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Underground coal mine workings as potential places for Compressed Air Energy Storage

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Abstract. The article gives a brief overview of current developments and projects of Compressed Air Energy Storage (CAES). Typical CAES configurations such as Adiabatic CAES and Diabatic CAES are described. The concept of air storage in isolated workings of closed coal mine is presented taking into account availability of such places in the Silesian Coal Basin of southern Poland. The article also discusses major challenges of such concept such as insulation of underground workings, geomechanical stability of workings and site availability. As a proof of concept examples of underground coal mines converted into natural gas storage sites are given. Types of underground workings that could serve as a part of potential compressed storage site are listed and an example of volume calculation available in coal mine for storage is given.

1. Introduction

The key element providing flexibility in energy generation and supporting the use of renewable energy resources is energy storage. Energy storage serves various purposes where the primary one is to balance centralized and distributed energy generation, particularly in the era of renewables, while the other is providing energy security. The share of renewable energy sources (RES) for electricity production in European Union is constantly growing with projected targets reaching at least 32% in 2030 and possibly over 80% in 2050[1]. In USA 17% of all electricity generation is supplied by RES, China has also set targets to reduce its carbon emissions per unit of gross domestic product by 60–65% by 2030 from the 2005 levels where renewables will play a crucial role reaching 20% by 2030[2]. This means that significant amounts of excess renewable energy (on the order of TWh) will start to emerge in EU and in other large economies, with surpluses characterized by periods of high power output (GW) far-off in excess of demand. It may happen that this periods will coincide with periods of low RES energy generation, hence non-renewable generation capacity will be required. This will also put strain on the transmission and distribution system, balancing supply and demand of electricity will become even more difficult. An extensive study on energy storage in EU [3] revealed that demand for power-to-power storage will grow up to 10 times the currently installed capacity, or about 400 GW in the EU. There is no doubt that the problem of energy storage will be a challenge for energy sector in the next decades. This, in combination with limited number of solutions for large energy storage systems may cause problems for the entire EU energy system.

To date, two main large energy system storage are in use. First is the Pumped Hydroelectric Storage (PHS). PHS is an energy storage technology with a long history, numerous installations and reliable operation history. It also has the highest energy capacity. With an installed capacity of 127–129 GW in 2012, PHS represents more than 99% of worldwide bulk storage capacity and contributes to about 3% of global generation. Another solution is the Compressed Air Energy Storage (CAES) which can provide power output of over 100 MW with a single unit [4]. The PHS installations require convenient topography and vicinity of a lake or a river. In case of CAES the most important issue is the geology setting namely, existence of leak tight and pressure resistant structures which can be easily accessible with boreholes. So far, only leached salt domes proved to fulfil these conditions. Other concepts of energy storage which currently are at different levels of technology readiness are shown in Fig. 1.

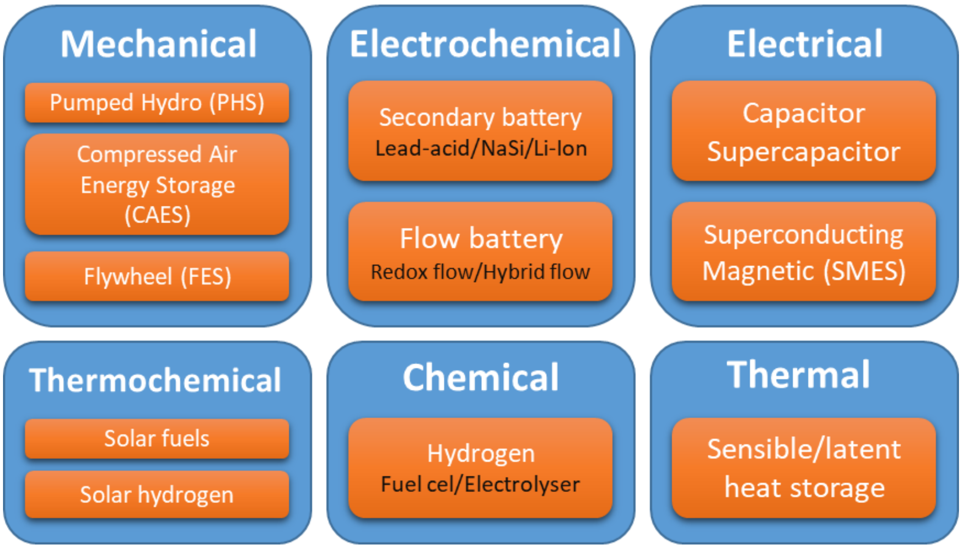

Figure 1. Classification of energy storage technologies (based on[4])

In this paper, a brief review of current developments of CAES technology is given and the concept of storing compressed air in abandoned or closed coal mines is described with particular focus on the Upper Silesian Coal Basin region in southern Poland.

