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Commercial Grid Scaling of Energy Bags for Underwater Compressed Air Energy Storage

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Abstract

Large scale ability to store surplus energy for use during periods of high demand is a formidable asset in reduction of energy cost, improving electric grid reliability, and addressing climate change. An Energy Bag is a fabric balloon-like vessel anchored to a sea- or lakebed for the purpose of storing surplus energy in the form compressed air. This mode of energy storage is attractive primarily because the passive pressure force of the deep water environment takes on the significant role of pressure vessel structure to maintain pressurization of the air stored within the Energy Bag. Upon further investigation it becomes evident that particular attention must be given to the storage volume and pressure required to economically satisfy requirements for commercial grid scale development of this novel technology. This paper provides an introduction to the benefits and prerequisites pertaining to commercial scale energy storage capacity as related to Energy Bag structure, volume, and deployment depth.

1. Introduction

Compressed air energy storage (CAES) is an energy storage technology whereby air is compressed to high pressures using surplus energy associated with off-peak levels of consumption. When energy demand exceeds supply, the compressed air can be released from the energy store to drive turbines that in turn facilitate the generation of electricity to be returned to the consumer grid. Underwater compressed air energy storage (or UWCAES) takes advantage of the hydrostatic pressure associated with water depth as its motive force. In the most commonly contemplated mode of UWCAES described in this paper, the compressed air is stored in a fabric balloon-like vessel or "Energy Bag" that is anchored to the sea- or lakebed where the pressure of the surrounding water takes on the role of pressure vessel (Figure 1).

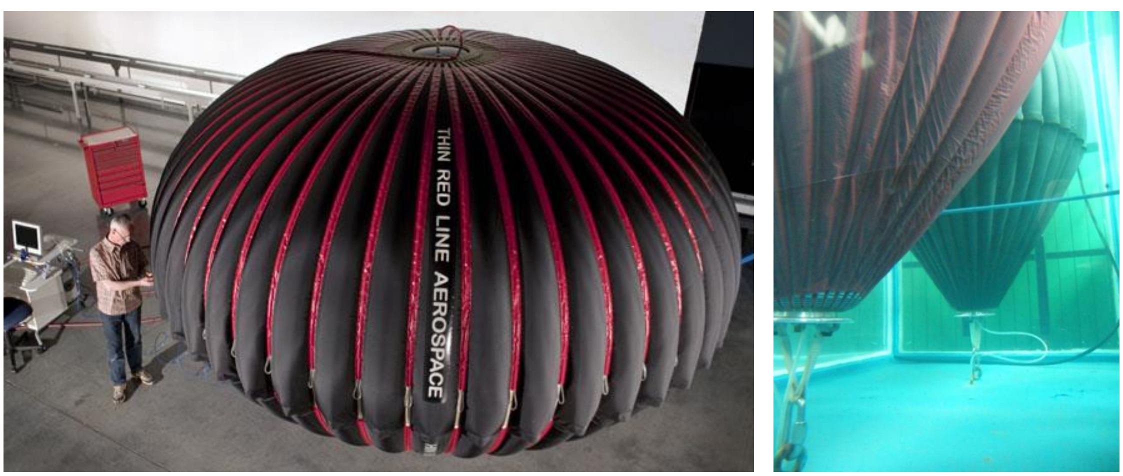

Figure 1. Thin Red Line Aerospace Energy Bags designed and fabricated for University of Nottingham UWCAES research. *Right*: Characteristic balloon-like profile when deployed underwater *(courtesy University of Nottingham).*

2. Technology Description and Benefits

Since the intent of submerged installation is to use the surrounding hydrostatic pressure to resist the pressure of the stored air, all pressure vessel structural requirements essentially disappear, diminishing structural mass of an Energy Bag to the merest fraction of a land-based pressure vessel of equal energy capacity. This design feature embodies the most favorable attribute of the technology. The Energy Bag is hereby relegated to (a) providing a membrane boundary between air and water, and (b) restraint of the buoyancy of the air bubble captive within the bag. Another benefit is that the stresses experienced by the materials in the fully inflated vessel remain essentially independent of the depth at which the vessel is anchored—and furthermore that, for all intents and purposes, the pressure within the bag remains constant regardless of the fill volume of the compliant fabric structure. Otherwise stated, exactly the same Energy Bag suffices for UWCAES regardless of its depth of installation, and the expansion turbine hardware used in energy recovery can be tailored to always run at its standard optimum pressure efficiency.

