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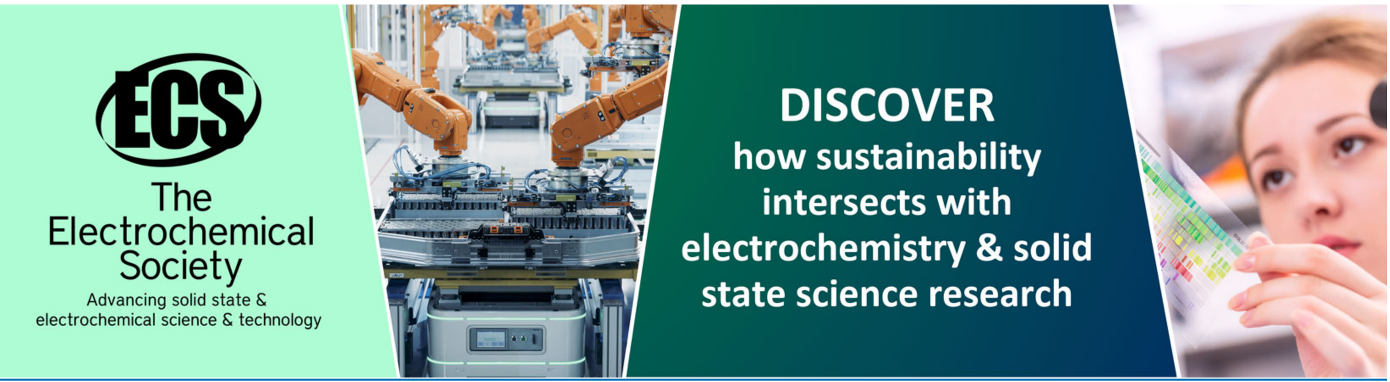

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An overview of potential benefits and limitations of Compressed Air Energy Storage in abandoned coal mines

Marcin Lutyński

Faculty of Mining and Geology, Silesian University of Technology, Akademicka 2, 44-100 Gliwice, Poland

marcin.lutynski@polsl.pl

Abstract. Compressed Air Energy Storage (CAES) is one of the methods that can solve the problems with intermittency and unpredictability of renewable energy sources. The storage is charged by increasing air pressure with the use of electrically driven compressors, which convert the electric energy into potential energy. The pressurized air is stored in compressed air storage volumes (caverns, voids, porous structures etc.) of any kind and can then be released upon demand to generate electricity again by expansion of the air through an air turbine or gas turbine. Limited availability of salt caverns in Europe creates difficulties in the implementation of this concept on larger scale. This paper deals with underground storage part in CAES concept and lists benefits related to the storage of air in abandoned coal mines. Examples of natural gas storage in abandoned coal mines are given and compared with the compressed air storage. The study shows an example of coal mine volume calculation. The non-exhaustive list of problems and solutions associated with this idea is given in order to develop this concept at larger scale.

1. Introduction

An increased share of renewable energy, particularly wind power and photovoltaics, in an energy mix of European countries create difficulties for the regional stability of the electricity grid on the supply side. The reason of this is the constant growth of the share of wind power and photovoltaics in the last ten years. In total, between 2004 and 2015, the share of renewable energy almost doubled, reaching 16.7% of gross final energy consumption in 2015, at the same time wind and solar energy are growing the fastest. In 2015, the EU generated 26.0 million tons of oil equivalent (Mtoe) from wind energy — a more than five-fold increase compared with 2004. In the same year, solar energy contributed 13.1 Mtoe which is more than 18 times as much as in 2004, see figure 1 [1]. Wind and solar generation both experience: intermittency; a combination of regional meteorological uncontrolled variability and local unpredictability, and dependency on resources that are location dependent. Intermittent renewables are challenging because they disrupt the conventional methods for planning the daily operation of the electric grid. Power from these sources fluctuates over multiple time horizons, forcing the grid operator to adjust its day-ahead, hour-ahead, and real-time operating procedures. On the demand side, sudden increase of electricity need cannot be covered by renewables and requires a permanent stand-by of conventional power suppliers. These vital supply and demand aspects along with distribution inter-regional aspects are posing serious challenges for generation authorities and grid operators during the course of integrating wind and solar generation with the conventional grid [2].