2. The concept of Compressed Air Energy Storage

The general concept of Compressed Air Energy Storage is fairly simple. Excess energy runs compressors which pump air into underground cavern and the air is decompressed when the energy is needed through a turbine which is fueled by natural gas. This configuration is called diabatic CAES (see Figure 2). The major problem in conventional diabatic CAES is the low efficiency as a result of heat loss during the compression stage and energy used for heating the air before the turbine. Other concepts include Adiabatic CAES (A-CAES) presented in Figure 3 where heat is recovered and stored and isothermal CAES (I-CAES) where increase and decrease of temperature is avoided when air is compressed and decompressed respectively (see Fig 4).

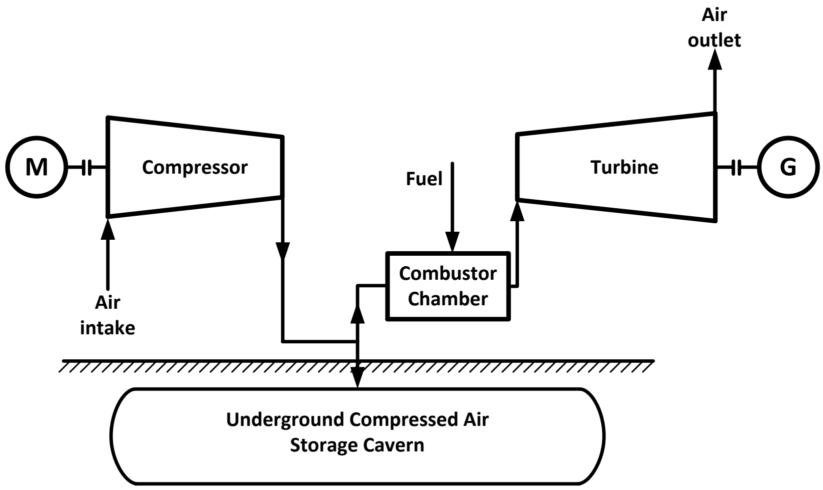

Figure 2. Concept of diabatic CAES (D-CAES)

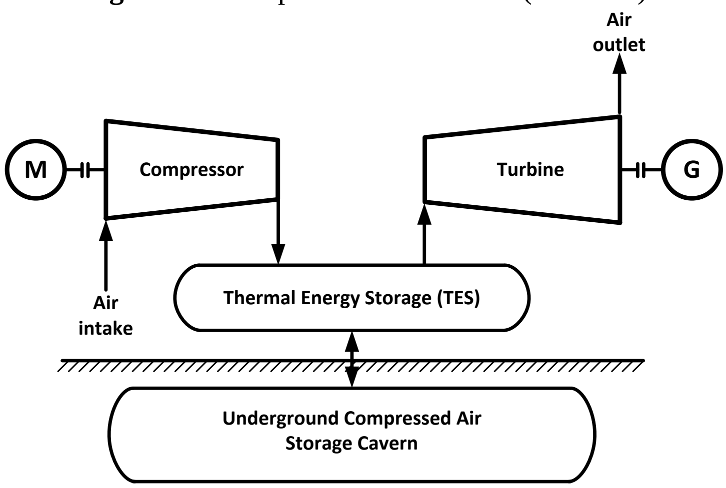

Figure 3. Concept of adiabatic CAES (A-CAES)

