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Integration of renewable energies in the electricity grid from energy storage plants in disused mining structures

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Abstract. Energy Storage Plants (ESP) can be considered an alternative to solve the intermittency problems associated to variable renewable energy (VRE), such as wind and solar photovoltaic. This paper explores the use of closed mines as underground reservoir for Underground Pumped Storage Hydropower (UPSH) and Compressed Air Energy Storage (CAES) plants. Investment cost and stored amount of energy are compared in both technologies. Mining structures in disused coal mines in NW Spain have been selected as a case study to analyse the potential of energy storage in disused mining structures. Pumped Storage Hydropower is the most mature large-scale energy storage technology that dominates both the total installed power capacity and the energy storage capacity. An alternative to UPSH plants could be CAES plants, which are systems to store energy in the form of compressed air, and work in a similar way to conventional gas turbines. Abandoned salt cavern or closed coal underground mines are typically used as underground compressed air storage, giving new uses to the infrastructure of abandoned mines. The results obtained show that 130 MW of electrical power could be installed in UPSH and CAES plants in closed mines with an investment cost of about 225 M€.

1. Introduction

A recent study of the International Renewable Energy Agency (IRENA) analyzes the potential effects of the energy transition until 2050 for the G20, found that by that date over an 80% of the world's electricity could derive from renewable sources [1]. Moreover, the EU's 2050 decarbonisation objectives, with a target of 80-95% reduction in greenhouse gas emissions [2], will require a significantly higher share of renewables into the EU electricity grid. Then, the most important concern with respect to some forms of renewable energy such as solar and wind energies is their intermittence and the fact that their production over time cannot be matched to variations in demand.

All electricity systems require a certain degree of flexibility services, which allow grid operators to react to unexpected changes in demand or to the loss of large chunks of supply [3]. In today's power systems, solar and wind power still have limited impact on grid operation. Electrical energy storage provides a mechanism of decoupling the electricity generation from energy harvesting, and potentially compensating for the intermittence of power generation from renewable energy sources. Currently, the expansion of renewable energies requires the development of fast and flexible energy storage systems. Electricity storage will play a crucial role in enabling the next phase of the energy transition, and it will have become the key to improve the efficiency of renewable energy and increase its utilization.



This paper analyses the potential of the disused mining structures as underground reservoir for UPSH and CAES plants. The amount of energy produced depending on the storage volume and the investment cost of both technologies are also compared. Finally, uncertainties and drawbacks of using closed mines as energy storage plants are exposed.

2. Materials and methods

2.1. Study area

The Asturian Central Coal Basin (CCB) is located in NW Spain. It is a coal mining area exploited during the last 200 years with more than 30 underground coal mines. The depth of the underground mines is between 300-700 m with a very extensive network of tunnels [4]. During the last decades the mining activity has created large volume of voids that can be used for energy storage projects. Currently, there are several coal mines in closure phase, where a feasibility analysis could be carried out. If they are not used for other applications, the coal mines will be flooded.

2.2. Underground Pumped Storage Hydropower

Pumped storage hydropower (PSH) is a mature and commercial utility-scale technology currently used at many locations in the world, employing off-peak electricity to pump water from a reservoir up to another reservoir at a higher elevation [5,6]. Then, when electricity is needed, water is released from the upper reservoir through a hydroelectric turbine into the lower reservoir to generate electricity. In a typical PSH plant, the two reservoirs are located on the surface level. In contrast to a conventional PSH plant, in an Underground Pumped Storage Hydropower (UPSH) plant, the upper reservoir is located on the surface and the lower reservoir is underground [7-12].

Mining structures from closed mines are proposed as lower reservoir for UPSH plants [13]. Such storage volumes, combined with the depths at which some of these facilities are located and the high flows of groundwater, can be sufficiently appealing to establish an UPSH plants with a Francis turbine-pump. In an UPSH plants, the excavation of ventilation shafts to facilitate the exit of the air is required. During the water filling of the underground reservoir are two fluids interacting inside the lower reservoir, water and air [14]. The presence of air flow inside the underground reservoir could increase the pressure and decrease the available net head, leading to a reduction in the generation of energy.