3. UWCAES Energy Density related to Depth

In view of the aforementioned benefits of UWCAES using Energy Bags, it becomes clear that the basic goal is to install storage at the greatest practical depth since energy storage capacity increases with increasing depth pressure. At depth D the hydrostatic pressure P_{abs} is given by

$$P_{abs} = P_{atm} + \rho g D \tag{1}$$

where ρ is the density of the water (approximately 1.025 kg/m^3 for sea water) and g is standard gravity. To distend the Energy Bag, air entering the bag must undergo compression to counteract the pressure at the depth of installation. Two thermodynamic cases thereby bound the energy density offered by the Energy Bag system. Heat is generated in the compression process, and lost when the air is released from the high pressure Energy Bag store. If both the compression and ultimate de-compressive release of stored air occurs slowly enough to allow the store to continually adjust to the temperature of the oceanic environment through heat exchange, the process is considered *isothermal*. Because the significant heat of compression is essentially wasted, this is the least desirable storage option, with an energy density given by

$$u_{isothermal} = rP_{atm}\ln(r) \tag{2}$$

where r is the pressure ratio between storage pressure and atmospheric pressure, P_{atm}. Conversely, if the heat of compression is stored and subsequently re-purposed to heat the air as it is released to drive energy recovery turbines, we obtain the much higher *adiabatic* energy density given by

$$u_{adiabatic} = rP_{atm}\left(r^{((\gamma-1)/\gamma)} - 1\right)\left(\frac{\gamma}{\gamma-1}\right) \tag{3}$$

Further to the aforementioned formulae, the isothermal and adiabatic CAES energy densities associated with ocean depth are found in Table 1 and graphically displayed in Figure 2.

Table 1. Underwater CAES energy density associated with deployed depth

Depth (m)	Storage pressure (bar)	Energy density (kWh/m^3)		Ratio of adiabatic and isothermal energy densities
		Isothermal	Adiabatic	
50	6.04	0.30	0.39	1.30
100	11.07	0.74	1.05	1.43
200	21.12	1.78	2.84	1.59
300	31.18	2.97	5.04	1.70
400	41.23	4.24	7.55	1.78
500	51.29	5.59	10.32	1.85
600	61.34	6.99	13.30	1.90

Besides the nonlinear increase in storage density with increasing depth in a fashion that conspicuously favors greater depth, we also obtain a very significant depth-related increase in energy density by implementing adiabatic capability. For example, increasing installed depth of identical Energy Bag structures from 50 to 500 meters increases stored energy density by a factor of almost 19—even in the most pessimistic, isothermal case. Optimized adiabatic recovery of compression heat theoretically returns 26.5 times greater energy density with the ten-fold increase in depth.

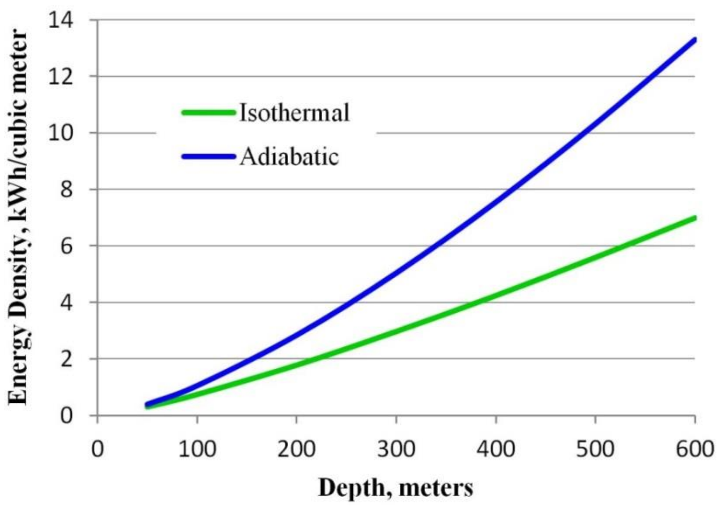

Figure 2. Compressed air energy density associated with submerged depth in sea water. Underwater CAES clearly favors deeper waters—especially since Energy Bag structural requirement remains constant for all depths.