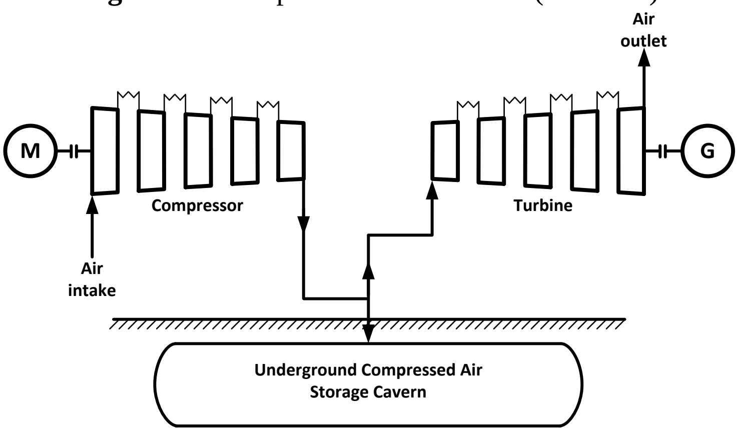

Figure 4. Concept of isothermal CAES (I-CAES)

Two D-CAES plants are in operation today. The first one is the 321 MW Huntorf plant in northern-west Germany belonging to E.ON Kraftwerke. For air storage underground salt cavern is used. In case of Huntorf there are two salt caverns of 310 000 m^3 volume at a depth of 600m with a pressure tolerance between 5.0 –7.0 MPa. Under working condition the plant runs in a daily cycle with eight hours of compressed air charging and two hours of expansion operation at a rated power of 290 $MWTh_e$. The second plant is the McIntosh of 110 MW capacity located in Alabama, USA. It belongs

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to PowerSouth company and was designed to be operated for up to 26 hours continuously at its full power. The storage capacity of a single cavern is approximately 560 000 m^3 at a depth of 450 m and stores compressed air in the range of 4.5 MPa to 7.4 MPa [5].

Other concepts under development include the ADELE project coordinated by RWE Power from Germany. In this concept, heat generated during the compression stage is stored in a separate Thermal Energy Storage (TES) unit. The TES unit will be constructed on the surface and consists of a solid material (concrete, stone) which will accumulate heat (see, Figure 5). During the discharge phase heat will be recovered from the TES unit. The A-CAES will be equipped with approx. 240 MW compressor power, 260 MW turbine power and approx. 1- 2 GWh capacity (i.e. 4 to 8 full load hours). The pressure of stored air will reach 7 MPa and the temperature of storage in TES unit 600-650°C. It is anticipated that the efficiency of this CAES system will reach 70% [6].

Figure 5. Laboratory testing of concrete reinforcement in the Thermal Energy Storage unit of ADELE project [6].

Another concept is the Norton project which is under development by FirstEnergy Corporation from USA. In this concept an underground limestone mine will be converted into compressed air storage. The Norton Mine will be developed for air storage by constructing conventional gas-type wells into the mine for air injection and withdrawal. The mine is currently open to the atmosphere only through two existing mine access shafts. The mineshafts will be sealed with impermeable plug materials. The mine was developed laterally with the use of room-and-pillar method of extraction. The depth of workings is approximately 670 meters below the surface. Mine stability has been proven for over 60 years and in-depth studies revealed that mine is stable as a pressure vessel [7].

3. Efficiency of CAES

The primary indicator of the thermodynamic effectiveness of each energy storage system is the energy storage efficiency. This indicator is defined as the quotient of the amount of energy obtained at the stage of discharge of the system and the amount of energy directed to the system at the charge stage. For an adiabatic or isothermal CAES system, the definition can be written as follows:

$$\eta_{\mathrm{CAES}} = \frac{E_{\mathrm{elG}}}{E_{\mathrm{elC}}}, \qquad (1)$$

where: E_{elG} - the electricity fed into the grid, E_{elC} - the electricity consumed by the compressor.

In the case of diabatic CAES, the use of the definition (1) may not be sufficient. Here, at the discharging stage, there is an additional flow of energy through the balance cover of system. It is the chemical energy of gaseous fuel, the oxidation of which in the part of the volume of air directed from the storage tank makes it possible to significantly increase the thermodynamic potential of the gas at the expansion stage.

