GEO ENeRGY

The role of the underground for massive storage of electric energy

Recently, a need to find means able to control and to regulate the fluctuations of the electric grids induced by the discrepancies between supply and demand of power has been identified. The increasing volatility of the price of electricity is one of the consequences of such intermittency. In addition more renewable energy resources are targeted to realize the EU's sustainability objectives, i.e. to reach 20% of renewables in the energy market from which a large part would come from wind and solar power generation highly influenced by unpredictable weather and economic fluctuations.

In this context energy storage systems have been developed to improve the performance of the power grid, meaning growing renewable energy systems, controlling the frequency, upgrading the transmission line capability, mitigating the voltage fluctuations and improving the power quality and reliability. These technologies can be defined in four categories: (i) mechanical energy (potential or kinetic): pumped hydro storage power plant (PHS), compressed air energy storage (CAES), flywheels; (ii) electrochemical and electrostatic energy: batteries, capacitors, superconductors; (iii) thermal and thermochemical energy: sensible heat and latent heat, sorption systems; (iv) chemical energy: hydrogen, methanation, etc. The appropriateness of such energy storage technologies to various applications can be evaluated according to several types of criteria: economic lifetime, life cycle, discharge power and energy stored, self-discharge rates, environmental impact, cycle efficiency, capital cost, storage duration, and technical maturity.

Depending on the regulatory regime, the commercial arrangements per country and the network connections, one should consider the full range of storage options, from small to large-scale energy storage (Fig. 1). Electric energy storage technologies involving the use of underground offer large storage capacities and discharge rates. Among the options for large-scale storage, we mention (i) underground pumped hydro-storage (UPHS) which is an adaptation of the classical PHS system, (ii) CAES and (iii) hydrogen storage from conversion of electricity into H_2 and O_2 by electrolysis.

The concept of conventional PHS system is based on using the potential energy between two water reservoirs positioned at different heights. Favorable natural locations like mountainous areas or cliffs are spatially limited given the geography of the territory. The UPHS system is an extension of this concept with the integration of one of these reservoirs in underground cavities (specifically mined or reuse of preexisting mines) to increase opportunities on the national territory. Large-scale storage of air (CAES) based on compression when there is excess electricity, and on expansion to spin a turbine in case of demand for electricity requires a large storage volume and a high confining pressure, which exists naturally in the underground and increases with depth. Hydrogen underground storage is part of the "power to X" or "P2X" concept, (X can be natural gas, H_2, synthetic fuels, heat, cold, etc.) which converts excess electricity into hydrogen gas available for reuse in refineries, for the transport sector, or for injection into the natural gas grid (up to a threshold ranging from few to 10% depending on the studies), or for conversion into methane (through the Sabatier process).

Each of these techniques requires the selection of appropriate geological formations (leached salt caverns, crystalline rocks, sedimentary porous rock, porous basalts or abandoned mines). The formation's specific characteristics should be in agreement with the design criteria of the electrical energy storage site. Knowledge of the underground obtained from past local experience with other applications (such as underground natural gas storage, underground fuel storage, geothermal production, CO_2 geological storage and nuclear waste disposal investigations) may help in the site selection process, and in evaluating the technical and environmental impact risks.

To date, the only existing operations of electric energy storage using underground in the world are two CAES plants located in Germany and in USA (see also Page 4). Aquifer thermal energy storage (ATES) could be mentioned, but this only applies to single building or to local heat grids (see also Page 2). Therefore, mapping of all possible underground energy storage sites, estimation of their storage capacity, techno-economic feasibility and the short and long term market perspectives are important future research areas.

