A Review of Offshore-based Compressed Air Energy Storage Options for Renewable Energy Technologies

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Abstract – This paper presents a synopsis of literature on various options for the storage of energy from offshore based renewable energy (RE) sources. The technology in focus is compressed air energy storage (CAES). An overview of the available storage technologies and a comparison of pumped hydro storage (PHS) and CAES; these being the main contestants for bulk energy storage, is presented. A qualitative description of the thermodynamic processes involved is included. The offshore storage concepts and prototypes set-up or being investigated are also detailed.

1. Introduction

The development of electrical energy storage (EES) technologies is the next step in the evolution of offshore renewables. Given that these sources are of a stochastic nature, the interfacing of large-scale renewable energy (RE) farms with the electrical grid network may cause problems affecting system stability and power quality [1] [2].

At present the United States (US) has about 24.6 GW of grid storage capacity. This is approximately 2.5% of the total electric production capacity. The database of the US Department of Energy (DOE) shows that 95% of the energy storage installations are pumped hydro systems (PHS). It is to be noted that both Europe and Japan have higher fractions of grid storage [3]. Expert commentators like Navigant Research estimate that energy storage will be a USD 50 billion global industry by the year 2020 [4]. Japan in particular, has conducted research to balance the mismatch between the demand load and the supply from its nuclear power plants. China and India have their own programs related to energy storage to support the rapid growth in their electrical energy needs [3]. Other technologies such as compressed air energy storage (CAES), thermal energy storage (TES), batteries and flywheels constitute the remaining 5% of the overall storage capability.

For the scope of this paper the storage concept of interest is compressed air stored in underwater flexible or rigid containers through adiabatic or isothermal compression processes. A very brief overview of energy storage in general is given, focusing on bulk energy storage for peak shifting, which is the case for offshore wind or solar farms. The different thermodynamic concepts have also been noted and various offshore technologies and prototypes which have been set up to date have been included.

2. Overview of Electrical Energy Storage Systems (EES)

2.1 Classification

Power grids deal with spatial imbalance between supply and demand, whilst energy storage systems address the temporal dimension. The resulting advantage of deploying energy storage systems increases the flexibility in operating the grid, especially if RE technologies are to be integrated [5]. These storage systems ensure that the expected quality and power characteristics are maintained [6]. EES systems can be categorised by function and form where the former refers to the various technologies and the latter to the many forms that energy storage can take [5] [7].

2.2 Applications

Energy storage systems can form an integral part of the electrical energy supply value chain from generation to distribution. EES systems have their primary importance in the integration of RE sources with respect to time shifting of the energy availability, thus optimising market spot prices and enabling better grid management due to balancing of supply and demand [2] [8] [7] [9] [10] [11].

Typical offshore wind farms to date vary in size from 207 MW (Rodsand II, Denmark) to 630 MW (London Array, United Kingdom). A typical 200 MW CAES plant would need a minimum storage capacity of 10,000 MWh; being the equivalent of a typical 50 hours of full plant output of wind turbines, assuming that the wind power density is constant throughout the year. In the case of seasonal storage, a minimum of 40,000 MWh would be needed.

When considering power loads in the range of MW and capacities in the range of GWh, PHS and CAES stand out as strong contestants due to the use of inexpensive media like air or water for interim storage of the generated energy [12] [13].

2.3 Technical and economic characteristics for onshore and offshore CAES

The technical and economic characteristics of CAES technology as noted to date for terrestrial use are being listed and compared to the expected offshore scenario in Table 1 below.

Table 1 – Technical and Economic Characteristics of CAES Technology [7] [14] [15] [16] [17] [18]

Characteristic	Terrestrial CAES	Offshore CAES
Technical Maturity	Deployed technology.	Experimentation and prototyping.
Storage Specifications	Naturally-occurring salt caverns with availability ranging from hours to months.	Use of flexible and rigid materials is being researched with capacities of a few hours to months in both options.
Energy Density	Low at 2 - 6 kWh/m^3 when compared to other technologies and implies the need for large storage volumes.	0.5 and 2.0 kWh/m^3 and depends on hydrostatic pressure and the respective storage volume.
Power Rating	110 - 290 MW.	A number of prototypes and proposals have been put forward.
Self-Discharge	< 10%	Depending on whether storage is rigid or flexible but losses are estimated to be of the order of 10%.
Lifetime	20 - 40 years.	Depends on a number of design details as per ongoing research.
Cycling Times	8,000 - 12,000 cycles. CAES technologies are based on mechanical equipment mostly.	
Round Trip Efficiency	Of the order of 40 - 70% depending on the overall construction design and on whether the thermodynamic process is adiabatic or isothermal.	