4. UWCAES Energy Storage Capacity

4.1 Installation Depth

From the preceding it is clear that the energy storage capacity of an Energy Bag increases dramatically with installation depth. 44% of the world's population lives within 150 kilometers of the coast [1]—a fact which generally bodes well for ocean based sustainable energy development. And fortunately there are many heavily populated coastal areas where deep water is found relatively close to shore. Balancing accessibility of deep water to both land and established electricity grids, and the operating efficiency of off-the-shelf turbo-machinery, we loosely identify an economically efficient target UWCAES installation depth of 400 to 700 meters. Greater depth is also vastly preferable for Energy Bag installation due to reduced impact of the required ballasted moorage systems (see following section) on the biological systems flourishing in shallower waters.

4.2 A Logical Scaling Context for Commercial UWCAES

We now consider the following example to provide a rational context for commercial grid scaling of energy storage capacity [2]. The London Array in the UK was the largest offshore wind farm in the world when it became operational in 2013. In this context we might wish to note that, with a total installed capacity of 630 MW, the Array produces the approximate equivalent of 4.2% of greater city of London's electrical energy [3]. Assuming 30% (or 189 MW) average output, 4.54 GWh energy storage capacity would be required to compensate for a one-day lull in the output of the Array. With energy densities of 5.59 kWh/m^3 (isothermal) and 10.32 kWh/m^3 (adiabatic) provided earlier for 500 meter depth, we find that up to 812,000 cubic meters of storage would be required at that depth to compensate for a one-day lull at London Array. UWCAES compensation for the aforementioned one-day lull in the London Array would therefore require a storage volume equivalent with 23 Energy Bags of the same 36,000 cubic meter volume as the Echo II satellite shown in Figure 3. Furthermore, each bag would need to be installed at 500 meter depth to fulfill the requisite energy storage capacity. For a *single* Energy Bag with this effective operating volume and energy storage capacity we are presented with the following approximate requirements:

- 500 meter installation depth
- 360,000 metric ton structural capacity to restrain the buoyancy load with a factor of safety (FOS) of 10
- 50 kilometers of 10 cm diameter × 7 MN tensile strength rope is needed to fabricate 512 meridional buoyancy load restraint tendons linking the top polar apex of the Energy Bag to the ballast anchor (assuming use of the high performance Dyneema™ SK75 fiber)
- The fabric portion of the Energy Bag covers 8000 square meters.
- Total tendon mass is over 300 metric tons. Total Energy Bag mass is 400 to 500 tons.
- 180,000 metric ton ballast requirement, assuming a FOS of 5 over the buoyancy load
- When submerged, the ballast requires 130,000 cubic meters of concrete (≈3.6 times the volume of the Energy Bag itself), or 180,000 cubic meters of aggregate; or 26,000 cubic meters of scrap steel.

Figure 3. NASA passive communications satellite Echo II: A 41-meter diameter/36,000 cubic meter Energy Bag volume equivalent *(courtesy NASA).*

It may predictably be countered that smaller Energy Bags might suffice despite the commercial scaling requirement for energy storage capacity provided above. However, one should then consider that 27,500 Energy Bags of the 5 meter diameter size shown in Figure 1 would be needed to achieve the equivalent capacity of the 23 unit volumes shown in Figure 3. These would all need to be installed at 500 meter depth and furthermore pneumatically interconnected. Reflecting upon the preceding comparison and the data provided in Section 4.2 we are obliged to acknowledge the need for a very specific design approach that will predictably accommodate the magnitude of the architecture required.

