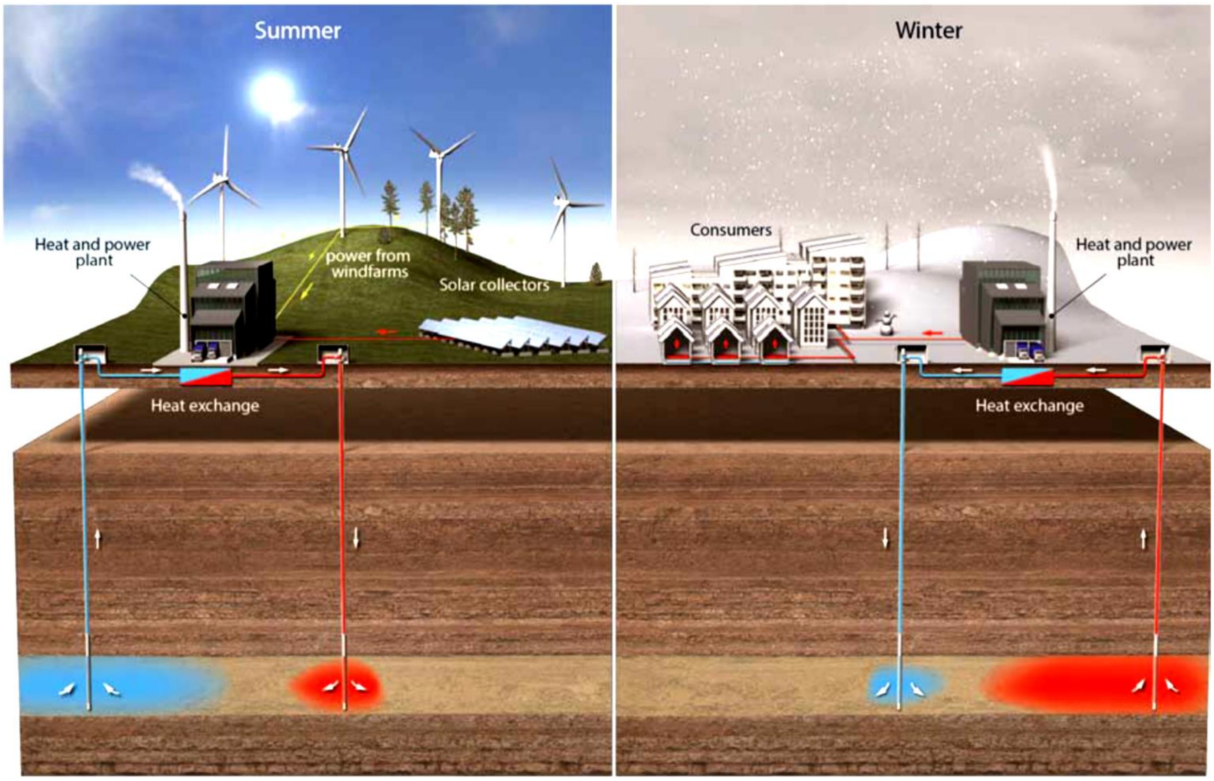


Fig. 3.1: Principle of seasonal heat storage (Kallesøe & Vangkilde-Pedersen, 2019)

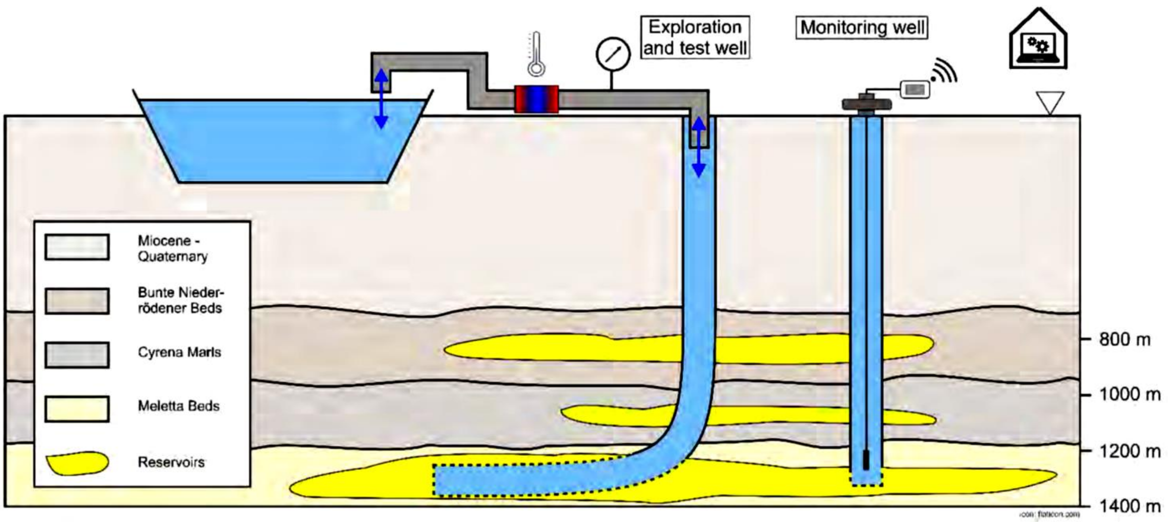


Fig. 3.2: Illustration of DeepStor project with injection and monitoring well, heat exchanger and basin as water buffer (KIT, 2020)

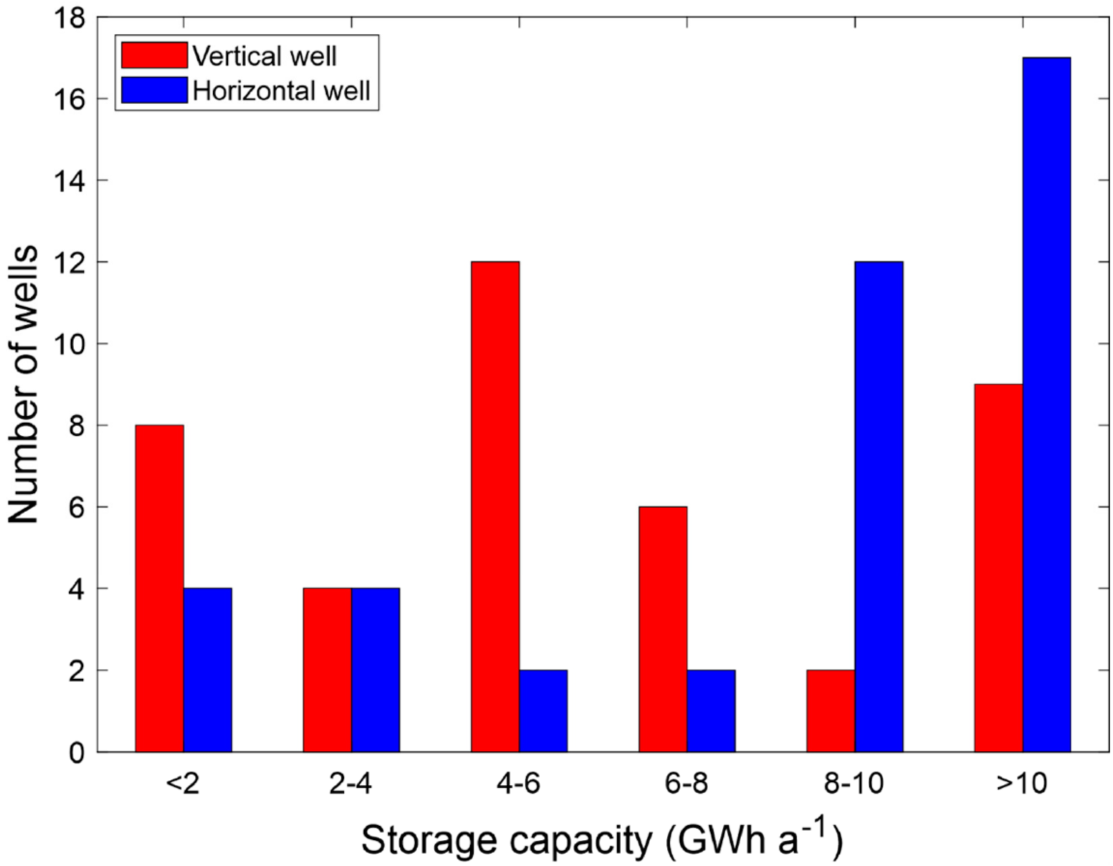


Fig. 3.3: Storage capacity for selected depleted oil fields in the Upper Rhine Graben (Stricker et al., 2020)

Tab. 3.1: Pros and cons of different heat storage concepts (Fleuchaus et al., 2018)

(+ + + high; + + moderate; + low).

	PTES / TTES	ATES	BTES
Storage medium	Water; water/ gravel	Groundwater/ sediments	Groundwater/ sediments
Subsurface requirements	+	+ + +	+ +
Required pre-investigation	+	+ + +	+ +
Maximum storage capacity (kwh/m^3)	+ + +	+ +	+
Storage volumes	+	+ + +	+ +
Space requirement	+ + +	+	+
Investment costs	+ + +	+	+ +
Maintenance	+	+ + +	+
Environmental interaction	+	+ + +	+ +

Fleuchaus et al. (2018) provide an overview about the current and potential of heat storage in aquifers worldwide (see also Tab. 3.1).

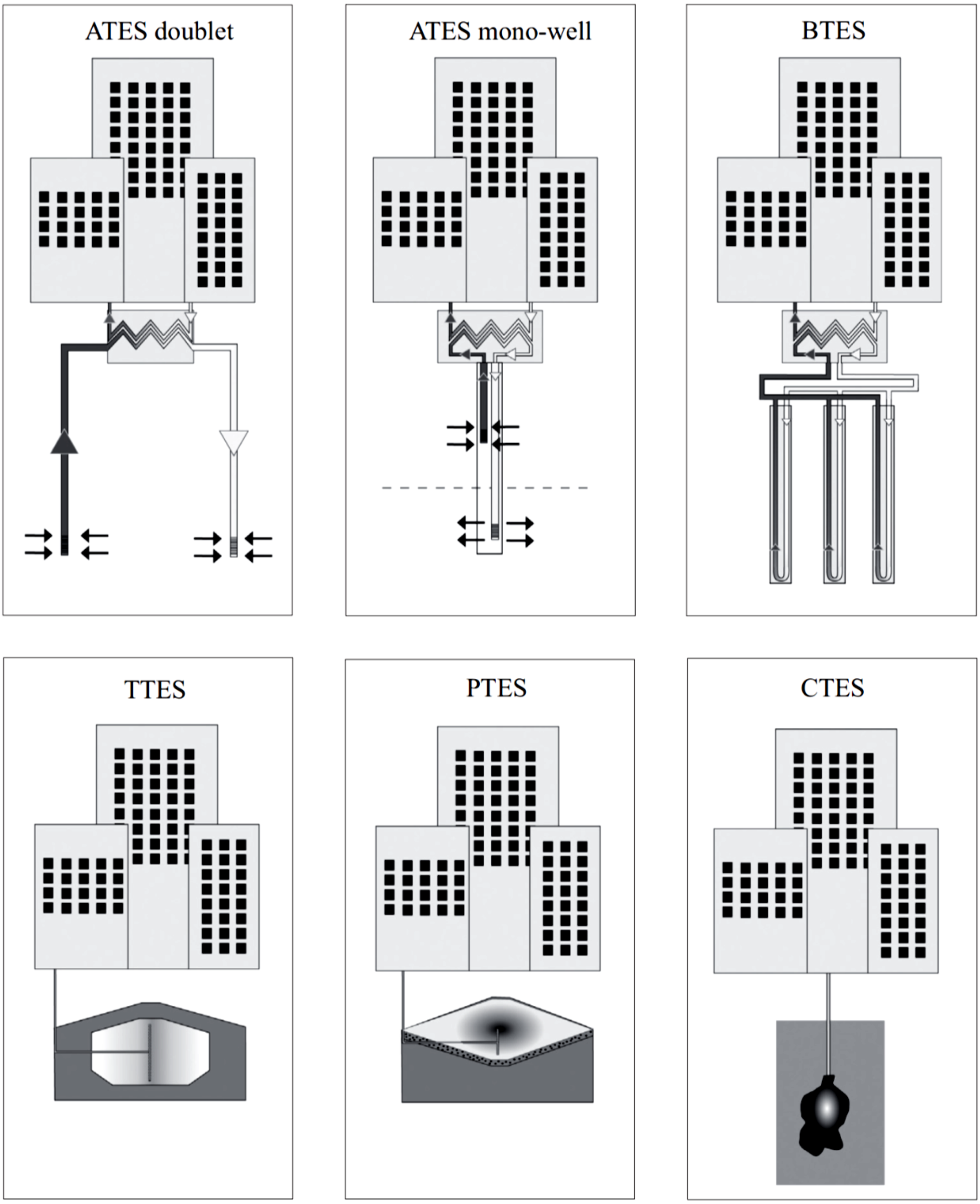


Fig. 3.4: Overview about typical concepts for thermal energy storage: ATES = aquifer thermal energy storage , BTES = borehole thermal energy storage, TTES = tank thermal energy storage, PTES = pit thermal energy stotage, CTES = cavern thermal energy storage (Fleuchaus et al., 2018)

