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Design and testing of Energy Bags for underwater compressed air energy storage

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A B S T R A C T

An Energy Bag is a cable-reinforced fabric vessel that is anchored to the sea (or lake) bed at significant depths to be used for underwater compressed air energy storage. In 2011 and 2012, three prototype sub-scale Energy Bags have been tested underwater in the first such tests of their kind. In the first test, two 1.8 m diameter Energy Bags were submerged in a tank of fresh water and submitted to over 400 complete inflation/deflation cycles. The Energy Bags generally performed as expected despite minor air leakage which allowed water to accumulate in the bag's pneumatic fill/exhaust line which was initially connected to the base. In the second test, a 5 m diameter Energy Bag was submerged at 25 m depth in seawater at the European Marine Energy Centre (EMEC) in Orkney. Damage incurred by the Energy Bag upon initial deployment necessitated repair, emphasising the need for itemised handling and deployment protocol, and correspondingly robust bag materials. The Energy Bag was re-deployed and cycled several times, performing well after several months at sea. Backed up by computational modelling, these tests indicate that Energy Bags potentially offer cost-effective storage and supply of high-pressure air for offshore and shore-based compressed air energy storage plants.

1. Introduction

Compressed air energy storage (CAES) is an energy storage technology whereby air is compressed to high pressures using off-peak energy and stored until such time as energy is needed from the store, at which point the air is allowed to flow out of the store and into a turbine (or any other expanding device), which drives an electric generator.

In simple terms, compressed air storage can either be isochoric (constant volume) or isobaric (constant pressure). In an isochoric store, the storage volume remains constant and the pressure of the stored air changes with the amount of stored energy; in an isobaric store, the storage pressure remains constant and the storage volume changes with stored energy. Isobaric storage has two advantages over isochoric storage: (1) expander efficiency can be 10–15% higher, since the pressure of the air at the input of the expander can be roughly constant throughout the discharge process without the need to throttle the air; (2) energy density is higher, since no cushion gas must be left in the vessel to support the external pressure (e.g. to prevent the weight of surrounding earth from causing an underground cavern to collapse).

The most common technology for small-scale storage of compressed air is the cylindrical pressure vessel. It can easily be shown that storing air in a steel cylinder at 70 bar costs upwards of £200 per kWh of storage capacity, if the cost of steel (including fabrication) is £4000/tonne. (If a spherical vessel is used, this could be reduced by 25% to a minimum of £150/kWh.) To store large amounts of compressed air, it is much more economical to exploit features in the environment, such as rock formations [1] or the ocean.

There are two commercial CAES plants in existence, one at Huntorf in northern Germany and the other at McIntosh in Alabama, USA. In both of these plants, off-peak electricity from the transmission system is used to power the compressors, but the idea of directly compressing air using specially designed wind turbines has been proposed [2], and air is compressed as part of the power-take-off system in several wave energy converters [3]. The compressed air at both Huntorf and McIntosh is stored in large man-made caverns underground, created by solution mining of salt domes, as shown in Fig. 1. The salt cavern substrate is particularly well-suited to CAES as it is self-sealing under pressure, thereby minimising leakage of trapped gases. There are many locations around the world (including over 20 in the USA) where natural gas is injected into excavated salt deposits for storage [4].

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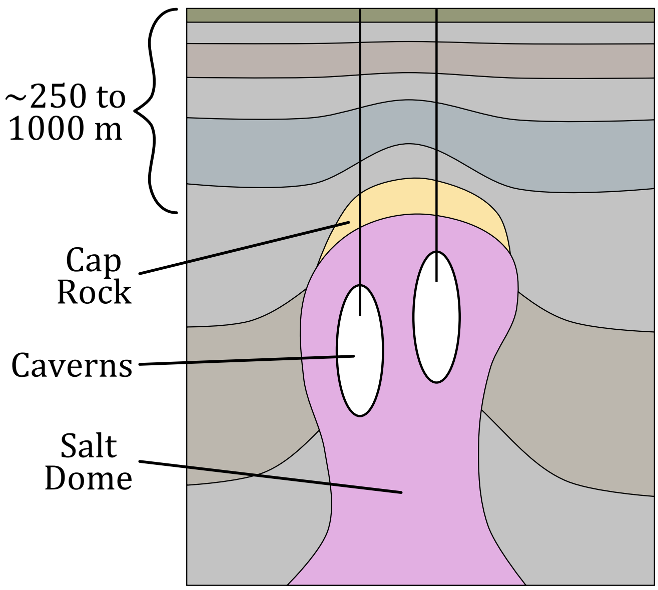

Fig. 1. Cross-section of two salt caverns in an underground salt dome.