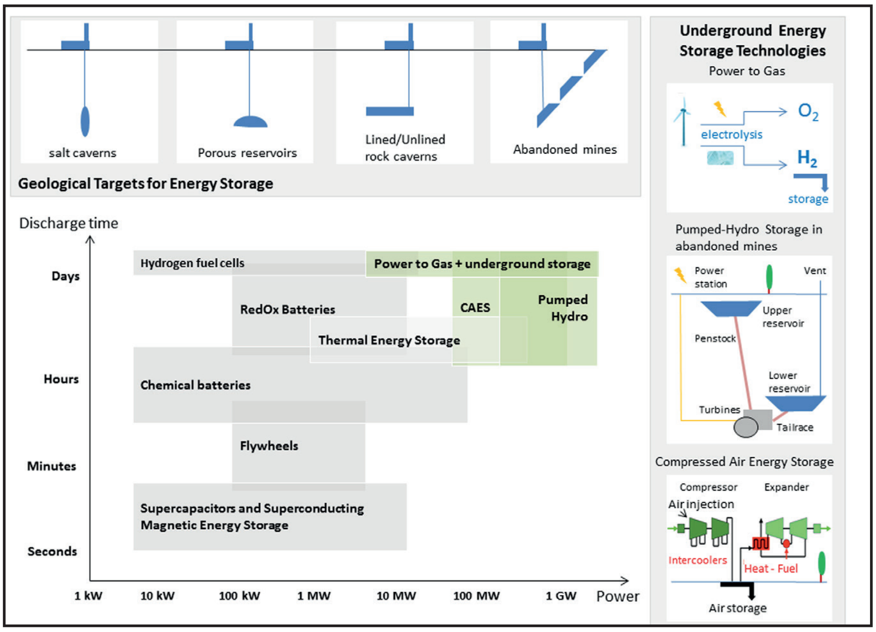

Fig.1 Ranking of electrical storage technologies according to discharge time and power capacity (updated after ENEA-consulting, France). Use of underground is marked by green and represented by Power to gas, pumped hydro storage in abandoned mines and compressed air energy storage (aquifer thermal energy storage differs as it is not connected to the electric grid). Four typical geological targets are salt caverns, porous reservoirs, lined rock caverns and abandoned mines

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Research on thermally loaded rocks: prospects for underground thermal energy storage

Efficient and inexpensive energy storage systems undoubtedly play a significant role in the modern sustainable energy strategy. The thermal energy storage, defined as the temporary storage of thermal energy at high or low temperatures, appears to be the most appropriate method to handle the mismatch occurring sometimes between the energy supply and demand.

Energy storage is a priority research area of the Czech Geological Survey, and several projects focused on this topic are currently ongoing, in cooperation with ISATech Ltd., ARCADIS CZ corp., Technical University of Liberec, PROGEO Ltd. and Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic.

In the Underground Research Laboratory Josef in central Bohemia (http://www.uef-josef.eu, Fig.2), granitic rocks are being studied as the host environment for the underground thermal energy storage (www.geology.cz/mokrsko/english). This project is designed to study the thermal energy flow in the granitic rocks in terms of efficiency and safety. An in-situ experiment has been set up to evaluate the influence of cyclic heating up to 95°C and cooling on the thermo-hydro-mechanical and chemical characteristics of the rock. The long-term in-situ heating experiment (Fig.3) describes changes in geomechanical, chemical, petrological and hydrogeological properties of a granitic environment during and after repeated heating and cooling cycles. The duration of one cycle of heating-cooling to semi-steady state lasts nine months.

The rock massif is monitored in ca. 10 m surroundings of a single heating borehole, drilled in faulted and fractured granitic rocks penetrated by dense swarms of quartz veinlets. Appropriate attention is thus paid to changes in the flow and circulation of groundwater and to the deformation of the rock massif caused by thermal expansion related to the cyclic heating. These are the key parameters necessary for the safe design and construction of underground structures and facilities intended for the storage of thermal energy or for disposal of materials that produce heat (e.g. nuclear waste). Specific objectives of the project are to determine and verify:

- the extent and range of possible influence of thermal stress on the structure of granitic rocks
- possible changes in hydraulic, hydrochemical, petrographic and geotechnical parameters of rocks in relation to the distance from the heat source
- effective rock thermal parameters and correlation with numerical models involving temperature, stress, strain and hydrodynamic simulations.