4 Underground waste storage

Underground waste storage comprises:

- Nuclear waste storage (low level waste, intermediate level waste and high-level waste)
- Toxic waste
- Industrial waste

For more details see our e-book chapter 27: “Underground waste disposal”.

5 Underground transport, communication and energy/raw material distribution

Underground transport systems cover the classical elements like railway and road tunnels (see also our E-book chapter 41: “Tunnelling in rock masses”), metro systems but also tunnels for pedestrians. This includes also underground railway stations with corresponding links and shopping areas, like the project “Stuttgart 21” (see Fig. 5.1).

New ideas emerge, like CargoCap systems (underground electrical good transport systems built with trenchless embedding (see Fig. 5.2) or large ship tunnels (see Fig. 5.3) to shorten distances and to avoid ship accidents due to complicated weather conditions, subsea topography or heavy waves. Underground communication systems cover networks of copper or fibre glass cables.

Cai & Nelson (2019) provide an overview about the use of underground space for transport. They distinguish between five forms of underground transport:

- Underground railway systems
- Underground car parks
- Urban underground roads and expressways
- Underground freight transport systems
- Underground pedestrian systems

In 2019 more than 10 million passengers use Shanghai’s metro system with the total route length of about 650 km. The underground pedestrian system RESO in Montreal covers about 32 km of tunnels.

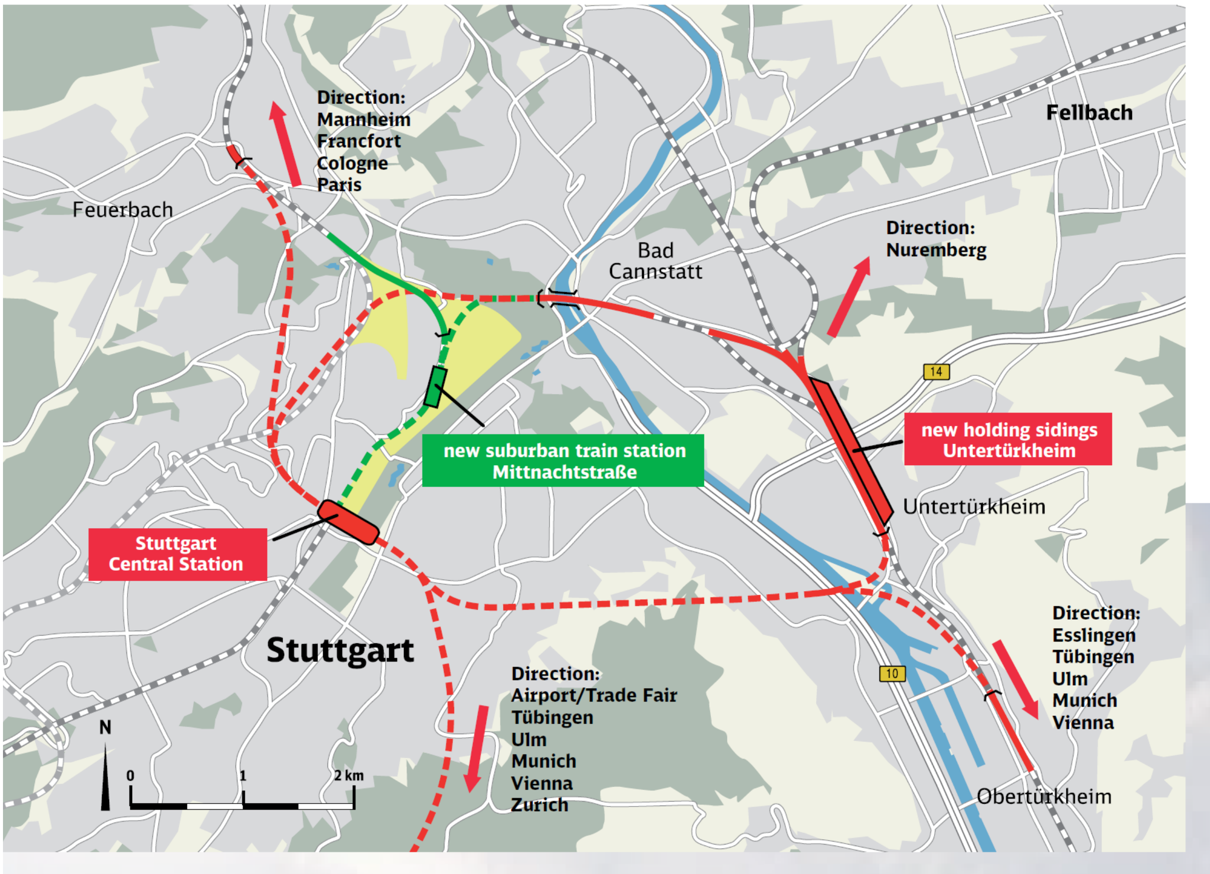


Fig. 5.1: Project ‘Stuttgart 21’ (DB, 2015; Bretschneider & Schuster, 2013)

Fig. 5.2: CargoCap concept (Aldejohann & Wagner, 2010)

Fig. 5.3: Stad ship tunnel in Norway (Andreassen, 2018)

6 Underground water supply and storage systems

Underground water distribution systems are common in cities and villages in two different forms, as:

- Fresh water systems
- Waste water systems (Fig. 6.1)

Underground water channels are also common to connect water reservoirs as well as water reservoirs with nearby river systems and the consumer. Exemplary, Fig. 6.2 shows the drainage tunnel system in the northern part of the Thuringian Forest (Germany).

Underground discharge tunnels can help to avoid flooding events in mega-cities. In the outskirts of Tokyo (Japan) about 50 m below surface a huge underground tunnel and cavern system was constructed to store floodwater. The system can handle up to 200 m^3/s water inflow. The water is stored in pressure-controlled tanks (see Fig. 6.3). Fig. 5.4 shows the waste water treatment plant Viikinmäki, which can handle the waste water of about 650,000 inhabitants (Kämpii, 1994). This plant started operation already in 1994.

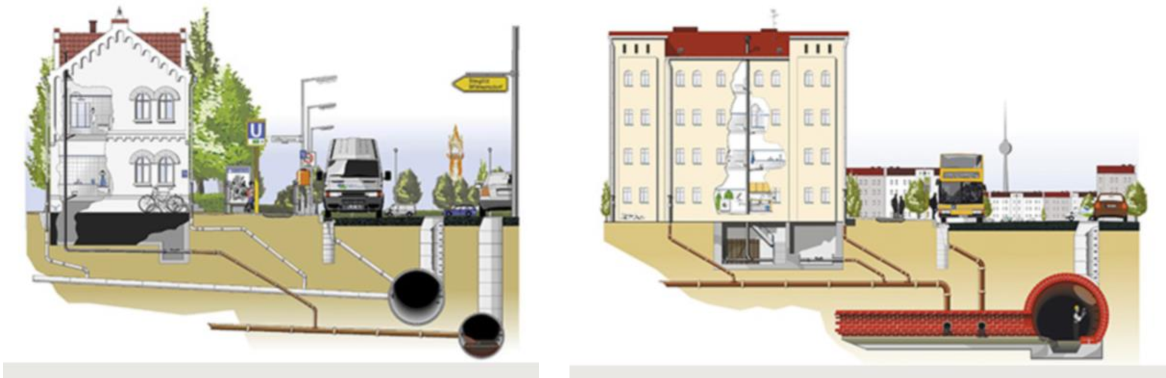


Fig. 6.1: Illustration of waste water systems in a city (BW, 2020)

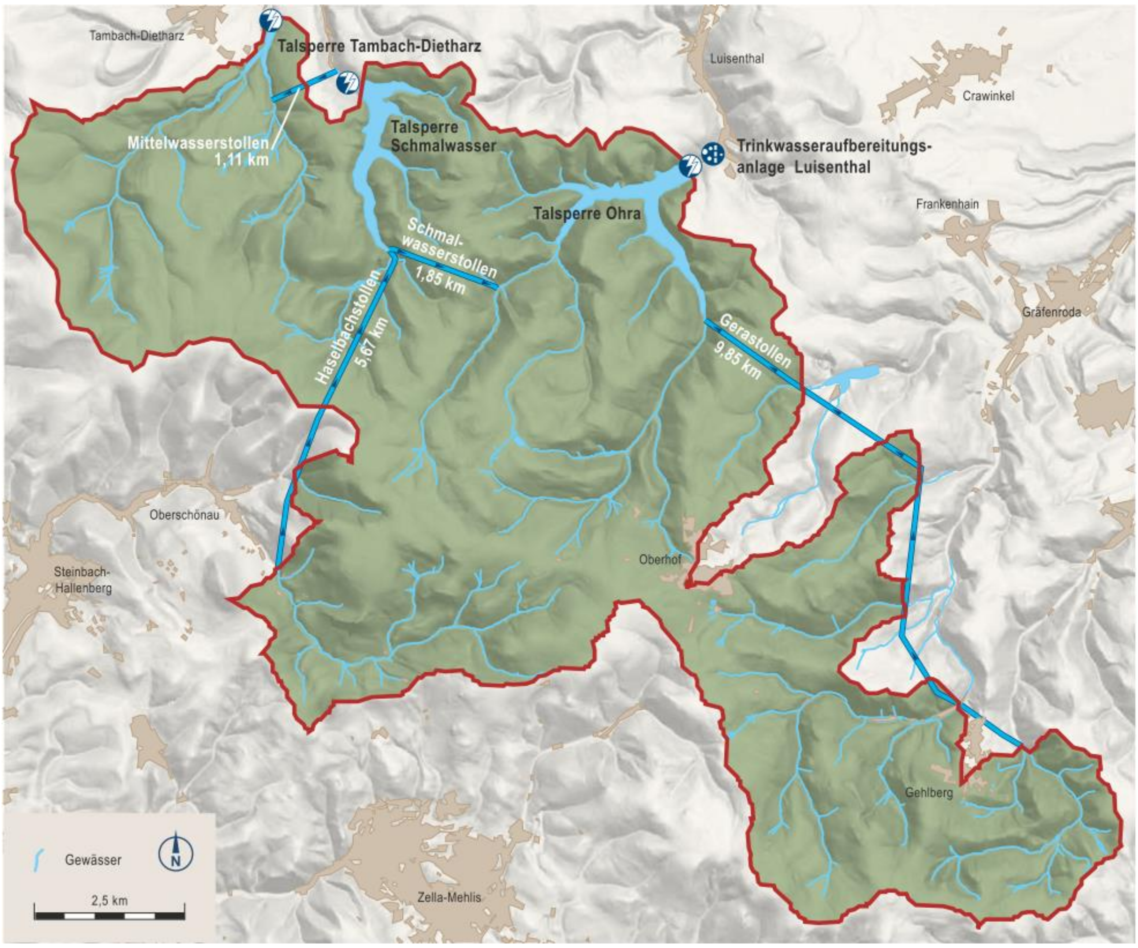


Fig. 6.2: Drainage tunnel system in Thuringia (Germany) (TFWV, 2020)