The literature on the subject uses different definitions of efficiency for the assessment of diabatic systems. Most often, in the case of analyzes of the most popular systems operating in the USA and Germany, the following definition is used:

$$\eta_{\mathrm{D-CAES(1)}} = \frac{E_{\mathrm{elG}}}{E_{\mathrm{elC}}+Q_{\mathrm{f}}}, \tag{2}$$

where: Q_{f} – the chemical energy contained in supplied fuel.

However, the use of equation (2) for determining efficiency can be controversial due to summation in the denominator of various forms of energy, i.e. electricity and chemical energy of fuel. In [8] the authors discuss the use of three alternative definitions of the efficiency of diabatic systems, which from a thermodynamic point of view are less controversial:

$$\eta_{\mathrm{D-CAES(2)}} = \frac{E_{\mathrm{elG}}}{\frac{E_{\mathrm{elC}}}{\eta_{\mathrm{elR}}\cdot\eta_{\mathrm{tr}}}+Q_{\mathrm{f}}}, \tag{3}$$

$$\eta_{\mathrm{D-CAES(3)}} = \frac{E_{\mathrm{elG}}-E_{\mathrm{elC}}}{Q_{\mathrm{f}}}, \tag{4}$$

$$\eta_{\mathrm{D-CAES(4)}} = \frac{E_{\mathrm{elG}}-Q_{\mathrm{f}}\cdot\eta_{\mathrm{gas}}}{E_{\mathrm{elC}}}. \tag{5}$$

where:η_{elR} - the efficiency of a reference base load power plant, η_{tr} – the efficiency of electricity transmission to the energy storage system, η_{gas} - the efficiency of conversion of chemical energy to electricity.

The use of one of the definitions (2) - (5) makes it more convenient when comparing diabatic CAES system with other energy storage technologies.

4. Examples of mines converted into gas storage

As it was mentioned in the previous chapters, the technology of storing compressed air in salt caverns has been proven by successful operation of Huntorf and McIntosh plants for over 30 years. Nevertheless, the availability of salt structures for CAES is limited [9]. One of the place where compressed air could be stored are underground mines. This concept has been presented in [10,11]. Abandoned or closed coal mines have been used for natural gas storage in the past. Three industrial scale installations have been in operation for several years. Two coal mines were used as temporary natural gas storage in Belgium: Peronnes and Anderlues, located between Mons and Charleroi and a third mine was in Leyden, USA. In contrary to compressed air, methane is easily adsorbed on coal and the storage capacity of these mines was largely enhanced by sorption. The Anderlues storage facility was operating between 1980 and 2000. This site had a relatively low storage pressure (max 0.35 MPa) but the reservoir volume in total was estimated between 6 and 10 Mm^3. This was enough to store approximately 20 Mm^3 of CH_4. Peronnes Mine was also located in the gassy Hainaut Coalfield in Southern Belgium and could store 120 Mm^3 of CH_4 [12]. Another good example is the Leyden mine in Colorado, USA where storage operation started in 1961. Although there was a public debate on the possible leakages from the site it was proven to be successful for over 40 years. The gas was stored under the maximum operating pressure of 1.8 MPa with maximum storage capacity of 21 Mm^3 [13]. Cross section of Leyden mine is shown in Figure 6.

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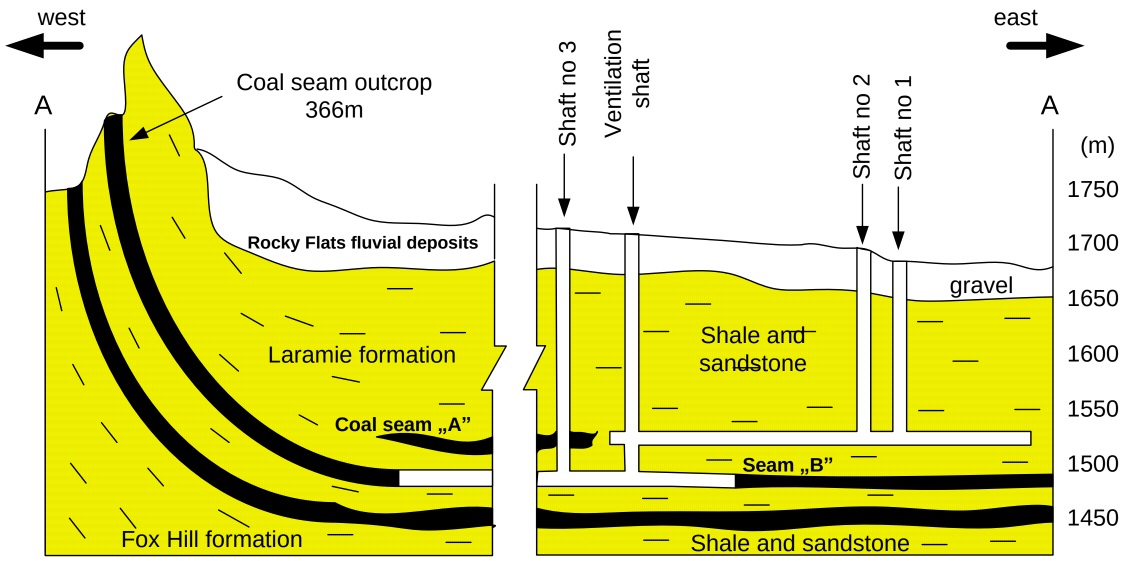