The scheme of an UPSH plant is shown in Figure 2. Upper and lower reservoir, penstock, Francis pump-turbine (located at the powerhouse with motor-generator) and vent shaft can be observed in the Figure 2. Maximum gross head, H_G , (mH₂O) between upper and lower reservoir is also indicated. The penstock would be built in the vertical shaft currently in existence. This storage concept in closed underground mines presents some advantages in comparison with conventional PSH, such as the higher possibility of social acceptance, the larger number of potential sites and lower environmental impacts [15,16]. The amount of stored energy in an UPSH plant depends on the water storage volume (m³) and the available net head (mH₂O), and it is given by the following equation:

$$E_{\text{UPSH}} = \frac{9.81 \cdot Q \cdot H_N \cdot \eta \cdot t_c}{1000} \quad (1)$$

where E_{UPSH} is the stored energy, in MWh per cycle, Q is the water flow rate, in m³ s⁻¹, H_N is the net head, in mH₂O, η is the Francis turbine efficiency, which is typically assumed at 0.9, and t_c is the cycle time at full load, in hours.

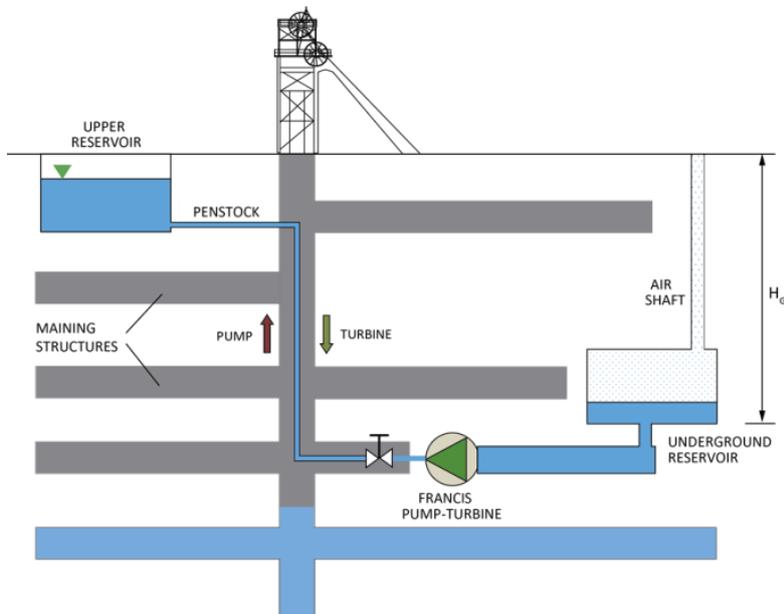


Figure 2. Scheme of an UPSH plant using closed underground mines as lower reservoir. Upper and lower reservoir, penstock, Francis pump-turbine and vent shafts.

2.3. Underground Pumped Storage Hydropower

CAES system stores energy in the form of compressed air (potential elastic energy) in a reservoir. CAES was investigated in the 1970s as a means to provide load following and to meet peak demand while maintaining constant capacity factor in the nuclear power industry. Currently, there are two CAES plants in operation in the world. The first operational CAES plant, built in 1978, was the 290 MW Huntorf plant in Germany, using salt caverns solution-mined in a salt dome. The second is the 110 MW plant with a rated energy capacity of 26 hours in McIntosh, Alabama [17,18].

CAES technology uses low cost, off-peak energy to run a compressor train to create compressed air, which it stored, usually in a big underground mining void, the air is then released during peak load hours and heated with the exhaust heat of a standard combustion turbine in an air bottoming cycle (Figure 3), some additional energy (typically natural gas) is used during the expansion process to ensure that maximum energy is obtained from the compressed air. The amount of stored energy at CAES plant is given by the following equation:

$$E_{\text{CAES}} = \frac{(\dot{m}_a + \dot{m}_{\text{NG}}) \cdot (h_3 - h_4) \cdot \eta \cdot t_c}{1000} \quad (2)$$

where E_{CAES} is the stored energy at CAES plant, in MWh per cycle, \dot{m}_a and \dot{m}_{NG} are the air mass flow and natural gas mass flow, respectively, in kg s^{-1} , $h_3 - h_4$ are the difference of enthalpy in expansion stage (gas turbine), η is the Gas Turbine efficiency, which is typically assumed at 0.8, and t_c is the cycle time at full load, in hours. Fig. 3 shows the scheme of a CAES plant with a compressed air storage at a pressure of 40-75 bar inside the closed mine, and the Brayton cycle as a conventional gas turbine.