Fig. 6.3: Underground discharge tunnel in Tokyo (TiJ, 2020)

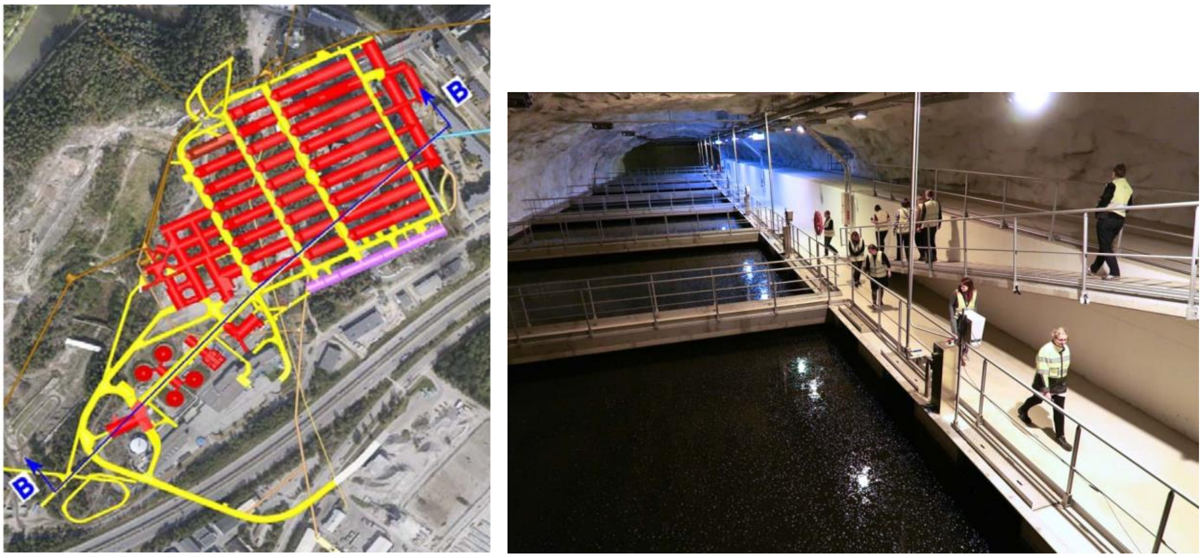


Fig. 6.4: Underground waste water treatment facility in Helsinki (Rockplan, 2020)

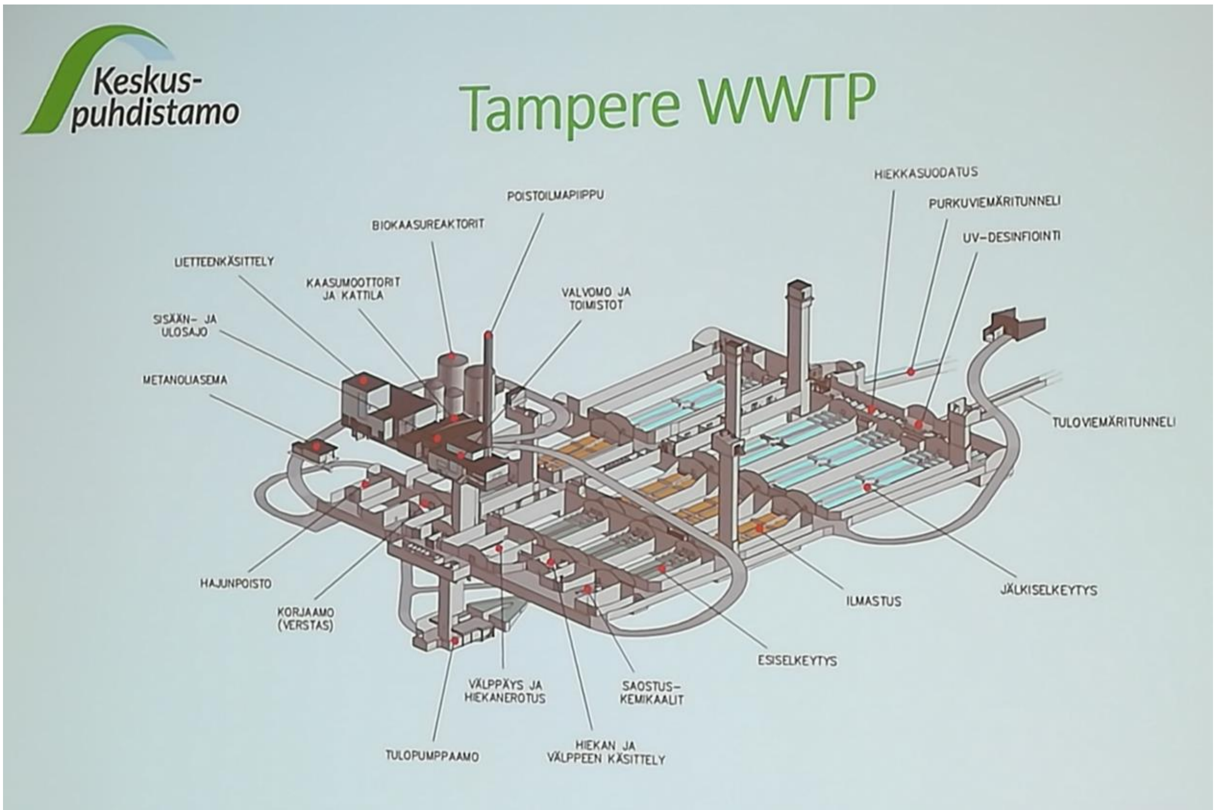


Fig. 6.5 Underground waste water treatment facility in Tampere (Finland)

The Sulkavuori waste water treatment device in Tampere (Finland) is constructed in competent hard rock and covers an underground area of about 300 x 300 m, includes 15 km of sewer lines and 2 tunnels with total length of 3 km (see Fig. 6.5). Total construction time is about 10 years, total costs are 350 Mio. Euros. The water treatment comprises mechanical, chemical and biological components. In total about 63.000 bolts and 22.000 m^3 shotcrete and 790.000 kg grouting cement are used.

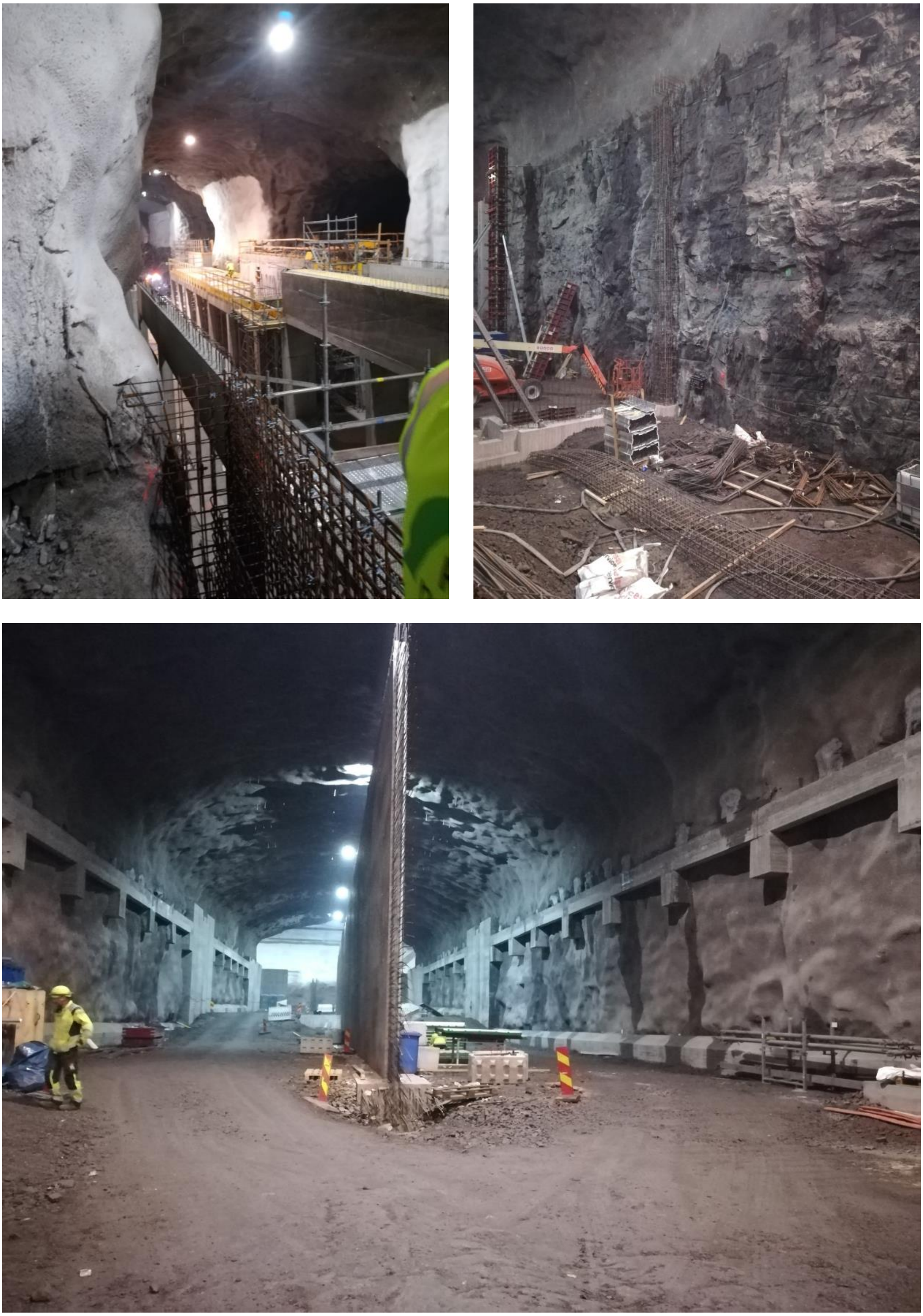


Fig. 6.6 Underground waste water treatment facility in Tampere (Finland) during construction (2022)

7 Underground production and storage facilities

The underground space can be used in many ways for production, interim storage of goods or raw materials. Underground computer facilities are becoming also popular. The main reason for these developments is the lack of space at the surface, especially inside the mega-cities, but also the favourable conditions underground:

- Less hazards from georisks (storm, earthquakes, floods etc.)
- Constant environmental conditions (for instance: relatively low and constant temperature)
- Less hazard from terror attack or destruction by war
- Reduction of the use of construction materials
- Long lifetime

Most important however - especially with regard to the climate change and the growing population - is the fact, that the shift of facilities to the underground reduces the sealing at the surface and makes the environment greener.

Fig. 7.1 shows a modern underground computing centre in Sweden and Fig. 7.2 shows an example for an underground aircraft production. A bigger potential is also seen for logistic centres. The use of underground space for production will strongly increase with increasing application of automatic robot-based production.