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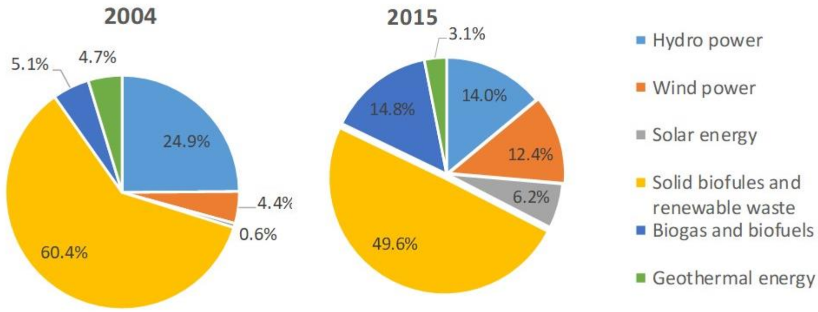

Figure 1. Gross inland consumption of renewable energy, by source, EU-28, 2004 and 2015 [1].

The most important aspect of this variation in power generation is the meteorological variability in power supply. Even if operators could predict the output perfectly, it still poses specific challenges to the grid operator. As a consequence on regional scale, the seconds to minutes time scale, grid operators must deal with fluctuations in frequency and voltage on the transmission system that, if left unchecked, would lead to blackouts. Therefore, operators supply active or reactive power into the grid for a supply/demand balance based on forecasted power generation. This is necessary to maintain a stable and safe frequency and voltage profile in the grid. In addition, with Photovoltaic and wind, two situations are possible when the maintenance of reserves that stand ready to provide additional power. When renewable energy generation produces less energy than predicted, one needs to ensure the availability of a dispatchable load to be 'exploited'. When excess power of renewable energy generation produces more energy than the predicted energy demand, the surplus energy needs to be stored. This is particularly challenging in a system where an inelastic demand has to meet supply in real-time, in the presence of only limited storage capacity.

This issue is referred to as the 'incompressibility of power systems' and is observed in different European electricity markets such as Belgium, Germany, France and the Netherlands, with hours showing negative electricity prices, as well on day-ahead, intra-day and real-time balancing markets. These negative prices show inflexibility of the grids, and therefore the difficulty of the system to cope with periods of excess generation. This is particularly difficult and seems irrational from the economical and engineering point of view when the energy producer has to pay for the electricity supplied [3].

The amount of wind and solar resources are on preferred locations. Unlike coal, gas, oil or uranium, it cannot be transported to a generation site that is grid-optimal. Generation must be co-located with the resource itself, which are often far from the load centers where the power is to be eventually used. New regional transmission capacity is often required to connect wind and solar resources to the rest of the grid. Transmission costs are especially important for offshore wind resources, and such lines often necessitate the use of special technologies not found in land-based transmission lines. Integrating wind and solar generation resources into the conventional electricity grid involves managing other controllable operations that may affect many other parts of the grid, including conventional generation [4].

Above-mentioned problems associated with renewable energy source and power instability will have a dramatic impact on future power generation, in particular for a) the countries where coal is a dominant energy source and b) the European areas with a less predictable regional weather forecast. Recent key findings of the report prepared by 32 companies and supported by EU shows that 'both power-to-power storage and conversion to other carriers have the potential to play an important role in providing flexibility to the power system. They will make it possible to ensure that large amounts of renewable energy are not wasted, but are used to reduce the amount of required non-renewable energy sources generation and decarbonised heating, transportation and gas grid expansion' [5]. It is anticipated that demand for power storage will grow up to 10 times until 2050. In line with the EU policy to reduce fossil fuel energy and secure the supply against international disagreements (i.e. Russian gas deliveries), existing energy infra-structure at regional level must be secured, improved and expanded.

One of the viable options is CAES – Compressed Air Energy Storage, a technology where vast amounts of air can be compressed and stored under pressure in existing underground caverns and mines. When electricity is required, the pressurized air is released, heated and expanded in an expansion turbine driving a generator for electricity production. This paper reviews current technologies of CAES and provides an overview of potential benefits and limitations of compressed air storage in abandoned coal mines.