In general, the concepts can be divided into Diabatic (D-CAES) and Adiabatic (A-CAES). D-CAES systems dissipates the extra heat with intercoolers into the atmosphere as waste. Upon removal from storage, the air must be re-heated prior to expansion in the turbine to power a generator which can be accomplished with a natural gas fired burner for utility grade storage. A-CAES collects and stores heat from the air compression process during the charge period, and reuses that heat instead of fossil fuels to raise the air discharge temperature at the expansion stage [19].

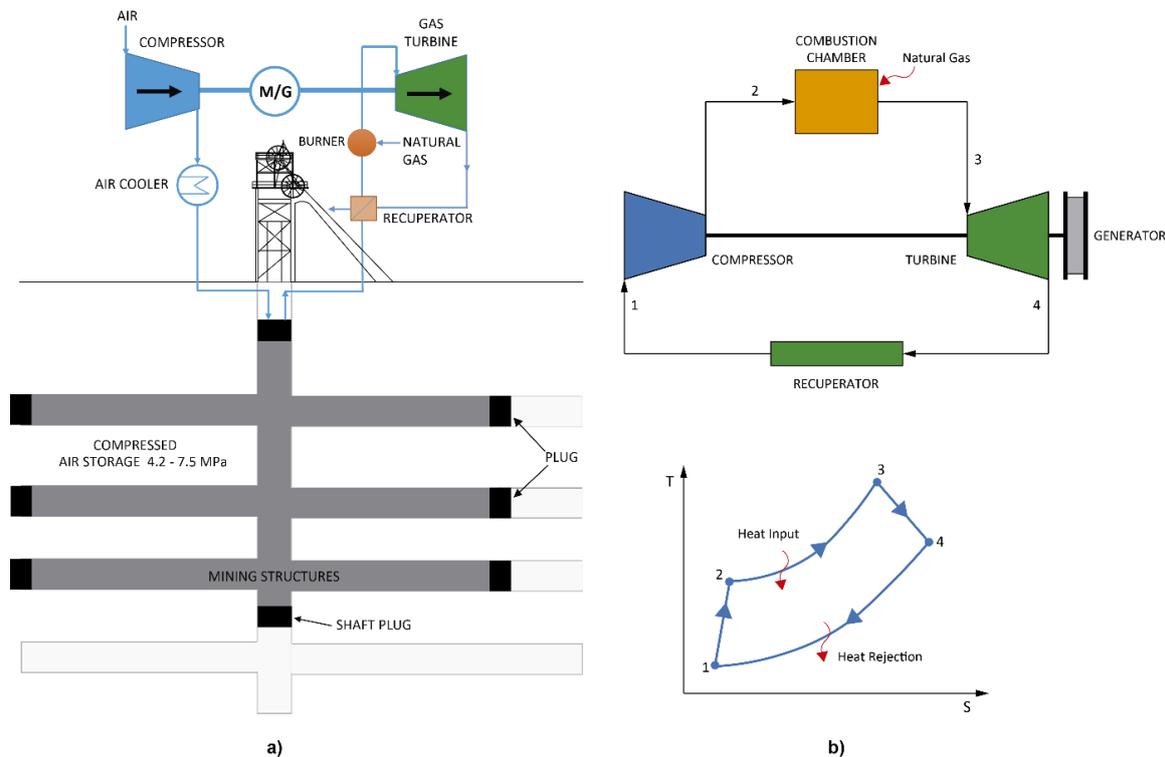


Figure 2. a) General scheme of a CAES plant using abandoned underground mines; b) Brayton cycle scheme with compressor stage, combustion chamber and expansion in a gas turbine.

2.4. Uncertainties and drawbacks

UPSH and CAES plants have environmental benefits. However, significant uncertainties and drawbacks have been detected [20, 21]. UPSH plants have higher investment cost than conventional PSH plants [13]. In addition, several factors such as impact of droughts, seismic activity or geotechnical problems due to the excavation of the underground reservoir should be analyzed in a feasibility study. Storage of air in abandoned mines has some major advantages over surface storage in tanks and other locations [19]: high storage capacities of mines, relatively low cost since the excavations already exist and the geology of the site is relatively well recognized, large surface area available for the installation of the plant infrastructure, and safe operation and protection against external factors since the underground system is only connected to surface by valves and pipes.