Figure 6. Cross-section of Leyden mine [13].

Concept of storing natural gas in coal mine was also explored in the Lower Silesia Coal Basin in Poland where Nowa Ruda coal mine was planned to be converted into underground gas storage. Estimated storage capacity varied depending on the storage pressure and storage mode. If only caverns, porous rocks and other workings (without remaining coal) were taken into account the storage capacity would vary from ca. 19 Mm^3 at the working pressure of 0.25 MPa to over 50 Mm^3 for working pressure of 0.6 MPa [14]. Storage capacity could be largely enhanced by coal adsorption to over 70 Mm^3

5. Underground coal mine workings as underground compressed air storage

Using underground coal mine workings as a potential compressed air storage seems to be a questionable concept at a first glance. However, when taking into consideration potential benefits it could be a viable and economic solution. This concept has many benefits and these are:

- relatively high storage capacity when comparing to salt caverns,
- convenient location in urbanized areas where energy storage is an often problem,
- already available geological survey data,
- accessibility to mine maps,
- well recognized hydrogeology of the potential site,
- potential access to state/regional or other funds for mine reclamation which could be used to develop the concept,
- lower cost in comparison to other underground sites since the excavations already exist and existing roof/wall support could be used,
- safe operation and protection against external factors (weather, equipment failure, terrorist attacks) since the underground system is separated from the surface and connected only by valves and pipes,
- large surface area available for the plant (former mine surface facilities),

This concept would be a viable solution only if the drifts and shafts are properly sealed and separated from the remaining coal seams. Another issue is the geomechanical stability of overburden in the longwall mining with roof caving method. Currently, most of the modern coal mines use a longwall method without backfilling. As a consequence, roof collapses and overlaying rock layers may fracture (Figure 7).