2. Basic concept of CAES

The concept of large-scale compressed air storage was developed in the middle of the last century. The first patent on CAES in man-made cavities, as a means of storing electrical energy was issued in 1948 in US by Frazer W. Gay [6]. In the manufacturing industry, compressed air is broadly used either as an energy carrier for pneumatic processes (such as drilling and/or carving) or it serves as a process fluid carrier (e.g. for cleaning or varnishing). Either way, compressed air is generated almost exclusively on site by employing electrical energy. For example, only in Germany, currently 16 TWh of energy are consumed annually to provide compressed air for industrial purposes, which amounts to about 2.5% of the German overall electricity consumption [7].

The overall concept of CAES, which is used in nowadays industrial surface facilities is well known. The storage is charged by increasing air pressure with the use of electrically driven compressors, which convert the electric energy into potential energy (exergy). The pressurized air is stored in compressed air storage volumes (caverns, voids, porous structures etc.) of any kind and can then be released upon demand to generate electricity again by expansion of the air through an air turbine or gas turbine (figure 2).

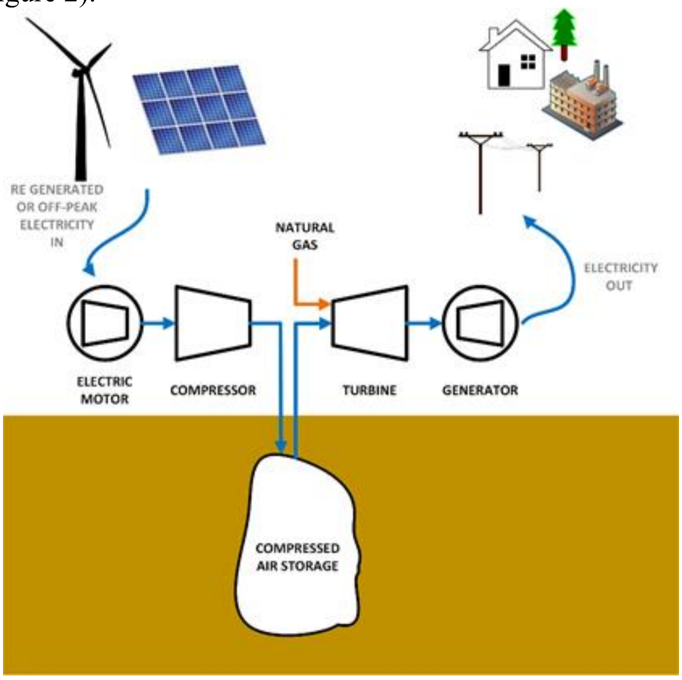

Figure 2. General concept of CAES.

There are several concepts existing today at different levels of development. In general, the concepts can be divided into diabatic, adiabatic and isothermal CAES. The different options are at three stages of technological readiness levels. The diabatic systems are proven, can be up-scaled and can be rolled out for salt domes. The adiabatic and isothermal systems however, are proven as a

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technology and need to be up-scaled and revised to be implemented in existing large space sub-surface infrastructures.

The basic concept of diabatic CAES involves storage of off-peak energy for later use with only the fraction of energy (gas or oil) that would be used by a standard gas or oil turbine. It is the least efficient option in comparison with other systems. However, it is the most matured one and there are currently two plants in operation using this concept: the 321 MW Huntorf plant in northern-west Germany belonging to E.ON Kraftwerke and the 110 MW plant in McIntosh (Alabama, USA) belonging to PowerSouth company. Both facilities use underground salt caverns for air storage. Comparison of technical parameters of operating D-CAES plants is presented in Table 1. During peak-off hours, the electric driven compressor injects air into underground cavern. When the power is necessary for the grid, the process is reversed and the air is returned to the surface to be burned in a natural gas turbine. Combustion gas is expanded in the two-stage turbine to spin the generator and produce electricity. The cycle efficiency of D-CAES plants is 42% and 54% respectively for Huntorf and McIntosh. The difference between the efficiencies of the installations is due to the presence of a recuperator in the McIntosh plant, which additionally preheats the combustion air for the gas turbines.