Underground storage of raw materials (see Fig. 7.3 and 7.4 for example) and the corresponding distribution networks (also partially underground) are vital parts of the economy of many countries.

Fig. 7.1: Data centre and office building of the Swedish internet-providing company Bahnhof AB (UGE, 2020)

Fig. 7.2: Underground factory SAAB Aircraft (UGE, 2020)

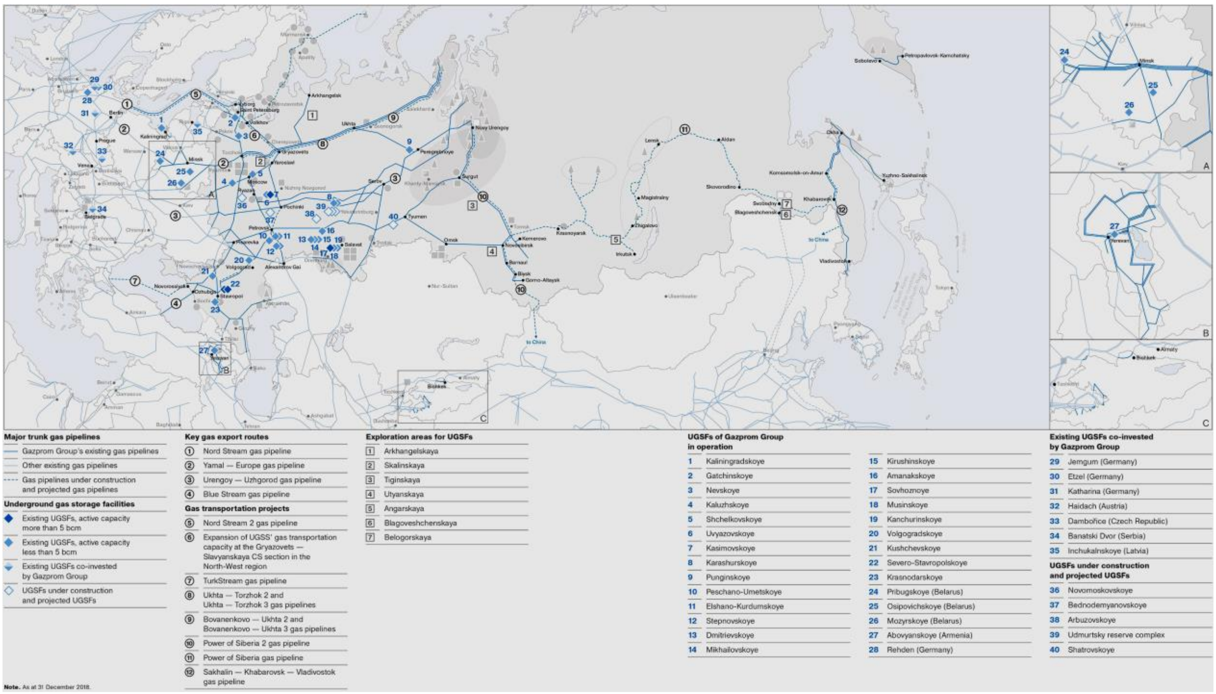


Fig. 7.3: Gazprom network for underground gas storage and gas transmission (Gazprom, 2020)

Fig. 7.4: Underground coal storage (Rockplan, 2020)

8 Underground living and recreation facilities

Indoor sport and cultural events are becoming popular and consequently also large underground sport and cultural facilities have been built (Fig. 8.1 to 8.4). The Norwegian Olympic ice hockey cavern (Fig. 8.3) built in 1991 is a milestone in using the underground space for sport facilities (Barton et al., 1994). There are many other innovative concepts how to use the underground space, like abandoned mines (Fig. 8.4) with huge caverns as multipurpose halls for conferences, concerts etc. or old quarries as congress and hotel facilities (Fig. 8.5). Interesting is also the 300 m deep earthscraper concept developed for Mexico City with museum, stores and living space (Fig. 8.6). As shown exemplary in Fig. 8.7 the underground space can also be transformed into a green area and recreation space.

Fig. 8.1: Underground church and swimming hall in Helsinki (Vähäaho, 2011)

Fig. 8.2: Underground sports hall in Helsinki (Vähäaho, 2011)

Fig. 8.3: Underground Gjovik olympic cavern hall, Norway (Holmstad, 2014)

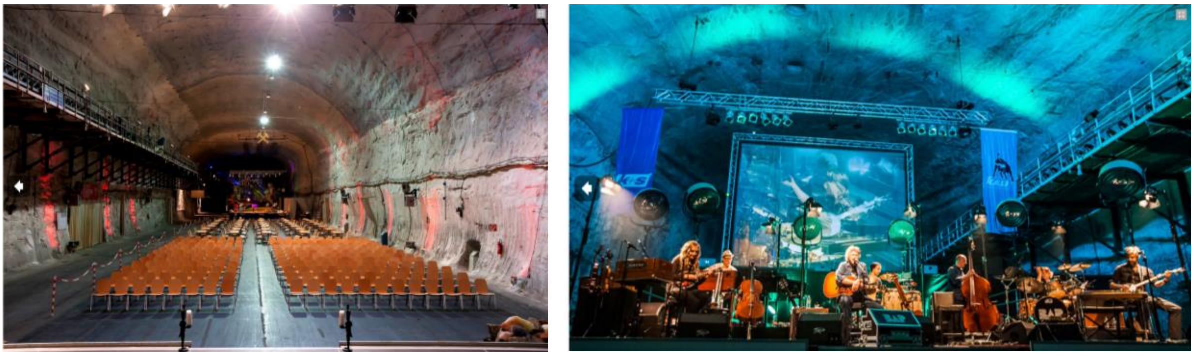


Fig. 8.4: Multipurpose hall in the abandoned salt mine ‘Merkers’, Germany (Merkers, 2020)

Fig. 8.5: Hotel and congress complex in an old quarry near Shanghai, China.

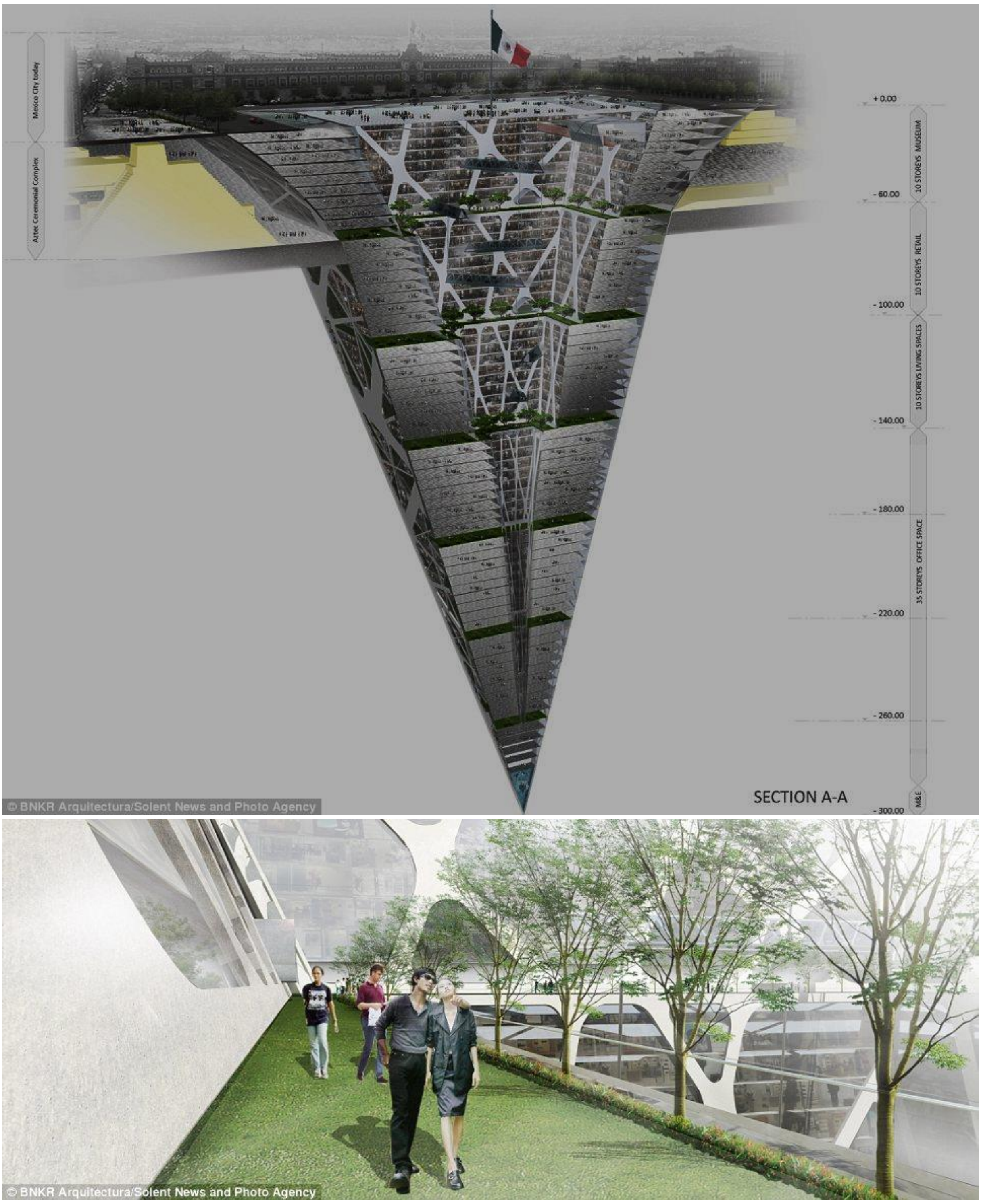


Fig. 8.6: Earthscraper project for Mexico (Allplan, 2020)

Fig. 8.7: Underground park 'Lowline', New York (Lowline, 2020)

Already since the 1960s the RESO underground complex in Montreal (Canada) is in operation. This mini-city is home to commercial as well as residential complexes with a host of shopping centres, banks, hotels, theatres, galleries, nightclubs, university buildings, restaurants, a library and a hockey ring. The underground mini-city is a 32 km long indoor pedestrian network covering an area of about 12 km^2. Half a million people use it each day (Besner, 2017). Fig. 8.8 gives an impression of the underground structure incl. a map of the complete RESO mini-city, which is well connected by the metro-system.

Fig. 8.8: Underground mini-city RESO in Montreal, Canada (Reso, 2020)

Fig. 8.9: Santa Fe Garden project in Mexico (WSP, 2018)

The Garden Santa Fe project in Mexico (see Fig. 8.9) consists of an above ground park with a running track and terrace that surrounds a seven-level underground shopping centre housing retail stores, entertainment, a food court and three levels of parking. Central to Garden Santa Fe's architecture are three inverted glass cones that project natural light and ventilation into the mall. The complex is powered by highly efficient photovoltaic cells that convert sunlight into electricity to charge the LED lighting system. An 8,500 m² green roof and on-site water treatment and reuse plant further reduce operational costs and the complex's carbon footprint (WSP, 2018).

In an abandoned salt mine (called “Glückauf” in Sondershausen, Germany), now used as museum and waste repository, a concert hall was constructed and inaugurated in 2001. This concert hall (see Fig. 8.10) has the dimensions: 26 x 18 x 10 m and is located 670 m below surface. Total construction time: 17 months. Capacity: 300 people.