5. Energy Bag Structural Scalability

5.1 Structural Determinism and Predictability

Besides initial thoughts of engineering challenges, likely the greatest potential road-block in implementation of commercial scale UWCAES is the regulatory aspect—especially pertaining to safety. Widespread skepticism is encountered when high performance inflatable structures are proposed as alternative to rigid architecture—and even more so in cutting edge applications seeking especially creative solutions. A good example is the current factor of safety of 4 required for fabric structures in aviation and manned space applications. This requirement ostensibly harks back to the Hindenburg era as indication of how challenging it is to change perceptions despite immense advancements in science and technology. It is assumed that implementation of pilot projects of increasing storage capacity will help pave the way to the largest grid scale UWCAES plants. However, in order to push past regulatory and insurance hurdles over the long term it will be necessary to adopt and certify Energy Bag containment architecture that displays the following attributes:

1. Structural determinism and performance-predictability in all sizes throughout scaling to the dimensions contemplated for grid-scale energy storage and associated operational volumes greater than 10,000 m^3.
2. Straight-forward structural characterisation using the same analytical tool to model all sizes of the intended architecture. Sub-scale prototype test data must extrapolate to, and correctly represent, full-scale structures.

5.2 Ultra High Performance Vessel

In the aftermath of Thin Red Line's (TRLA) design and fabrication of the pressure hulls of the Bigelow Genesis I and II inflatable spacecraft (launched in 2006 and 2007 respectively), TRLA research focussed on development of much more structurally determinate, performance-predictable fabric architecture [4]. The result of this multi-year effort is "Ultra High Performance Vessel" (UHPV) which was ultimately also applied to the University of Nottingham UWCAES test articles shown in Figure 1. In the course of numerous NASA research programs, UHPV architecture has now been highly characterised and validated as structurally determinate and highly predictable. Initially in the context of UWCAES, and later for general application, University of Nottingham developed sophisticated UHPV-specific analysis and modelling tools that reaffirmed UHPV predictability and provided more advanced insights into its structural behaviour (Figure 4). UHPV can be predictably scaled to any conceivable size—an attribute of fundamental benefit to UWCAES. UHPV can, for example, be doubled in diameter indefinitely simply by doubling the number of tendons while simultaneously doubling tendon strength. All the while the load on the fabric envelope remains constant because the circumferential spacing between the tendons is held constant:

- Tendons carry UHPV's global pressure load, and therefore only the tendons need to structurally be scaled upwards to accommodate the higher shell loads associated with larger geometries.
- Tendons are structurally predictable and readily scalable linear tensile strength members which can be made in virtually any conceivable strength with very little variation in properties.

Further to the aforementioned attributes, UHPV appears imminently suitable as universal Energy Bag architecture. The design also facilitates single point moorage and ease of packaging and deployment.

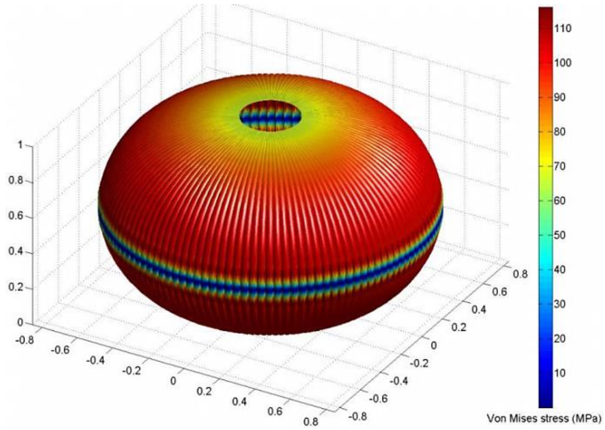

Figure 4. University of Nottingham modelling tool applied to 128 tendon UHPV architecture

6. Conclusions

This paper provided an introduction to the benefits of underwater compressed air energy storage (UWCAES) using flexible fabric Energy Bag architecture. Key insights were also provided regarding implementation of this novel technology in fulfillment of the prerequisites for commercial scale energy storage viability. The benefits presented by Energy Bag systems are conspicuous and considerable. Energy Bag performance is now well-developed and characterised further to successful testing in relevant environments [2, 5]. As such the developmental objective shifts towards commercial capacity whereby the scaling of Energy Bag architecture to the volumetric dimensions sought for commercial grid energy storage application will critically benefit from the highest degree of structural predictability. In this context the author considers Thin Red Line Aerospace's comprehensive, NASA space flight related verification and validation program of directly applicable architecture to be a valuable asset in the renewable energy community's drive for greater sustainability.

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