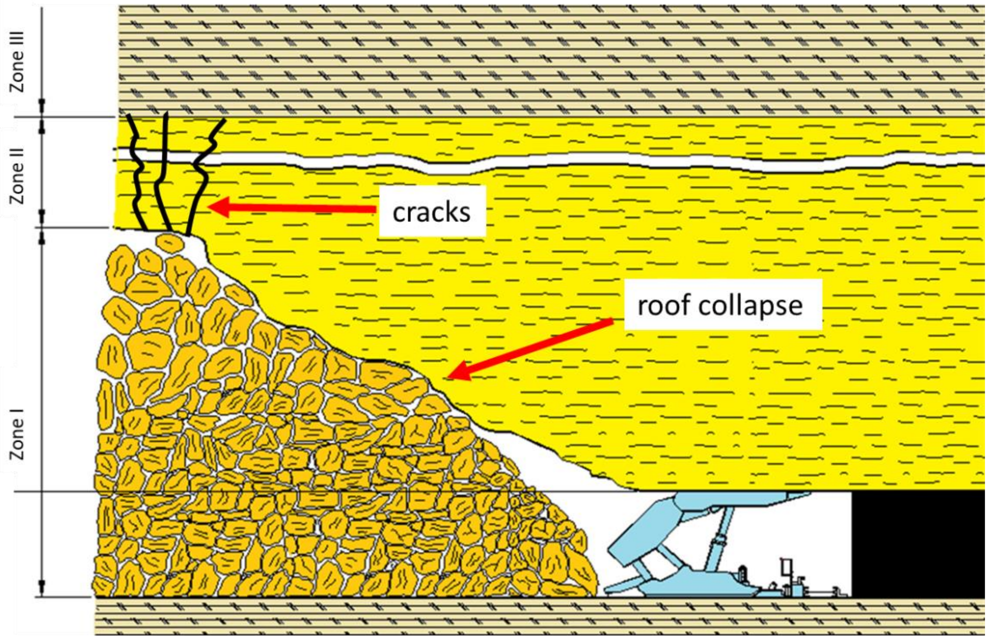

Figure 7. Longwall mining with roof caving and formation of cracks.

Another important consideration is the fact that compressed air in contact with coal may cause spontaneous combustion of coal and as a result uncontrollable fire. In order to reduce this risk remaining coal has to be separated from the storage site. If the coal mine is flooded or improperly sealed, coal mine flooding or uncontrollable inflow of water may reduce available volumes and increase moisture content of air which is not desired.

Even in regions where intensive mine operation has been carried at various depths (such as Upper Silesian Coal Basin in Poland) there is always a safety zone near the shaft which prevents it from skewing. In this zone roof support is designed for long term (permanent) use. Near shafts there are also large chambers for machine service or electrical equipment which could also enhance the volume of available workings (volume of single chamber itself is between 2000 and 7000 m^3). Other workings which could be used for compressed air storage include galleries or shafts and winzes. In Polish coal mines the typical roof support is the yielding steel arch support where cross-section area varies greatly between 5 up to over 36 m^2. The most common types have a cross-section area of 14.8 to 17.6 m^2. In Figure 8, a schematic view of typical yielding arch steel support crossing is presented.

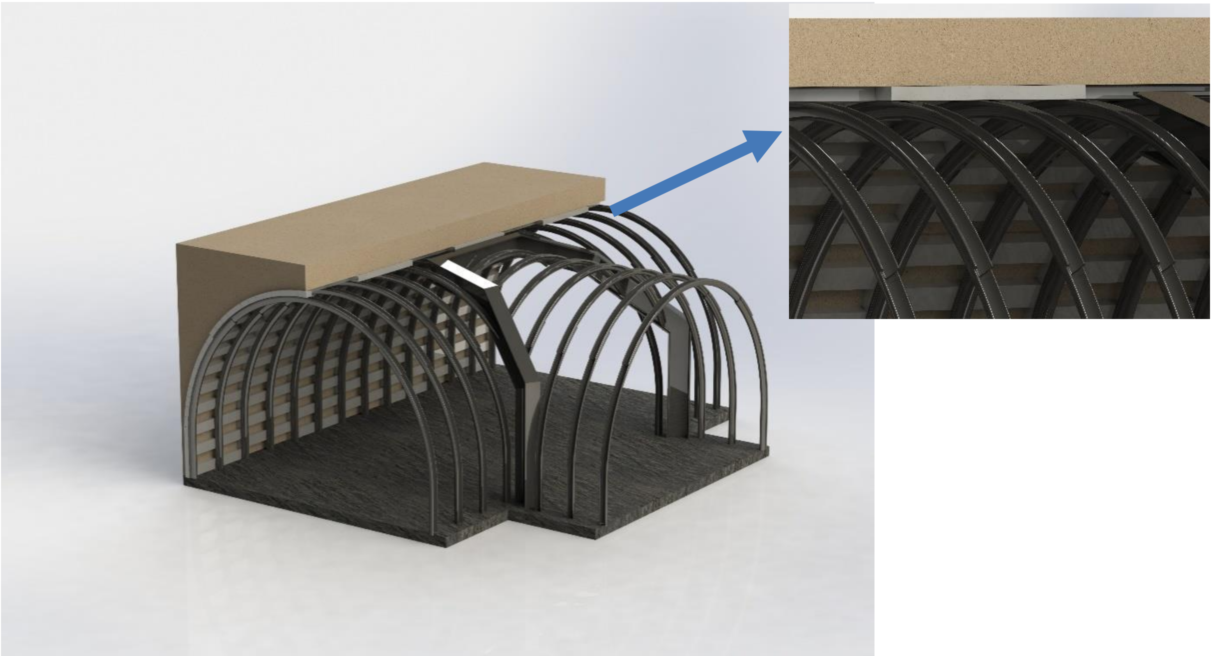

Figure 8. Typical yielding steel arch support with precast concrete liner used in Polish coal mines.