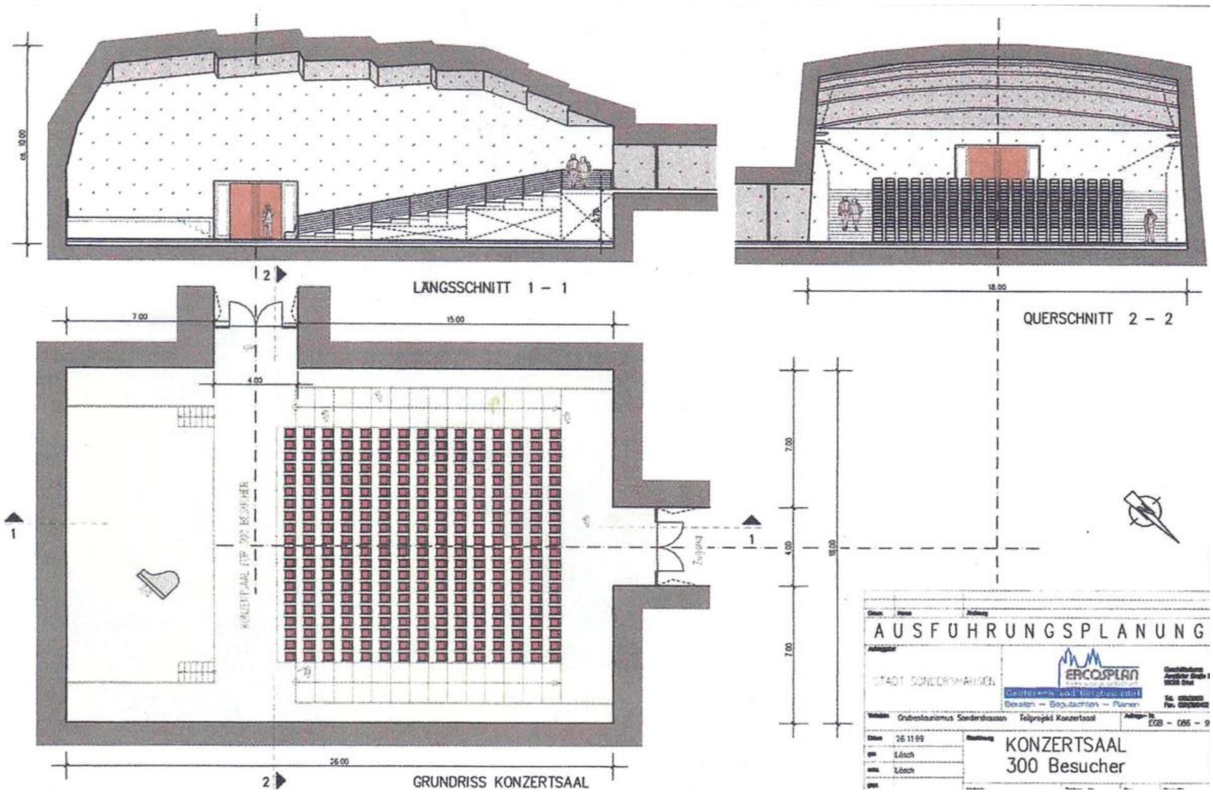


Fig. 8.10: Planning documents for concert hall in “Glückauf” mine Sondershausen (Bartl, 2022)

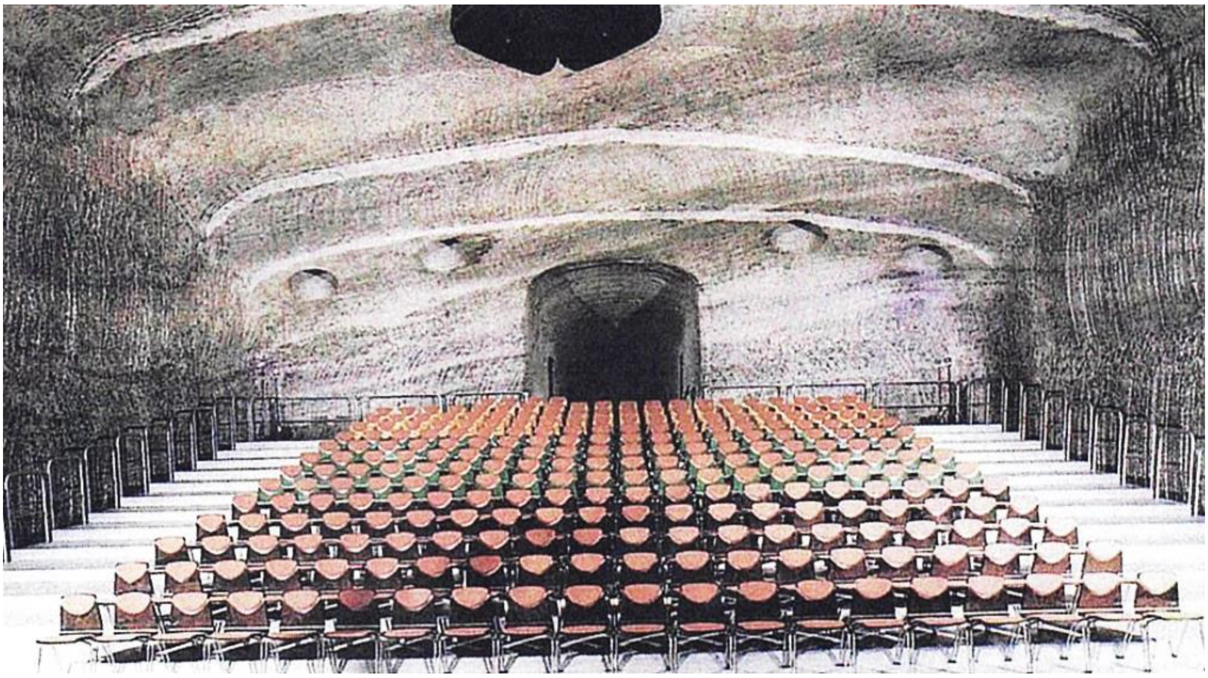


Fig. 8.11: Concert hall in „Glückauf“ mine Sondershausen (Bartl, 2022)

Fig. 8.12: Excavation process for concert hall in „Glückauf“ mine Sondershausen (Bartl, 2022)

9 Underground research facilities

Underground research facilities (URL = underground research lab) fulfil several tasks. The main purposes are:

- Execution of special physical experiments (validation of theories in theoretical physics, for instance neutrino and dark matter physics)
- Fundamental research in geosciences (exploration of the earth interior)
- Applied research for underground radioactive waste disposal
- Test of geotechnical constructions or devices
- Execution of dangerous tests (fire tests, explosive tests etc.)

An overview about URL's is given for instance by Bettini (2014), Delay et al. (2014), Fern (2018), Aptec & Chapman (2019), Pandola (2011) or Ianni (2023). Fig. 9.1 provides an overview about the large underground research labs worldwide. In addition the individual countries have a lot of smaller underground labs. Fig. 9.2 shows exemplary the large hadron collider (particle accelerator) in Geneva which consists of a 27 km long ring (tunnel like construction) with several chambers and shafts for installation of equipment. Fig. 9.3 and 9.4 show the layout of two URL's mainly used for radioactive waste disposal research.

Fig. 9.1: Location of large-scale underground research laboratories (Ianni, 2023)

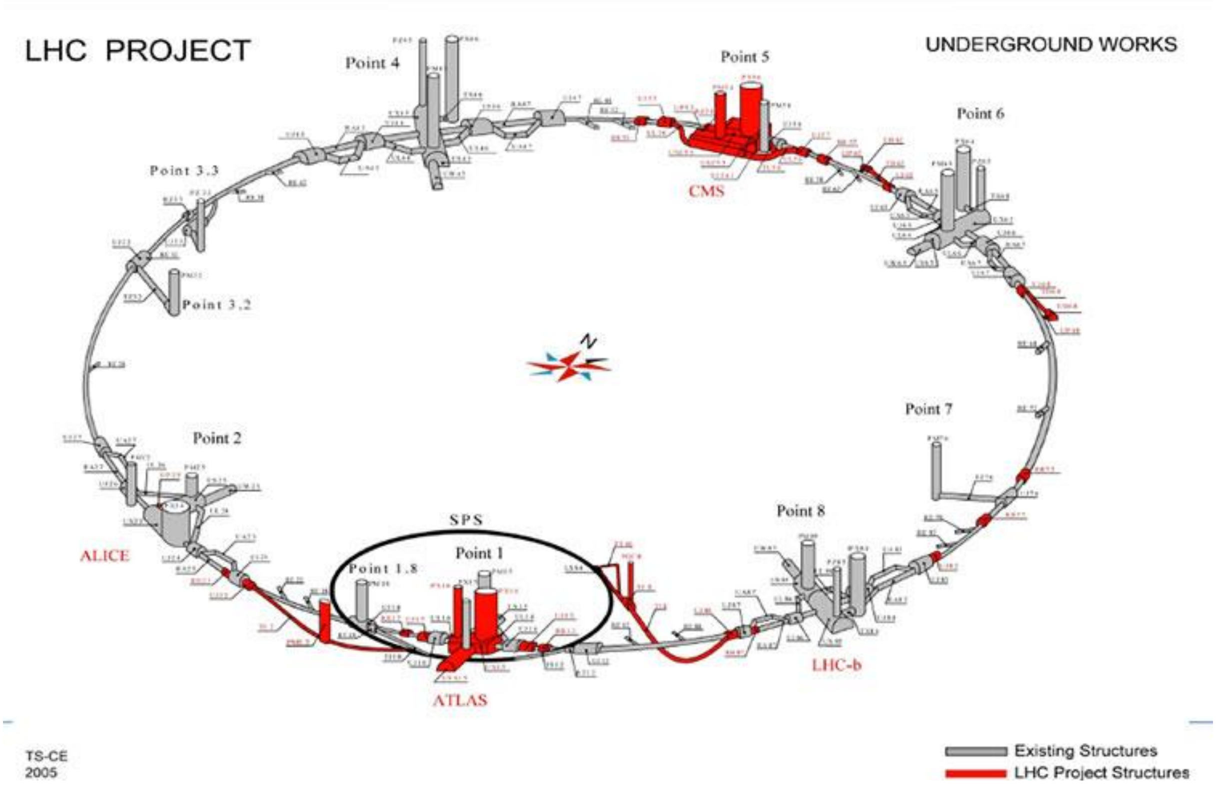


Fig. 9.2: Schematic description of the underground facilities at CERN (Fern et al., 2018)

