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Coal Mines in a New Role: Investigation of Underground Pumped Energy Storage

[1]Viktor Sándor Fazekas

[1]*Obuda University. Budapest, Hungary. fazekas.sandor@uni-obuda.hu*

Abstract

The article examines the possibilities of underground pumped energy storage in abandoned coal mines, with special attention to enhancing the security and stability of European power supply systems and the effective integration of renewable energy sources. It analyzes the geological, mechanical, hydraulic, and corrosion challenges of underground mine spaces, as well as factors influencing system stability. The study also addresses the economic aspects of investment, highlighting the long payback period and the positive role of social acceptance. The study highlights that the successful implementation of this technology could represent a significant step toward improving the sustainability and security of energy systems in Europe.

Keywords: underground energy storage, pumped energy storage, abandoned coal mines, energy system security, renewable energy integration

1 Introduction

The future of the European region in the field of energy storage is increasingly oriented toward the integration of renewable energy sources and climate protection targets, primarily the achievement of net-zero carbon dioxide emissions by 2050. In this process, energy storage becomes a key role, enabling the management of variable generation from solar and wind sourcesas well as fluctuations in energy demand. Energy storage makes it possible to ensure reliable energy supply, enhance system flexibility, and reduce dependence on fossil fuels. [1]

According to the Ten-Year Network Development Plan (TYNDP), by 2040 the optimal energy storage systems will be based on the combination of several technologies, whose comparison is presented in Figure 1. Short-term storage is expected to rely primarily on lithium-ion batteries, which mainly follow the daily generation cycle of solar power and enable fast charging and discharging of energy. In the medium term, pumped hydro energy storage plays an important role, offering large storage capacity and effectively managing short-term fluctuations, while providing long-duration storage with more favourable technical characteristics compared with lithium-ion batteries. Based on current knowledge, hydrogen-based storage appears to be the most effective solution for long-term, seasonal energy storage. Hydrogen offers high energy density and very low self-discharge over time, making it suitable for bridging periods of extreme supply–demand imbalance. In this context, salt caverns could be utilised as promising geological formations for hydrogen storage, as rock salt is highly impermeable to gases, allows the creation of large-capacity underground voids, and exhibits minimal ageing effects during operation. [1][7]

The energy storage mix of the individual European countries depends on available resources and energy demand. For example, France, Italy, Austria, and Switzerland primarily rely on pumped hydro storage, while Germany, Poland, and Finland tend to prefer hydrogen-based storage technologies. In some countries such as Greece, the Netherlands, and Denmark, batteries dominate as the main energy storage solution. [1]

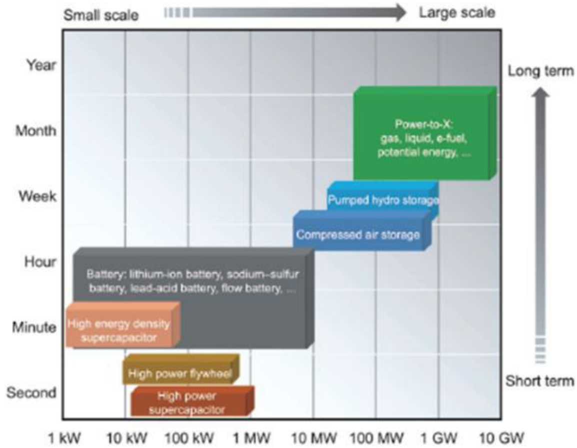

Figure 1. The classification of different energy storage technologies according to storage duration [5]

2 Difficulties of underground pumped hydro storage technology

Underground pumped hydro storage can be an attractive option for the energy transition, primarily because it eliminates the topographical constraints typical of conventional pumped hydro facilities, thus enabling deployment even in flat regions. This approach significantly reduces landscape intervention, but it faces several serious technical challenges in implementation. Although pumped hydro storage is a mature technology, there is currently no documented, operational facility using abandoned underground mine galleries as lower reservoirs. [4][5][6]

According to the concept, the upper reservoir is located at the surface, while the lower reservoir is situated, for example, within an abandoned mining facility or a man-made tunnel (Figure 2). In the placement process, operational efficiency must be considered; a high head increases capacity and reduces the required underground reservoir volume, thus moderating costs. However, using abandoned coal mines as lower reservoirs poses technological and geological challenges. The structural stability of mine galleries, water and gas flows, temporal changes in rock mechanical properties, and the condition of previous mining infrastructure all affect the safe and reliable operation of the reservoir. Therefore, detailed fundamental research, geophysical surveys, and modeling of the mechanical and hydraulic behavior of mines are necessary for optimal design and operation. [2][3][4]

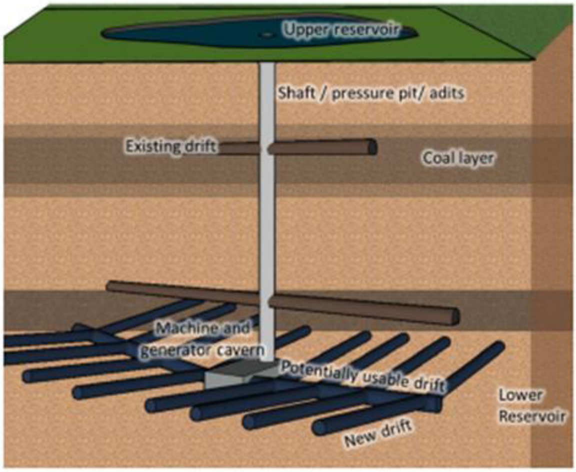

Figure 2. Conceptual arrangement of underground pumped hydro storage [4]