Table 1. Comparison of technical parameters of operating D-CAES plants [8].

Plant	Huntorf	McIntosh
Cycle efficiency	42%	54%
Energy input for 1 kW h_{el} energy output	0.8 kW h_{el}/1.6 kW h_{gas}	0.69 h_{el}/ 1.6 kW h_{gas}
Energy content (in relation to power output)	642 MW h	2640 MW h
Planning-construction-commissioning	1969 - 1978	1988-1991
Compression		
Max. electricity input	60 MW	50 MW
Max. air mass flow rate	108 kg/s	Approx. 90 kg/s
Compressor units	2	4
Charging time	Approx. 8 h	Approx. 38 h
Storage		
Cavern pressure range	4.6 – 7.2 MPa	4.6 – 7.5 MPa
Cavern volume	310 000 m^3	538 000 m^3
Expansion		
Max. electricity output	321 MW	110 MW
Control range (output)	100-321 MW	10-110 MW
Discharging time (at full load)	Approx. 2 h	Approx. 24 h
Start-up time (normal/emergency)	14/8 min	12/7 min
Max. mass flow rate	455 kg/s	154 kg/s
HP turbine inlet	4.13 MPa/490°C	4.2 MPa/538°C
ND turbine inlet	1.28 MPa/945°C	1.5 MPa/871°C

The major problem in conventional diabatic CAES is the low efficiency as a result of heat loss during the compression stage. A number of concepts have been developed in order to preserve the heat and reuse it during the discharge process. Concepts which include heat loss in the process are called adiabatic CAES (A-CAES) and can be divided into A-CAES without and with separate Thermal Energy Storage. The first method is to store hot air inside the compressed air cavern (A-CAES without Thermal Energy Storage). The major drawback of this concept is the fact that adiabatically compressed air (up to a moderate 1 MPa) heats up to the temperature of 277°C and most of the CAS cannot withstand such high temperatures. Therefore, a development of this concept is to provide an additional, separate Thermal Energy Storage in order to store heat generated during the compression phase and add it when the air is decompressed. A more promising technology is the A-CAES with a TES (Thermal Storage System). In this case, the recovered process heat from the compression is

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stored in a separate TES and cooled air can be stored in a conventional Compressed Air Storage (CAS) [9].

The third concept, which is being under investigation, is the isothermal CAES where the increase of temperature is avoided when air is compressed, and decrease in temperature when the reservoir is discharged. For that purpose, a piston machinery is used which can perform a slow compression or expansion process when enough time is left for the heat exchange process inside the machinery. In this case, additional exchange contact surface area is needed or a liquid piston is used. Other concepts involve spraying liquids into the plug room of a common piston machine or the compression of a pre-mixed foam [8].

Among all the CAES methods, typical diabatic CAES is a proven and relatively effective method to store energy. The most important problem in this technology is the Compressed Air Storage which as shown in Table 1 has to be under high pressure (up to 7.5 MPa).

3. Underground Compressed Air Storage

The technology of storing air in caverns can be safe and reliable as proven for over 30 years by many natural gas storage facilities and two CAES plants in operation. The most common, proven and reliable location for CAS are salt caverns ie. solution mined salt domes. Salt caverns are widely used for natural gas storage and currently in Europe there are over 141 storage facilities accounting for over 98 168 Mm^3 of natural gas storage [10]. Unfortunately, the distribution of Permian salt domes which are favorable for natural gas storage or CAS is uneven. Majority of Permian deposits is located in the Northern part of Europe not necessarily close to energy sources, see figure 3 [11]. Other locations include Mesozoic (Spain, Portugal) and Tertiary (France, Romania) salt deposits.

As it can be seen in figure 3, the distribution of salt deposits limits the use of them as potential air storage. There are however other options where CAE can be stored and these are:

- Depleted gas reservoirs,
- Rock caverns,
- Small underground aquifers,
- Abandoned coal mines.

Depleted gas reservoirs could serve as CAS as the geology of such reservoirs is well known and the overburden is impermeable. However, the residual gas, remaining water and various oxide gases may cause significant problems to the surface installation (oxidation from the air, corrosion, etc.) in this case the deliverability of gas. Further, complex reservoir geology may disturb cyclic injection and production. So far, there is no installation for CAES in depleted gas reservoirs.