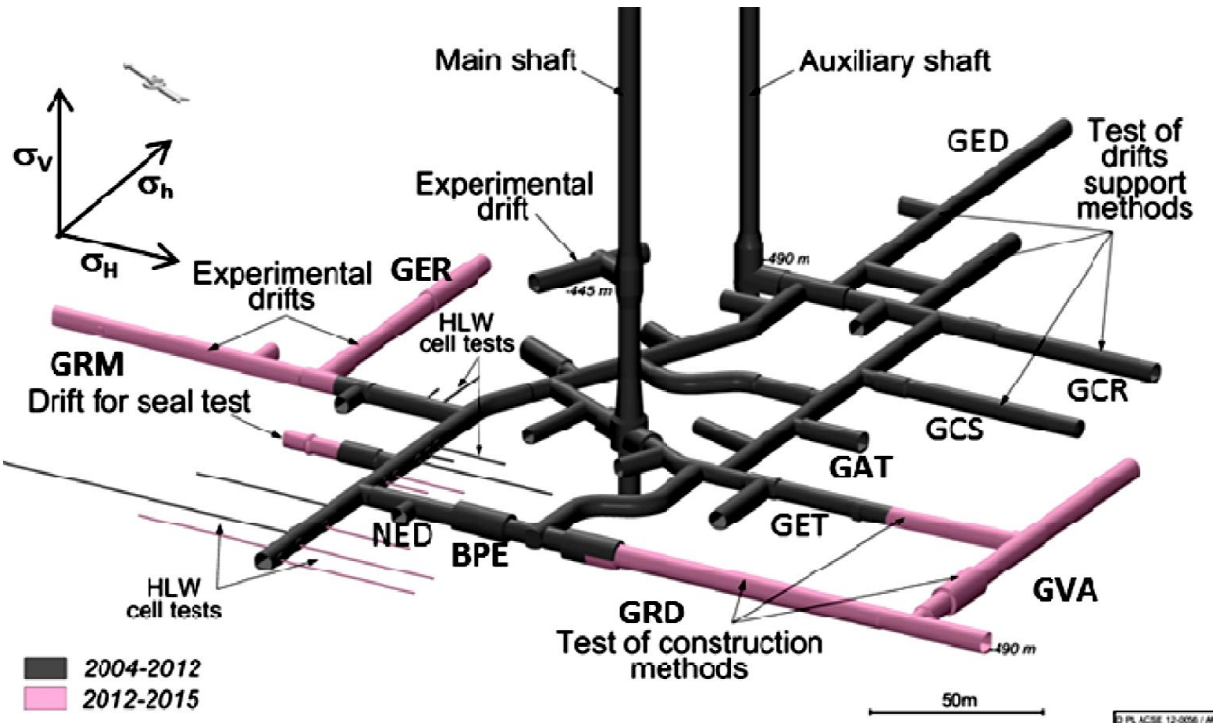
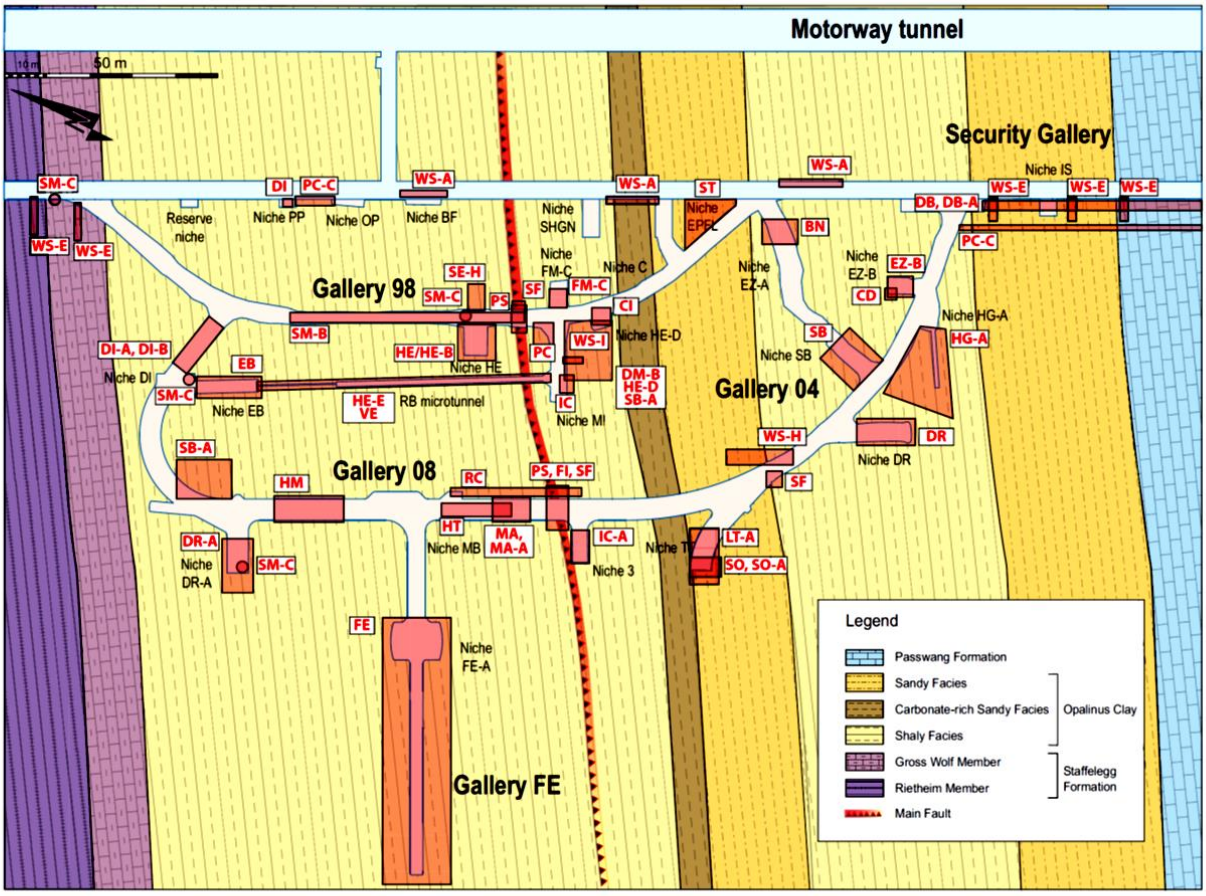


Fig. 9.3: Drift network at the URL Meuse / Haute-Marne (Armand et al., 2015)

The major rock mechanical and geoengineering problems related to the URL's are:

- URL's have to follow specific and high-level safety regulations
- special design of underground structure is necessary according to the task of the URL

- type of rock mass, location and depth of URL's is depending on planned usage
- URL's for physical experiments must guarantee extremely high precision in construction (extremely small tolerances) and minimum deformations during operation
- Rock mechanical incl. HTM-coupled parameters and characteristics of the rock mass have to be determined in detail with high accuracy and high resolution



Experiments discussed in Special Issue

BN	Bitumen-nitrate-clay interaction	HT	Hydrogen transfer
CD	Cyclic deformations	IC	Iron corrosion of Opalinus Clay
CI	Cement-clay interaction	IC-A	Corrosion of iron in bentonite
DB	Deep inclined borehole through the Opalinus Clay	LP-A	Long-term monitoring of parameters (porewater pressures)
DB-A	Porewater characterisation-Benchmarking		
DI	Diffusion in rock	LT-A	Clay properties, analyses of labtesting
DI-A	Long-term diffusion	MA	Microbial activity in Opalinus Clay
DI-B	Long-term diffusion	MA-A	Modular platform for microbial studies
DM-B	Long-term deformation measurements	PC	Porewater chemistry
DR	Diffusion and retention experiment	PC-C	Gas porewater equilibrium
DR-A	Diffusion, retention and perturbations	PS	Petrofabric and strain determination
EB	Engineered barriers	RC	Rock mass characterisation
EZ-B	Fracture generation	SB	Selfsealing barriers clay - sand mixtures
FE	Full scale emplacement demonstration	SB-A	Borehole sealing experiment
FI	Fluid-mineral interactions in Opalinus Clay during natural faulting and heating	SE-H	Self-sealing with heat (Timodaz)
		SF	Self-sealing of tectonic faults
FM-C	Flow mechanism (tracer)	SM-B	High resolution seismic monitoring
HE/HE-B	Heater experiments I and II	SM-C	Permanent nanoseismic monitoring
HE-D	THM behaviour of host rock (heater test)	SO	Sedimentology of Opalinus Clay
HE-E	In-situ heater test in VE microtunnel	SO-A	Palynology of the Opalinus Clay
HG-A	Gas path host rock & seals	ST	Seismic transmission measurements
HM	Experimental lab investig. on HM-coupled properties & behavior Opalinus Clay	VE	Ventilation test
		WS-A/E/H/I	Porewater profiles, wet spots

Fig. 9.4: Plan view of URL Mont Terri and 43 key experiments (Bossart et al., 2017)

The INFN Gran Sasso National Laboratory (LNGS) in Italy is the largest underground research lab in the world. It is constructed as a by-pass to a 10 km long highway tunnel which crosses the Gran Sasso massiv (dolomite rock mass in central Italy). It consists of three huge experimental halls, each of them 100 meter long, 20 meter wide and 18 meter high. The total volume is 180.000 m^3. The overburden height is about 1400 m and provides strong cosmic ray flux reduction. Therefore, this lab is well suited for fundamental physical experiments, but is also used for geo-scientific and geo-engineering research, see for instance De Luca et al. (2018) or Guidotti & Castellani (2017).

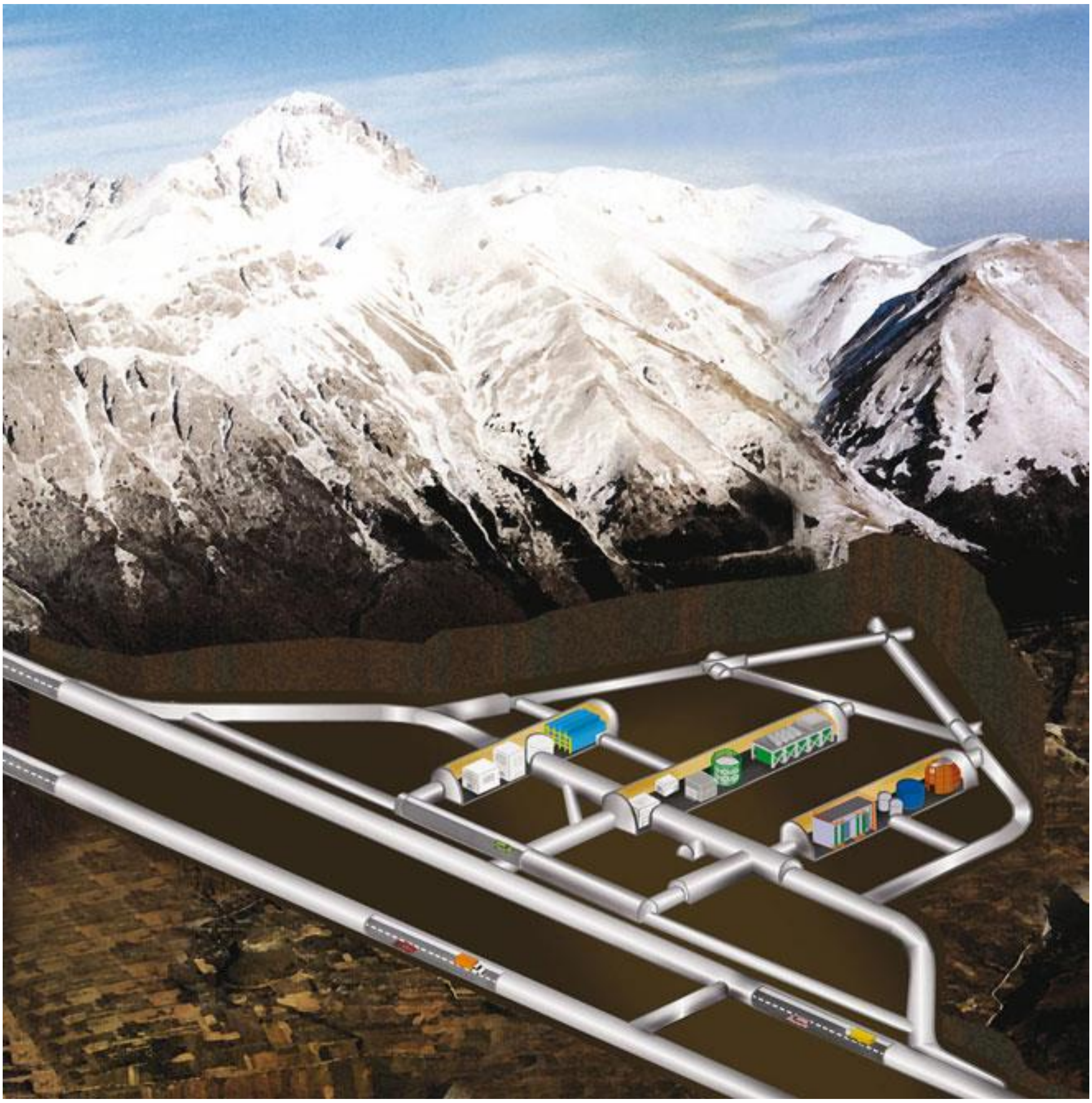


Fig. 9.5: Gran Sasso URL (www.lngs.infn.it)

Fig. 9.6: Gran Sasso URL (www.lngs.infn.it)

The currently deepest URL (JinPing) is located in China, 2400 m below surface. It is mainly used for fundamental research in physics. Fig. 9.7 and 9.8 illustrate the underground openings and lab facilities, respectively.