A fundamental technical obstacle in the design phase is the insufficient knowledge of the structural geometry and condition of abandoned mines. Since the closure of the mines, these may have undergone post-mining processes such as weathering, dissolution, hydration, leaching, swelling, subsidence, and creep along fractures, all of which have significantly altered the original volumes and stability of the mine tunnels. [2][5]

Due to the incomplete or outdated nature of mine plans, designers are unable to accurately estimate critical dimensions such as storage capacity or available hydraulic head, which are essential for the optimal sizing of turbine equipment. In coal mines in the Ruhr region, for example, the available depth (head) typically ranges between 500 and 1000 meters, but the deepest points can reach up to 1600 meters. Since existing mine tunnels are generally unsuitable (or insufficient in capacity) for serving as lower reservoirs, new, lined, circular tunnels are often required, especially in geologically unfavorable areas containing soft rock. [2][4]

The long-term stability of abandoned mines depends on time-dependent geometric changes, including alterations to the original state of the rock mass and supporting structures. During operation, tunnels are subjected to cyclic transitions between wet and dry conditions. This cycle is particularly problematic for clay-rich rocks, as their strength and stiffness decrease significantly due to water absorption. In sandstone, a reduction in tensile strength is also observed as a result of repeated wetting and drying cycles. The loosening/weathering process occurs due to pressure differences between air-filled and water-saturated pores, a phenomenon well-known in coal mines and potentially leading to structural instability. [2]

Swelling and shrinking cycles in clay and siltstone can cause deformation and accumulation, resulting in the disintegration of the rock mass and the deterioration of its fundamental properties. The stability of rocks is further affected by continuous mechanical loading, in addition to the alternating wet and dry cycles. Although the maximum amplitude of operational water pressure is only a few kPa compared to geological and tectonic stresses in the surrounding rock mass, continuous cyclic loading can cause serious problems. These cyclic stresses may lead to fatigue failure, causing the rock mass to loosen and lose cohesion, and accelerating the accumulation of deformation. [2]

During the feasibility assessment, the temperature of the water circulating in the underground reservoir must also be considered, as it may differ from the temperature of the surrounding rock. This creates a thermally affected zone around the reservoir, where temperature gradients ranging from -5°C to -40°C can develop. The resulting temperature decrease induces transient thermal contraction in the rock, generating thermally induced stresses. If the temperature change occurs suddenly, it can cause mechanical instability, such as spalling or cracking in the tunnel walls. These cyclic thermal stress variations can lead to long-term thermal fatigue over time. [2][4]

2.1 Support system

The support systems in tunnels were originally designed for mining activities, and their current condition is uncertain due to lack of maintenance and gradual deterioration over time. Since closure, ongoing corrosion poses a significant risk, with water-induced corrosion being the most common type, caused by groundwater in the mine. The corrosive effect of mine water is further intensified by the presence of peat acids and bacteria. Groundwater may contain salts, sulfate ions, chloride ions, and bicarbonate ions, which accelerate the corrosion of the support system, thus affecting the fundamental stability and safety of the tunnel system. [2]

2.2 Mine gas

Gas release primarily occurs during mining activities, due to the decreasing stress and pressures inside the rock materials, opening existing fractures and forming new gas migration pathways. Long-term risks are increased by the continuous deterioration of rock and concrete lining properties over time, which may lead to increased permeability. This heightened permeability facilitates the movement of mine gas and other fluids between the reservoir and the surrounding rock. During operation, the presence of mine gas can cause difficulties in maintaining tunnels, especially if gas concentration is too high. During pumping or turbine cycles, fluctuating water levels displace air, as mine gas tends to accumulate in the upper parts of tunnels. Therefore, it is essential to install adequate ventilation shafts in tunnels to ensure the safe removal of displaced air and any released mine gas. When converting or using galleries, care must be taken to create optimal airflow conditions, thus minimizing risks. [2][6]

2.3 Hydrodynamic challenges

The connection of the lower suction pipe to the pipe network is achieved exclusively through a single connection point, lacking the kinetic energy conversion effect of diffusers or open surface reservoirs typical for conventional pumped storage systems. This configuration leads to increased inflow velocities, which may cause flow instabilities and oscillations, particularly in bends or junctions. The reservoir water level gradually rises or falls during filling and emptying cycles, while local hydrodynamic phenomena, such as wave motion, occur. These waves propagate from their source, resulting in elevated water levels and velocities within the pipes. If the wave height exceeds the freeboard of the reservoir, a pressure surge can occur. When the wave reaches the reservoir ceiling, the free-surface flow becomes pressurized, closed-system flow, leading to local pressure increases that may impair turbine efficiency and reduce their operational lifespan. [2]

3 Conclusion

Underground pumped hydro storage systems are potentially competitive solutions for large-capacity energy storage. Their successful technical implementation and addressing associated economic challenges could make these systems advantageous for increasing the flexibility of energy systems. Current estimates suggest that the investment costs for underground systems are generally higher than for surface pumped-storage facilities.

However, the return on investment largely depends on market energy price volatility and is strongly influenced by the size of the facility, with typical payback periods ranging from 8 to 15 years, which is considered competitive in the market for high-capacity energy storage solutions. [2][3][4][5]

In addition, when implementing underground reservoirs, the level of social acceptance is a significant factor, which is generally more favorable compared to conventional surface structures. This environmental adaptability can facilitate faster and more efficient project implementation, reducing potential implementation risks. Overall, if technical and economic challenges can be overcome, the widespread adoption of underground pumped hydro storage could represent a major advancement in the security, sustainability, and operational stability of energy systems, thereby opening new opportunities for Europe to efficiently integrate renewable energy sources.

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