Another proposal is to store compressed air in aquifers. This concept is being investigated, but it suffers from many drawbacks, such as pressure drop by the loss of oxygen in the aquifer, microbial growth, and decrease in permeability of the reservoir [12].

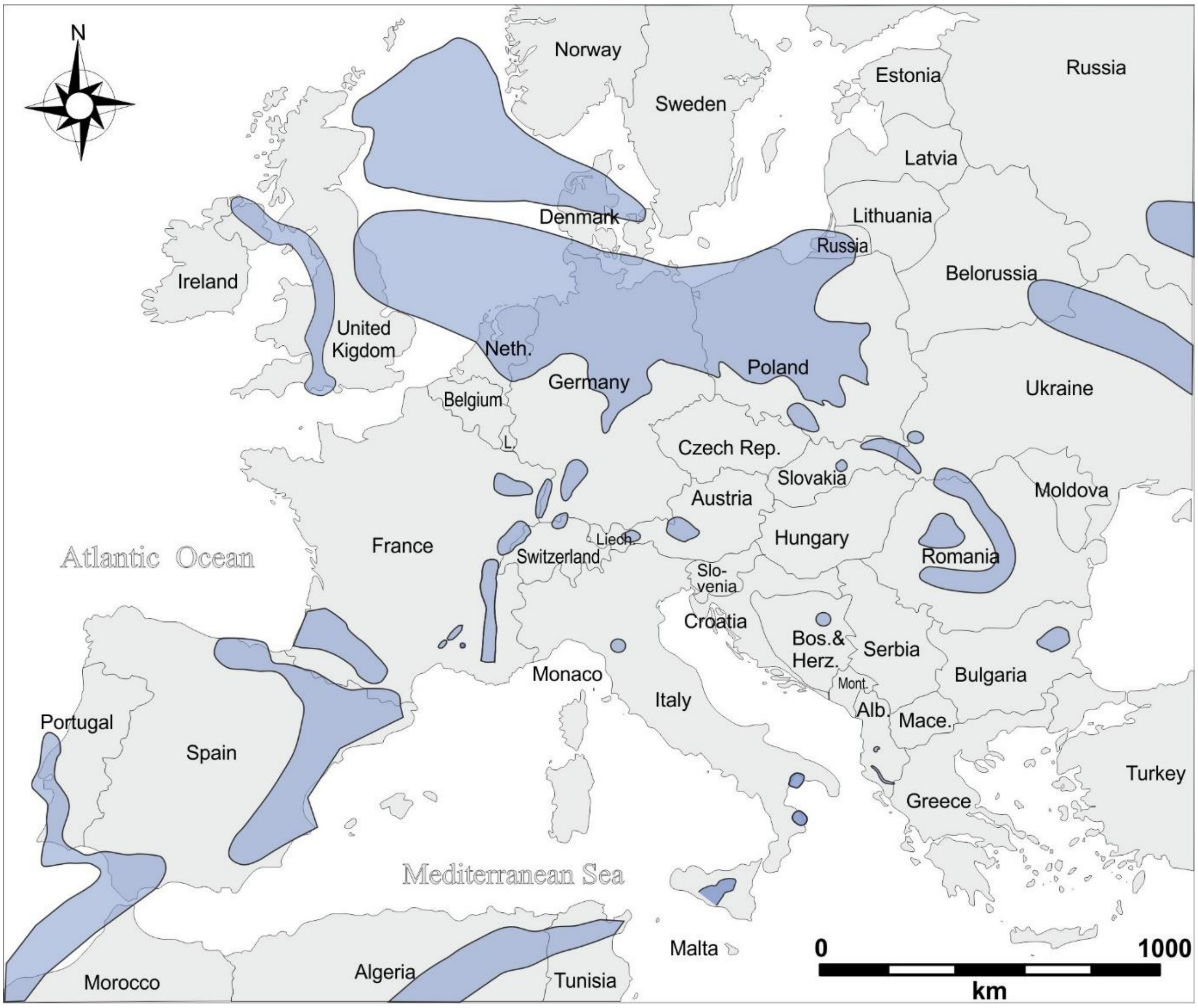

Figure 3. Salt deposits location in Europe [11].