3. Results and discussion

Table 1 shows the results of energy production in UPSH plants by applying Eq. (1). A net head between 100-600 m H₂O and a water storage volume between 0.1-0.5x10⁶ m³ have been considered.

Table 1. Stored energy in UPSH plants. Net head between 100-600 mH₂O and storage volume between 0.1-0.5x10⁶ m³. Francis turbine efficiency: 0.9.

Storage volume x10 ⁶ (m ³)	UPHES - Energy [MWh cycle ⁻¹]					
	Net Head [mH ₂ O]					
	100	200	300	400	500	600
0.10	23.92	47.83	71.75	95.66	119.58	143.49
0.20	47.83	95.66	143.49	191.32	239.16	286.99
0.30	71.75	143.49	215.24	286.99	358.73	430.48
0.40	95.66	191.32	286.99	382.65	478.31	573.97
0.50	119.58	239.16	358.73	478.31	597.89	717.47

The maximum amount of energy is 717.47 MWh cycle⁻¹, considering 600 mH₂O and a water reservoir of 0.5x10⁶ m³. Table 2 shows the results of energy production in CAES plants by applying Eq. (2). A storage volume of compressed air between 0.05-0.25x10⁶ m³ and inlet temperature in gas turbine (expansion) between 1,000-1,200 K have been considered. The total energy produced by CAES plant was found in a storage of 0.25x10⁶ m³ and an inlet temperature of 1,200 K, with a value of 888.98 MWh cycle⁻¹.

Table 2. Stored energy in CAES plants. Gas turbine inlet temperature between 1,000-1,200 K and storage volume between 0.05-0.25x10⁶ m³. Gas turbine efficiency: 0.8.

Storage volume x10 ⁶ (m ³)	CAES - Energy [MWh cycle ⁻¹]				
	Gas Turbine Inlet Temperature (K)				
	1,200	1,150	1,100	1,050	1,000
0.05	186.76	178.92	171.07	163.60	155.52
0.10	442.00	423.44	404.87	387.19	368.05
0.15	529.16	506.93	484.71	463.54	440.63
0.20	719.65	689.43	659.20	630.41	599.25
0.25	888.98	851.64	814.31	778.75	740.25

A comparison between the amount of energy produced, type of turbine, flow rate (water in UPSH and air + natural gas in CAES plants), installed power, storage capacity and investment cost is shown in Table 3 for UPSH and CAES plants. The amount of energy produced by the energy storage plants reaches 225 GWh year⁻¹ with an investment cost of 225 M€. The total installed power is 80 MW (Francis pump-turbine) and 50 MW (Gas turbine) for UPSH and CAES plants, respectively.

Table 3. Summary of the specifications of the proposed energy storage plants

Parameter	UPSH	CAES
Underground reservoir (m ³)	300,000	100,000
Type of turbine	Francis	Gas Turbine
Output power (MW)	80	50
Flow rate (kg s ⁻¹)	20,800	140
Energy (MWh year ⁻¹)	105,600	120,000
Overall Efficiency (%)	75 %	52 %
Investment cost (M€)	177,60	48,00

4. Conclusions

The increase in the share of renewable energy sources requires efficient energy storage systems such as UPSH and CAES plants. In the present study closed underground coal mines in NW Spain are proposed as underground reservoir for UPSH and CAES plants. The use of disused mining structures for ESP has important environmental benefits. Abandoned coal mines have the potential to be excellent sites for renewal energy storage using the underground mining infrastructure according to the paradigm of the circular economy and in consequence giving new economic activities in historical mining districts

Flow rates of 20,800 kg s⁻¹ of water and 145 kg s⁻¹ of compressed air and natural gas could produce 225 GWh year⁻¹ in UPSH and CAES plants, respectively. Francis turbine-pump and gas turbine could be installed with a net electric power of 80 MW and 50 MW, respectively. The investment cost of the

massive ESP amounts to 225 M€. UPSH plants have an investment cost of 2,220 € kW⁻¹, while CAES plants have a lower cost, reaching 960 € kW⁻¹.

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