Monitoring boreholes (0.4 to 10.5m long, ca. 130m total length, Fig.3) are used to monitor changes in thermodynamic, geotechnical, hydraulic and seismic properties of the rock. Seventy temperature sensors are monitoring the 3D spreading of the temperature field. Additionally, resistivity and seismic profiles are measured on the rock surface at temperature regime switches (heating/cooling). Geotechnical monitoring is focused on stress and strain changes in the rock matrix (stress meters and strain gages), pore pressure (piezometers) and displacements induced along fractures (microcrack meters, 3D fissurometer and magneto-strictional dilatometers). Present results indicate very rapid reaction of the rock massif to fluctuations in rock heating intensity and the large extent of these artificially induced stress changes. The changes appear without any observable hysteresis, i.e. they behave as fully reversible in respect to irregular experimental heat supply modifications. Moreover, these results also suggest an important impact of rock heating on intensive growth of specific microorganisms, which may also significantly influence future underground industrial applications.

A complementary research is being conducted in the frame of a project titled "Reversible Storage of Energy" (http://www.resen.cz, Fig.2) that investigates possibilities of energy storage using a high-temperature source which transfers thermal energy to rock. Effective heat transfer is realized using newly developed thermally conductive geopolymer injected into the rock environment. Laboratory testing on both micro- and macro-scale rock samples from 35 localities in the Bohemian Massif is focused on finding lithologies suitable for application of the thermally conducting mass and repeated heating to 360°C without significant rock degradation and chemical reaction with the mass. This project is topped by building of a 1m–scale demonstration experiment of heat storage and retrieval complemented by numerical simulations of the processes involved.

Results of the two projects described above will also be utilized in future research focusing on the repositories of spent nuclear fuel in deep geological structures.

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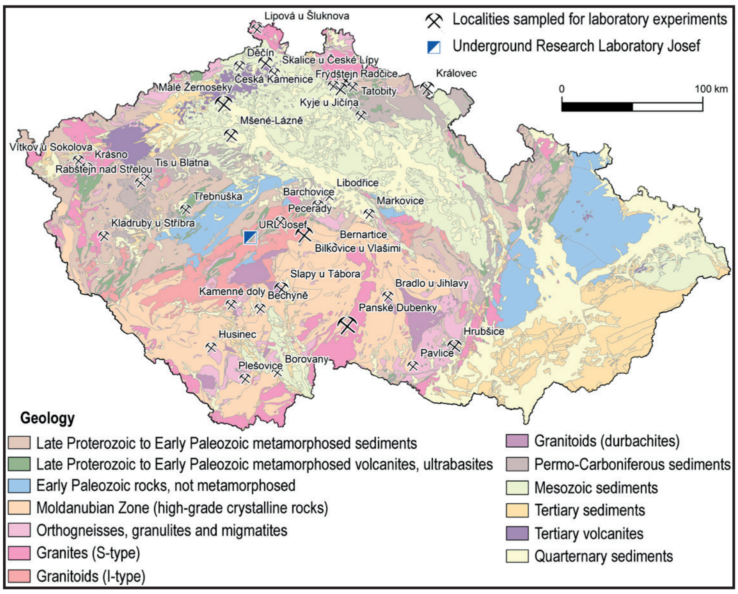

Fig.2 Geological map with 35 localities in the Bohemian Massif sampled for the "Reversible Storage of Energy" project and localisation of the granitic rocks studied in the Underground Research Laboratory Josef

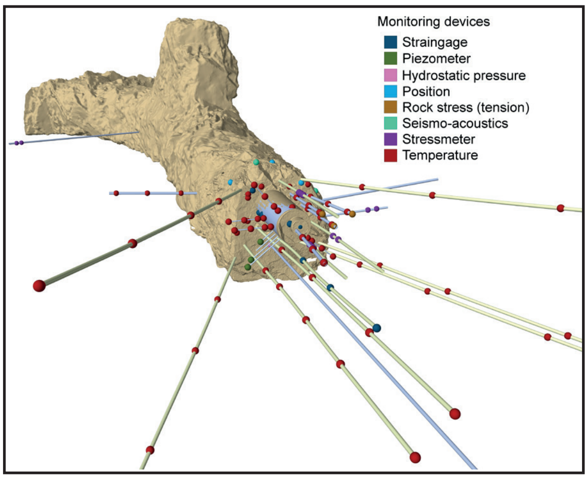

Fig.3 3D visualization of the in-situ experiment instrumentation. The shaded relief represents outer shell of the entry adit, thin tubes are monitoring boreholes 0.4 – 10.5m long and spheres mark position of individual measuring devices, installed either in the monitoring boreholes or on the walls of the adit. The wide dark "tube" represents the heating/cooling borehole, 2.2m long. Hydrostatic pressure device is about 0.5m below the wide heating borehole