Fig. 9.7: Underground structure of JinPing Underground Research Lab, China (Yue, 2023)

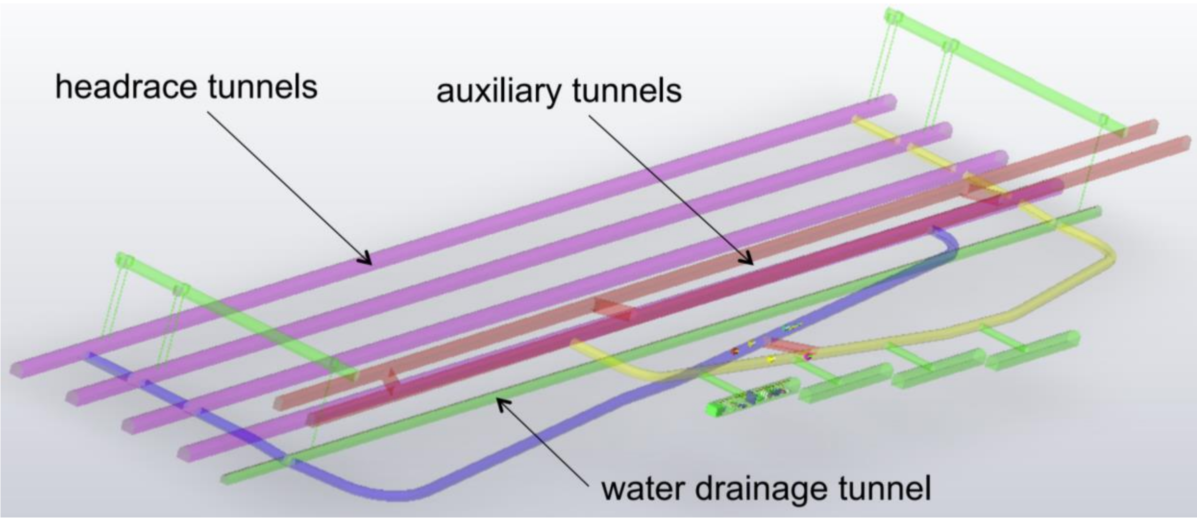


Fig. 9.8: Underground structure of JinPing Underground Research Lab, China (Li et al., 2015):

10 Underground structures for military and defence use

The underground space can also intensively be used for military (see for instance DOA, 2019) and defence purposes. Underground military structures cover for instance the following facilities:

- Silos for ballistic missiles
- Underground production of weapons
- Underground storage of fuel and military equipment
- Underground storage of food, medical equipment etc.
- Underground command and communication facilities
- Underground harbour or air craft basis

Underground defence structures cover special facilities (bunkers etc.) but also standard infrastructural elements (tunnels, caverns etc.), which can be used as space for survival of the population in case of a war or terror attack. Such underground survival space needs sufficient ventilation (air conditioning), fast access, some medical equipment, communication channels etc. Underground defence structures have to withstand bombing raids (dynamic impacts) as well as biological and chemical attacks. Fig. 10.1 and 10.2 show such systems.

Example:

Between 1941 and 2001 the underground military defence system Sasso San Gottardo (Swiss Alps) was in operation. Now it is a museum. It was built in a granitic rock mass about 2,100 m a.s.l. and is partially supported by thick concrete lining. It comprises a drift system of about 2,500 m and provides space for about 400 persons. Own electricity generators, communication tools and provisions allow self-supporting living inside the tunnel system for about 6 months. Fig. 10.3 gives some impressions. The upper photo shows the location of the drifts and rooms in red colour as plane view. In total, Switzerland has about 2,000 underground military and defence facilities of different size and purpose for over 100,000 people.

Fig. 10.4 shows a civil defence shelter in Helsinki, Finland.

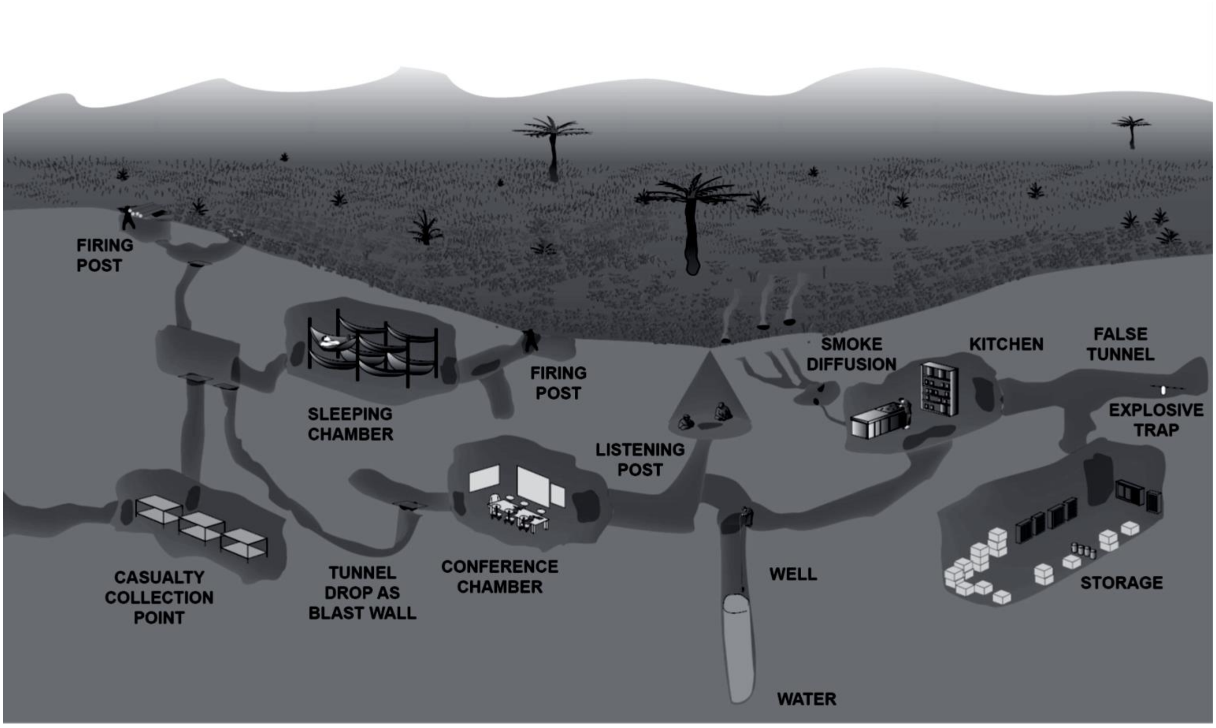


Fig. 10.1: Underground military structure in a jungle environment (DOA, 2019)

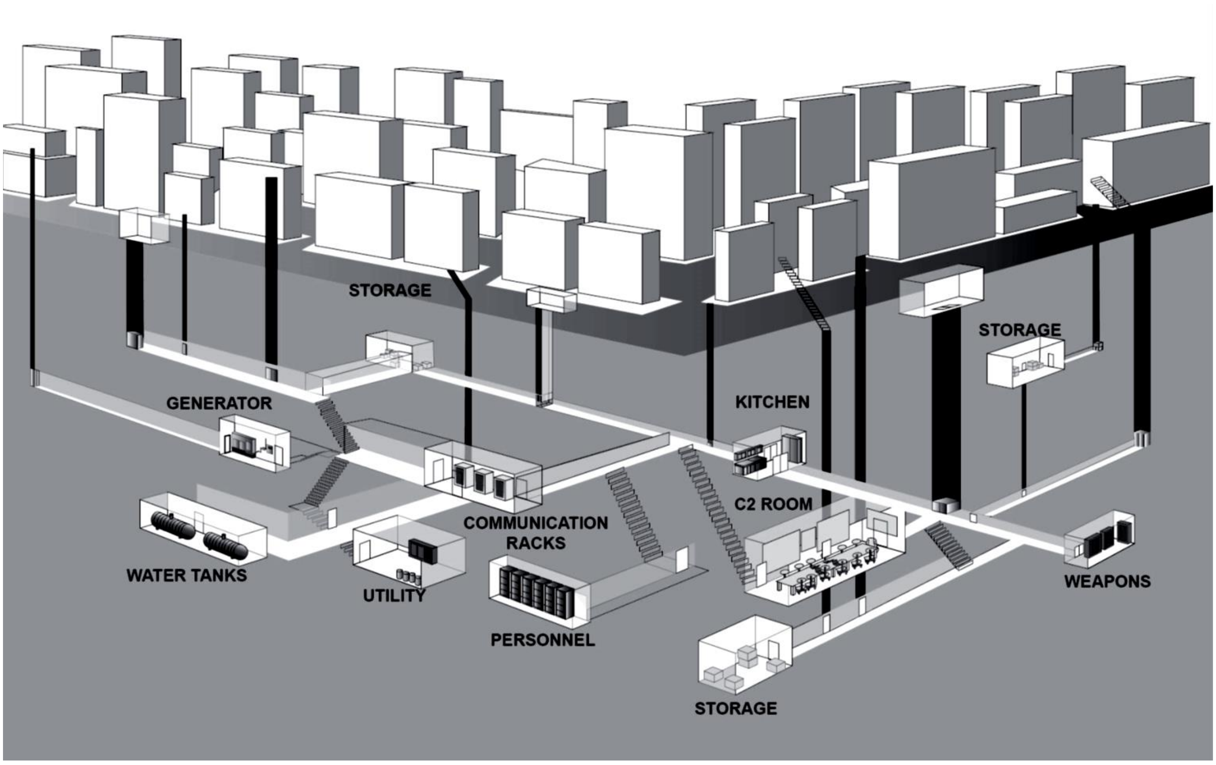


Fig. 10.2: Underground military structures in an urban environment (DOA, 2019)

Fig. 10.3: Underground defence system Sasso San Gottardo, Switzerland

Fig. 10.4: Underground civil defence shelter in Helsinki, Finland (Rockplan, 2020)

Example:

During the Cold War, Norway constructed an arctic naval base, called “Olavsvern Complex” near Tromso. This underground military habour is protected by a 270 m thick gabbro rock mass formation and consists of a 340 m long basin for submarines, military boats, stores etc.

Coughlin (2024) provides an interesting overview about several large underground constructions used for quite different purposes, not only for military use.