Rock caverns excavated in hard rocks also have been used for liquid storage all over the world. This technique has two variants. Either the liquid is stored in unlined caverns using hydrodynamic sealing or the cavern is lined with metal and/or shotcrete/concrete [13, 14]. The first option is rather difficult to apply for CAS, however as an alternative, polymers are proposed by Terashita et al. [15] in a former Japanese zinc mine in Kamioka and a coal mine in Sunagawa.

Abandoned coal, rock and base metal mines could serve as potential candidates that can be converted into CAS. A huge advantage of coal mine location is the fact that in a majority of the cases they are located near power plants and reduces the energy transport lines. The concept of storing natural gas and CO_2 in abandoned coal mines is not new and for natural gas storage was proven in various locations [16, 17]. Three industrial scale installations are known and commercial operation started as early as in 1961. 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. These installations prove that storing gas in coal mines is a feasible concept. It has to be highlighted that in case of abandoned coal mines natural gas storage can be enhanced by sorption on remaining coal seams. The Anderlues storage facility was operating between 1980 and 2000 at very low pressure (max 0.35 MPa). However, the reservoir volume below the thrust fault at 600 m depth was estimated by the operator between 6 and 10 Mm³ (mainly based on regional assessments of accessible parts of old mine workings). This allowed for the storage of about 20 Mm³ of CH_4 (14 000 tons) at working reservoir pressures. The amount of adsorbed CH_4 in coal was almost 8 times higher than the free gas capacity since the total storage capacity of the reservoir was 180 Mm³ or 130 000 tons CH4. Sorption phenomena on remaining coal seams was also observed in gas reservoirs in Leyden and other Belgium mine [18]. This however cannot be the case in Compressed Air Storage since oxygen may cause self-combustion of coal and as a result an underground fire.

4. CAS in abandoned coal mines

As mentioned in the previous paragraph there is a possibility to store compressed air in abandoned coal mines if the drifts and shafts are properly sealed and separated from the remaining coal seams. The general concept of CAS in abandoned coal mine is presented in figure 4. This concept considers sealing of underground workings from the remaining coal seams and drifts which may be prone to collapse or deformation. It also considers applying liners on the surface of drifts and shaft in contact with air to prevent leakages.

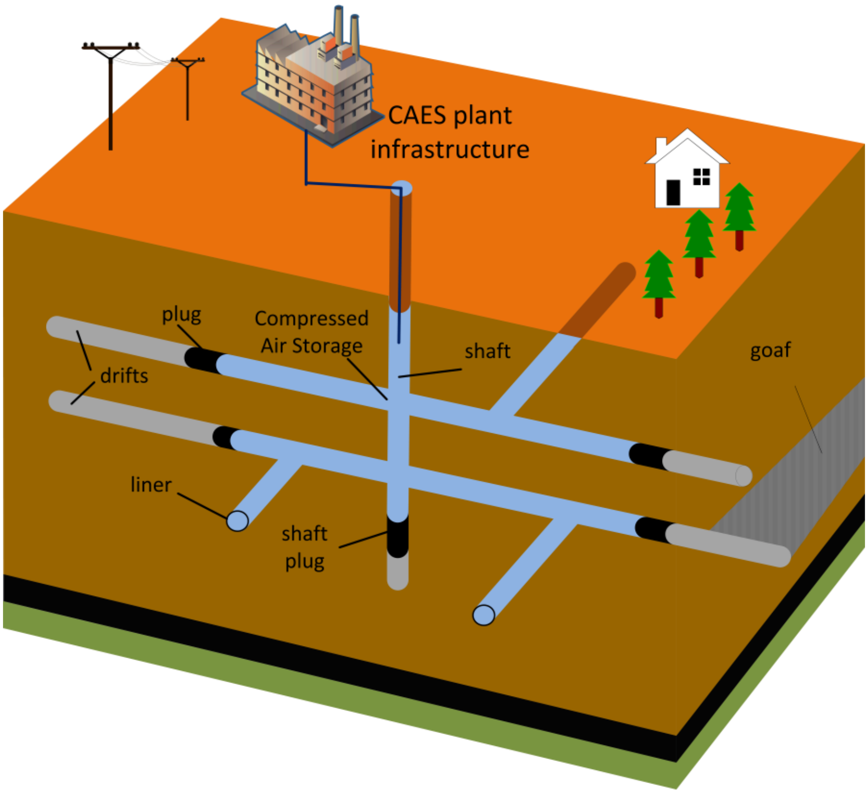

Figure 4. General concept of Compressed Air Energy Storage in abandoned coal mine.