In an underground compressed air store, the lithostatic pressure in the surrounding rock provides resistance to the high pressure of the stored air. Underground CAES has the potential to be very low cost: a study carried out by the United Nations in 1999 found that underground gas storage in salt caverns cost no more than $1/m^3 [5]. Taking inflation into account, if this price could be achieved for underground CAES at 80 bar, the cost per unit of energy storage capacity (in 2012 money) would be no more than £0.09/kWh (and storage in aquifers and depleted gas fields could be less than half this). However, excavation of large caverns requires suitable geology and detailed consideration of the structural parameters to ensure long-term integrity and to preclude the potential of collapse, which could lead to seismic disturbance and surficial subsidence.

Underwater compressed air energy storage (or UWCAES) takes advantage of the hydrostatic pressure associated with water depth. There is an abundance of space in suitably deep water around the world, devices installed underwater cannot be considered an "eyesore", and failure of an underwater compressed air store would likely have a lower impact (both in terms of environment and safety) than failure of an underground CAES plant or pumped storage plant.

In an underwater compressed air store, the surrounding water acts as the pressure restraint, having the same effect as the surrounding earth in an underground store. It makes sense to store the air at a pressure roughly equal to that of the surrounding water (rather than storing at a higher pressure), so that the requirements of the containment structure are minimal. The structure needs only to withstand small differential pressures (which are at a maximum at the top of the vessel), and to carry the resulting buoyancy forces.

The stresses experienced by the materials in the fully inflated vessel are essentially independent of the depth at which the vessel is anchored. This is because the stresses are a result of net buoyancy and differential pressure, and both the net buoyancy of a *fully inflated* vessel and the differential pressure across the walls of the vessel are roughly independent of depth. In fact, net buoyancy will decrease slightly as depth is increased because the air inside the vessel increases in density at a higher rate than the surrounding water.

Another benefit of underwater CAES is a result of the fluid nature of water: the volume of an underwater compressed air store can change as it is filled and emptied, and so the pressure of the air in store is roughly constant and independent of the amount of air in store. This isobaric characteristic is similar to that obtained when operating cavern storage with a *shuttle pond* [6], and allows more efficient turbomachinery to be used than with an isochoric system such as cavern storage without a shuttle pond, where the volume of gas in the cavern remains constant at all fill levels.

The compressed air in the underground CAES plants at Huntorf and McIntosh is stored at a maximum pressure of around 70 bar (7 MPa). In order to store the air underwater at this pressure, the vessels should be at a depth of 700 m (hydrostatic pressure increases by 1 bar for every 10 m of increased depth). However, the compressed air departing the caverns at Huntorf and McIntosh is throttled down to the operating pressure of the expansion turbine – around 40 bar. If the same turbine were used for an underwater CAES plant, the vessels should be at a depth of 400 m; such depths are found reasonably close to land along many of the world's coastlines.

For a CAES system which will not use any fuel or other external source of heat, the maximum energy density of the stored air is achieved if the heat of compression is stored after a single-stage compression and then restored to the air immediately before the air enters the expander. This is known as adiabatic CAES, and the recoverable energy per cubic metre of stored air is given by

$$u_{\text{adiab}} = rP_{\text{atm}}\left(r^{((\gamma-1)/\gamma)}-1\right)\left(\frac{\gamma}{\gamma-1}\right) \quad (1)$$

where r is the pressure ratio (between storage pressure and atmospheric pressure), P_{atm} is atmospheric pressure and γ is the ratio of specific heats (1.4 for dry air). This would require the air to be heated prior to expansion, up to a temperature given by

$$T = T_{\text{amb}}r^{((\gamma-1)/\gamma)} \quad (2)$$

where T_{amb} is ambient temperature.

Alternatively, a pessimistic assumption is that the air is expanded isothermally, in which case the energy density is given by

$$u_{\text{isoth}} = rP_{\text{atm}}\ln(r) \quad (3)$$

In an underwater storage vessel, it makes sense to store the air at a pressure equal to that of the surrounding water. At depth d, the (absolute) hydrostatic pressure is given by

$$P = \rho gd + P_{\text{atm}} \quad (4)$$

where ρ is the water density (typically 1025 kg/m^3 in seawater) and g is standard gravity. Hence, the pressure ratio

$$r = \frac{\rho gd}{P_{\text{atm}}}+1 \quad (5)$$

Assuming $P_{\text{atm}} = 101.325$ kPa, $\rho = 1025$ kg/m^3, $g = 9.81$ m/s^2, and T_{amb}=280 K, the energy density at various depths is given in Table 1.

It is worth making a simple assessment of the UK's energy storage requirements in order to have an idea of the potential market. With over 10 GW of installed capacity, wind power accounts for 53% of the UK's installed renewables electricity capacity [7], and it is widely used throughout the world. With high levels of generation from wind, lulls in the wind resource must be compensated for with generation from other sources, including energy storage. In the UK, lulls in wind can last for several days: in Refs. [8], MacKay shows that between October 2006 and February 2007 there were 17 days when the output from Britain's wind