Large-scale energy storage in the Netherlands

The Dutch Government has recently formalized an Energy Agreement with the pertinent stakeholders to realize a market share of 14% energy production from renewable energy sources (RES) by 2020, increasing to 16% in 2023. This implies that by 2020 about 45% of all electricity in the Netherlands is to be generated from RES (this share was only 10% in 2012). An additional challenge for the Netherlands is that the giant Groningen field has been depleted by over a half and is quickly losing its 'swing capacity'. To counter this loss in flexibility, various underground gas storages (UGS) have been constructed. But the overall concern of how to stabilize the grid for the increased volatility of the flows remains. In this respect, the business climate is unfavourable.

Currently, there are six natural gas storage sites operational in the Netherlands: four porous UGS (Norg, Grijpskerk, Bergermeer and Alkmaar), one UGS in salt caverns (Zuidwending), and one above-ground LNG peak shaver. Moreover, there is a salt cavern UGS in Epe (Germany) also serving the Dutch flexibility market (Fig. 4).

Despite the expected increase in volatility on the grid and the fast loss of swing capacity in the Groningen field, there are no plans for additional storages. Apparently, the market perspectives for investments in flexibility need to be improved first. But also, a view needs to be formulated on how improved market conditions would result in either centralized or decentralized flexibility solutions, and/or in demand curtailment at times when grid congestion is a problem. Indeed, this view is direly lacking and may even be the crux of the energy transition in the Netherlands.

Theoretical flexibility solutions for high MWh/high MW storage options in the Netherlands are: UGS (underground gas storage), PHS (pumped hydro storage) and CAES (compressed air energy storage). In the Netherlands, PHS is not feasible (no mountains/valleys to construct reservoirs). Other large-scale storage options have been considered in the past and are currently being re-looked into: underground PHS (UPHS) in two connected salt caverns: one shallow, one deep; UPHS in abandoned coal mines (desk studies done in the 1990s); underground H_2 storage (from electrolysis during excess wind energy, with the H_2-gas stored in salt caverns or depleted gas fields); H_2-gas converted to synthetic methane (syngas: power-to-gas/P2G) and stored underground. But these underground options are immature and would require significant R&D. For example, operating subsurface pump turbines for UPHS and increasing the thermodynamic efficiency by storing and recapturing the heat produced during the compression phase (adiabatic CAES) are major technological challenges.

In the Netherlands, there is no immediate need to increase the capacity of flexible electricity production. However, due to the government's ambitions of increasing the share of RES, and due to the depletion of the Groningen gas field, there will come a future need of increasing the nation's large-scale energy storage capacity. Options are to expand the capacity of current UGS sites, and construct new UGS sites (whether in depleted gas fields, salt caverns, or aquifers). Non-UGS solutions are CAES, UPHS, underground H_2 storage and P2G.

The main hurdle, however, seems to be a lacking national policy on how to develop the business incentives for investing in flexibility and, hence, in underground energy storage solutions. Ultimately, more consistency is to be achieved in the EU's and member state energy policies so as to allow market forces to select the winners and achieve level-playing-field efficient markets, where prices adequately reflect the scarcity of the commodity and associated (flexibility) services.

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Fig.4 Gas storages in the Netherlands (www.gie.eu/index.php/maps-data/gse-storage-map). Legend:
salt cavity – caverns: yellow triangles; depleted fields/gas fields: yellow rombs; above-ground LNG peak shaver: yellow flag; projects: red lined symbols

ENeRG – European Network for Research in Geo-Energy

ENeRG – European Network for Research in Geo-Energy is an informal contact network open to all European organisations with a primary mission and objective to conduct basic and applied research and technological activities related to the exploration and production of energy sources derived from the Earth's crust.
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Compressed air energy storage project within Columbia River Basalt in USA

In the first project of its kind the Bonneville Power Administration teamed with Pacific Northwest National Laboratory and industrial partners to evaluate the technical and economic feasibility of developing compressed air energy storage (CAES) in the unique geologic setting of inland Washington and Oregon in USA.