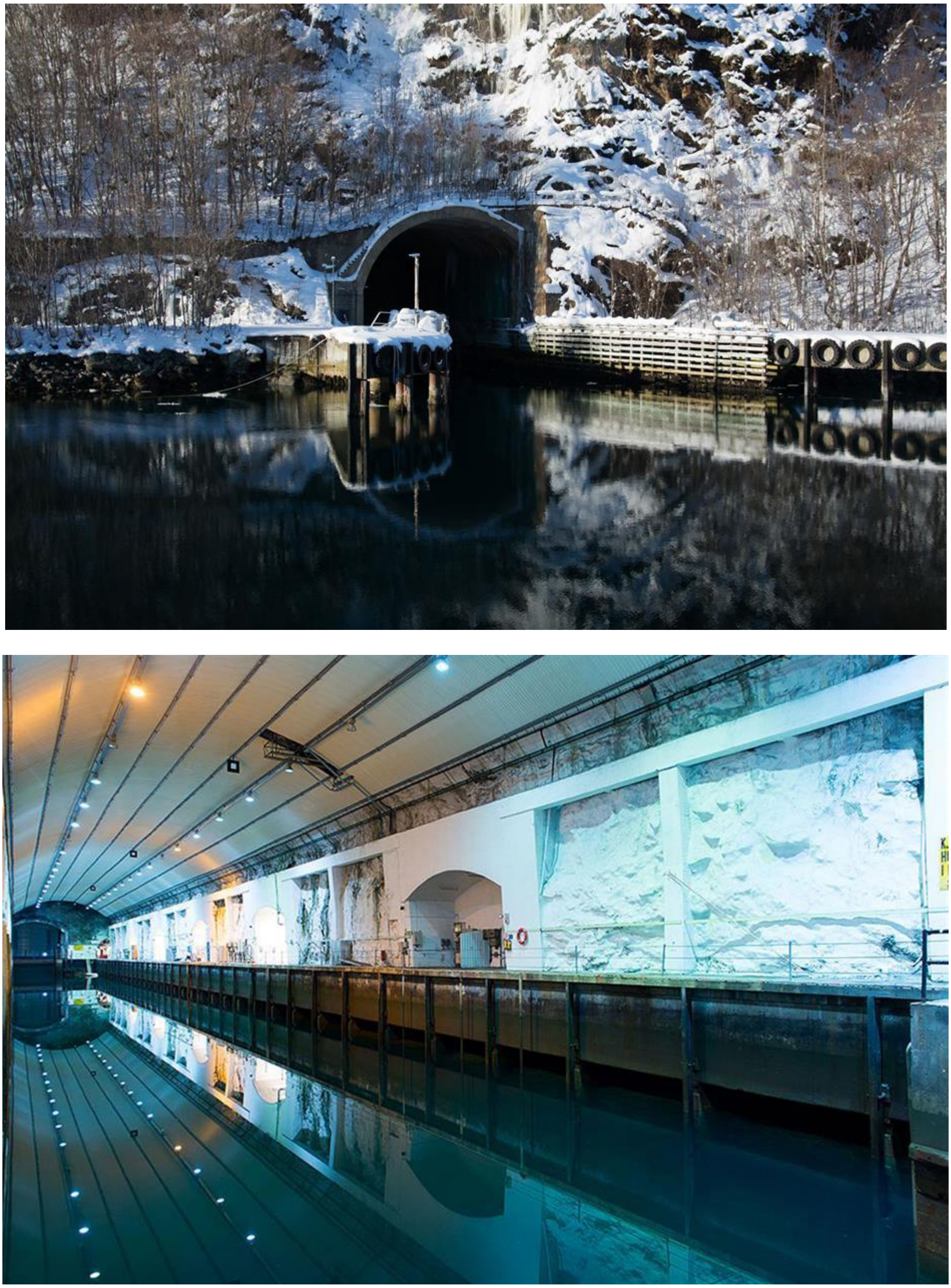


Fig. 10.5: Olavsvern Complex (Coughlin, 2024)

11 Smart cities

Smart city technology will significantly change structure and living conditions in the cities in the future. Bogan & Feeney (2020) provide an extensive overview about this concept. One important aspect with direct relation to geotechnical engineering is a massive utilization of the underground for several purposes like:

- Communication channels
- Transport of goods and persons
- Energy storage
- Storage of any kind of goods
- Shopping and recreation facilities
- Production facilities and computer centre
- Handling and temporary storage of waste
- Car parking
- Civil defence structures

The aim is minimize land use at the surface and consequently to protect the natural environment.

The NEOM-project in Saudi-Arabia follows this concept. The transport system will be placed underground and the surface is only used by pedestrians and cyclists. Also, most of the infrastructure will be placed underground. Along the 170 km long city area, it will possible to reach any place within 20 min using artificial intelligence in combination with different transport means like ultra-high-speed transit and connected means.

Fig. 11.1 shows the location of the NEOM-project in Saudi-Arabia. Fig. 11.2 illustrates the planned multi-layer concept of utilization of surface and underground.

Fig. 11.1: Location of NEOM-project, Saudi-Arabia (Neom, 2020)

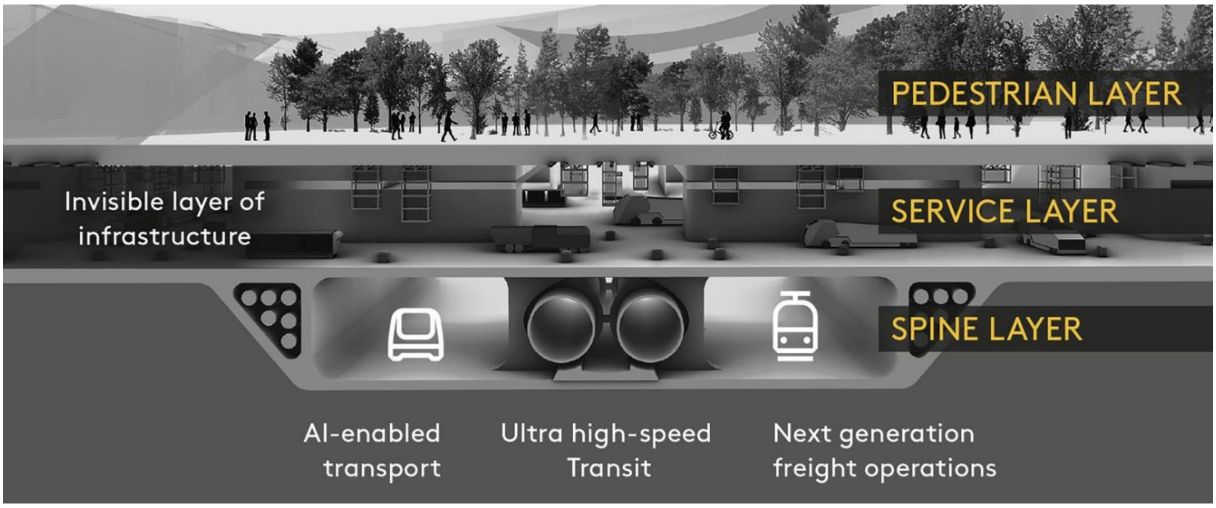


Fig. 11.2: Illustration of multi-layer concept of NEOM-project (Neom, 2020)

12 Underground hydrogen and hydrocarbon storage

Power-to-gas technology gives the possibility to store the excess power from renewable energy sources by converting electrical energy into gas such as hydrogen. In general, hydrogen blended with methane can be stored in abandoned underground mine excavations, as shown in the schematic diagram in Fig. 12.1.

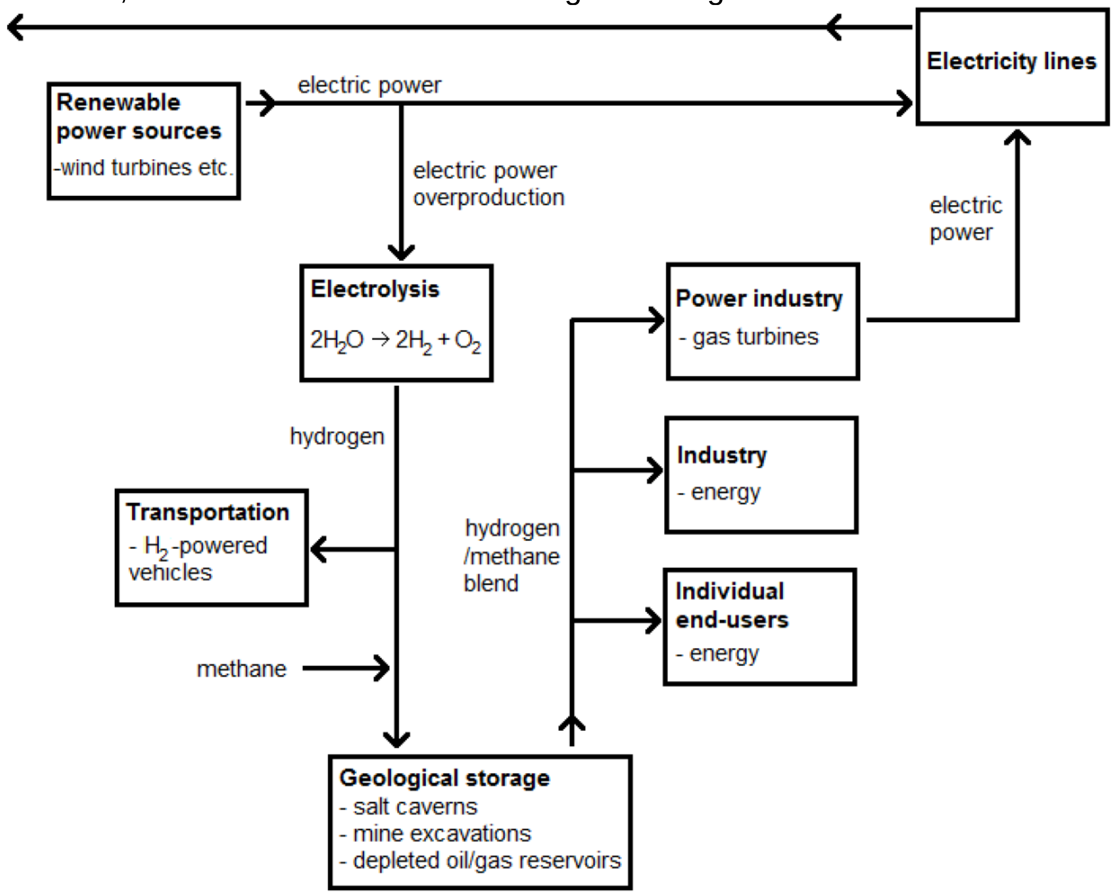


Fig. 12.1: Electrolysis-based hydrogen production with possible geological storage technologies (Gajda, 2021)

The advantage of this technology is, that coal and ore mines are usually located in highly urbanized and industrial areas. Hydrogen gas can be easily transferred to local facilities, using existing pipelines and railway transportation. However, the primary challenge of hydrogen gas storage in abandoned underground mine excavations is that the sealing capacity of the underground space defined by the tightness of the storage site.

Moreover, abandoned salt caverns are expected to store hydrocarbon energy (such as methane, natural gas) to reduce the risk of potential disasters of salt caverns and simultaneously support the strategic energy reserve (Liu et al. 2016). The principles for evaluating the tightness and suitability of a cavern are proposed, including such criteria like ‘‘no tensile stress,” ‘‘factor of safety” and ‘‘threshold of leakage amount”:

- No tensile stress. The pore pressure in the middle of the pillar should be less than the minimum internal gas pressure.
- Factor of Safety. The factor of safety (FOS) at the middle point of the pillar should be no less than 1.5 to maintain the stability of the pillar.
- Threshold of leakage amount. The total amount of gas leakage in the vicinity of the cavern should be less than 1% of the total amount stored in the cavern.

To improve the safety of salt caverns used for underground storage of hydrocarbons, Bérest & Brouard (2003) summarized several accident reasons, such as blow-out, product seepage and cavern instability.

13 Underground farming

The use of underground openings for agricultural utilization is already practise today (Lengefeld & Tegtmeier, 2019; GreenForges, 2022), especially for mushrooms and pharmaceutical crops, cannabis or vegetables. The underground openings offer several favourable conditions for growing plants, like constant environmental conditions, geothermal synergy, increasing urban farming capacity and safety. It can also be conducted in extreme cold regions covered by snow and ice.
In London, for instance, huge underground shelters built during World War II are now used to produce vegetables (see Fig. 13.1).

Fig. 13.1: London underground farm (Broom, 2021)

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