As it can be seen, the support lacks proper sealing since precast concrete is used as a liner behind the support. In order to convert such working into an impermeable air storage additional liner should be applied on the internal surface of the support (see Figure 9). The following materials could be used:

- shotcrete liners,
- geopolymer liners,
- polyurethane urea elastomers (PUU).

Before application of the liner a thorough check of support for corrosion, convergence control and integrity should be performed.

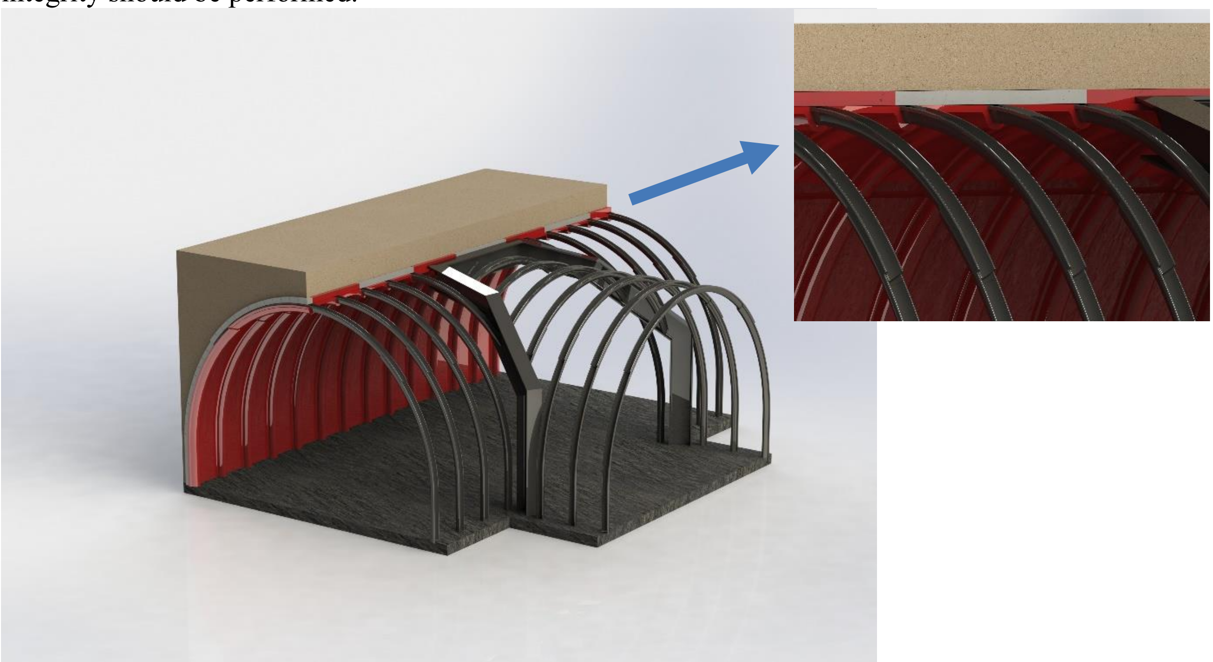

Figure 9. A concept of sealing yielding steel arch support with liners (in red).

6. Conclusions

With the increase in demand for energy storage technologies there is a need for seeking new solutions that could provide large scale energy storage. Compressed Air Energy Storage is one of the solutions, yet it requires leak-proof underground structures that will withstand high pressure and are located closely to the power sources. As one of the options, underground coal mines in European coal basins could be considered. Convenient location, well known geology of the site and already existing excavations are the key benefits of this idea. Nevertheless, there are many considerations that have to be taken into account and this is particularly leak-tightness and geomechanical stability of the overburden. Typical yielding steel arch support which is encountered in Polish coal mining could be used when a proper liner is applied. This concept however needs a thorough interdisciplinary studies that should integrate both energy efficiency issues as well as geological and geomechanical knowledge.

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