The basic idea of CAES is to capture and store compressed air in suitable geological structures underground. The stored high-pressure air is returned to the surface and used to produce power when additional generation is needed, such as during peak demand periods.

To date, there are two operating CAES plants in the world; a 110 MW plant in McIntosh, Alabama, commissioned in 1991 and a 290 MW plant in Huntorf, Germany built in 1978. Both plants store air underground in excavated salt caverns produced by solution mining.

The Pacific Northwest region east of the Cascade Mountain Range is dominated by the Columbia Plateau Province (CPP). The CPP predominantly consists of a set of continental flood basalt deposits that cover over 210000 km² of eastern Washington, northeastern Oregon, and western Idaho (a total volume >223830 km³). The Columbia River Basalt Group (CRBG) portion extends and is coincident with a very large fraction of the wind and thermal power generation resources in the region.

Data collected recently from natural gas exploration wells and CO_2 sequestration pilot project in the Columbia River Basalt were used to assess CAES potential in this region. Areas were evaluated for following key criteria: reservoir thickness ≥10 m, reservoir permeability k ≥500 millidarcy and effective porosity ≥10%, very low caprock permeability (≤1 microdarcy) and caprock thickness ≥30 m. The presence of an anticlinal structure to increase air recovery efficiency and prevent migration of the compressed air away from the storage project boundaries was included as additional criteria.

A first storage site was identified (>830 m depth) where a conventional CAES plant design could offer 231 MW of load during storage and 207 MW of generation. The novel use of deep flood basalts as the air storage reservoir (10% porosity) is a distinguishing difference from "standard" CAES plants deployed elsewhere that use solution mined salt caverns. Storage capacity was estimated at about 1.5 million metric tons (MMT) of air, with 40 days potential of continuous injection at plant capacity and a capability of over 400 hours of subsequent generation. The installed capital cost was estimated to be similar to conventional combined-cycle gas turbine plant at a levelized cost of electricity (LCOE) as low as 6.4 cents per kilowatt-hour (kWh), competitive with most generating options within the region.

A new type of no-fuel hybrid geothermal CAES plant was designed for a second site located near Yakima Canyon north of Selah (Yakima Minerals, Fig. 5). The geology at this site includes a basalt sequence underlain by thick sub-basalt sandstones (>3000 m depth). The plant would utilize geothermal and geopressure resources to produce power and will offer 150 MW of load during storage and 83 MW of generation capacity. Pressures at those depths result in higher density of air being stored, which combined with a very large reservoir structure provide for a very large air storage capacity. Simulations of continuous injection for 1 year representing 4 MMT of air filled less than 20% of the reservoir volume. The plant LCOE was estimated to be 11.8 cents per kWh and could be competitive with the region's peaking and renewables generation. A follow on study is presently ongoing looking at other regions in the U.S. where the geothermal-CAES plant design may have economic potential.

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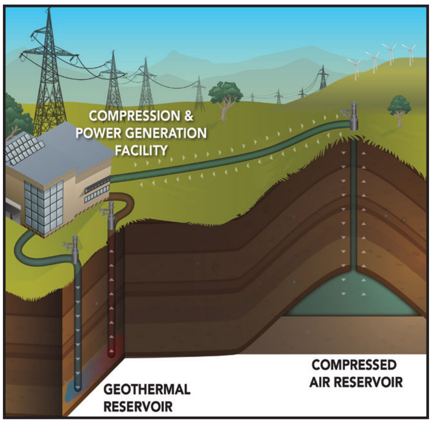

Fig.5 Compressed air energy storage at Yakima Minerals site. Geothermal energy recovery from water ≥150°C is predicted at the depth more than 3600 m. The storage reservoir is represented by thick sub-basalt sandstones with excellent permeability at the depth more than 3000 m

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