Storage of air in closed/abandoned mines has some major advantages over surface storage in tanks and other locations, these are:

- Very high storage capacities of mines as CAS,
- Relatively low cost since the excavations already exist and the geology of the site is relatively well recognized,
- Many locations are directly connected to regional renewable energy sources or other energy sources,
- 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 installation of the infrastructure (former mine surface facilities),
- Distribution of abandoned coal mines in urbanized areas in Europe where energy storage is a major problem.

A rough estimate of available volumes in an example coal mine located in the Upper Silesian Coal Basin in Poland is presented in table 2.

Table 2. Example calculation of coal mine volume

Type of workings	No. of workings	Volume (m^3)
Shafts	2	64 828.44
Level III (1050 m)	6	6 927.70
Winzes connecting levels III and II	1	26 805.60
Level II (850 m)	94	496 873.60
Winzes connecting levels I and III	20	153 210.00
Level I (650 m)	57	503 442.10
Total	180	1 252 087.44

Example calculation of volume in an typical coal mine located in the Upper Silesian Coal Basin in Poland shows that such volume is almost twice or three times larger than the volume of caverns used in existing CAES in Huntorf and McIntosh plants. Even when considering that large of parts or levels in a mine cannot be used for CAS, the remaining volumes would be still considerably high. This implies that the concept of CAES in closed or abandoned coal mines might be worth exploring. Obviously, there are still considerable problems to be overcome before this concept would be feasible.

The following, non-exhaustive, list of limitations related to this concept is shown below:

- Compressed air in contact with coal may cause spontaneous combustion of coal and as a result uncontrollable fire – all the remaining coal has to be separated from the storage site,
- Former mining operation at various depths causes cracks/fissures and fractures in the over- and interlaying strata or subsidence which may threaten overburden integrity and as a result will cause air leakage or infiltration of water into the compressed air storage,
- Coal mine flooding and uncontrollable inflow of water may reduce available volumes and increase moisture content of air.

Therefore, in order to start with any concept related to CAS in abandoned coal mines the following conditions have to be fulfilled:

- Storage facility has to be separated from any other coal mine to prevent air leakages or contacts with coal,
- Overburden integrity and drift stability is a major issue and should be carefully verified before any operation is started,
- Inflow of water has to be either controlled or location should be in dry mines,
- Workings accessible for air should be isolated with liners and plugs designed to withstand high pressures in storage facility (up to approximately 8 MPa).

Well recognized geological setting and information on the geomechanical properties of the rock mass surrounding the facility and choice of best available technologies of liners and plugs might ensure feasibility of this concept.

5. Conclusions

Increase in the use of renewables in the energy mix of European Union, apart from the obvious benefits, also creates problems for the grid operators. One of the solutions to deal with intermittency, unpredictability and local availability of renewables is the energy storage. So far, large scale energy storage sites are either pumped-storage hydroelectricity plants or Compressed Air Energy Storage facilities. In this paper the second concept is presented where particular focus is made on the underground storage part. Limited availability of salt caverns in Europe encourages researchers to seek for other options such as compressed air storage in closed or abandoned underground coal mines. This concept has distinct benefits such as close location to energy sources and relatively large volume of storage. Nevertheless, feasible studies are still immature and certain problems have to be overcome in order to develop a fully functional, large-scale operating concept. The major problems are related to the safety of operation i.e. isolation of workings designated for air storage from the remaining coal, provide leak tightness at high pressure, underground storage integrity and stability during injection/withdrawal cycles. Only after overcoming and solving these major issues this concept might be feasible.

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