Grid Support	Storage can give 30% - 100% of the capacity in a relatively short period of the order of minutes.	Present research is mostly intended to have energy storage to support RE generators with respect to arbitrage, long- or short-term storage durations or capacity firming.
Energy Capital Cost	Considered to be in the low range. € 2 - € 100/kWh.	The Hydrostor prototype has shown that commercial plant costs would be in the region of € 200/ kWh with the available technology.
O&M Cost	Bulk storage requires relatively large amounts of energy with frequent discharges throughout the year replacement and O&M costs are significant factors. USD 0.003/kWh.	No operational plants so no data is available.

3. CAES Thermodynamic Concepts

Compressed Air Energy Storage (CAES) plants can be designed using the thermodynamic concepts as noted in Table 2 [15] [19].

Table 2 – CAES Technology Concepts

Concept	Concept Description
1st Generation Diabatic CAES (D-CAES)	290 MW Huntorf plant built in 1978 in Germany, where the constant volume storage vessel is a salt cavern. Technology involves compression of air using electrical energy in a period outside peak time. When there is the need to energise the grid, compressed air is released and mixed with a gas in a combustion chamber to drive a turbine and a respective generator at an efficiency of the order of 42% [20] [21].
2nd Generation Adiabatic CAES (A-CAES) [without TES]	110 MW McIntosh plant (USA) commissioned in 1991 and then upgraded to 226 MW in 1998. Design was an improvement on the 1st generation due to the introduction of a recuperator which preheats the expanding air with the exhaust gases of an open cycle gas turbine plant, resulting in a lower heat rate and an overall efficiency of the order of 54% [20] [22].
3rd Generation Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) [with TES]	Storage of heat from compression by using a “thermal energy store” (TES). High temperature compressors for temperatures up to 600°C at 100 bar and also high temperature heat storage are needed [23] [24]. Various thermal energy storage concepts have been researched to date. Packed bed heat (PCB) exchangers have been proposed claiming a cycle thermal efficiency of 70%. Phase change materials (PCM) have been modelled optimising the melting temperature and enthalpy of the materials to achieve a simulated 85% cycle efficiency [15].
Isothermal Compressed Air Energy Storage (I-CAES)	Compression process would ideally be carried at constant temperature, implying that the air experiencing an increase in pressure does not gain heat. Thus thermal losses take place. This is possible if the temperature differences between the compressor and the environment are kept minimal; which in theory is possible through a very slow compression process. In

	practice, this is a big challenge to achieve for a process to be commercially viable. Cycle efficiency in the case of isothermal processes is expected to be of the order of 70% [25].

Further to the concepts noted in Table 2, a number of hybrid setups have been proposed along the years spanning from a combination of CAES and PHS where pumped hydro combined with compressed air (PHCA) has been investigated as a hybrid energy storage system. The important characteristic of this system is that the water pump and hydro turbine work under stable conditions, thus improving the working efficiency of the equipment and minimizing energy losses [26]. *Sigma Energy Storage* [27] has come up with a thermo-mechanical portable system claiming a high round trip efficiency and a low levelised cost of energy (LCOE). This solution has been designed to maximize thermal energy recovery during the air compression process in the storage unit through a unique thermal fluid formulated with particular ingredients that contribute to the overall efficiency. A small scale prototype with a high round trip efficiency and high energy density promises a compact system which could easily fit in containers and offer a modular setup for remote or free-standing locations [27] [28].

4. CAES Plants and Projects

To date, existent onshore CAES plants have proven that this technology can provide a number of ancillary services including load following and intermediate power generation services under commercial conditions in a reliable manner. Providing this technology for offshore use is presently under research and has a lot of commercial interest.

4.1 Onshore CAES plants

CAES is a technology which has been proven only at two commercial terrestrial sites to date. One is the facility in Huntorf, Germany, in 1978, having a storage volume of 310,000 m^3 at a depth of 600 m and the capability of producing 290 MW for 2 hours whilst using 0.8 kWh of electricity and 1.6 kWh of gas to produce 1 kWh of electricity under diabatic conditions. This plant has recently been upgraded to 310 MW. The other facility is the McIntosh, USA (1991) plant, having a storage volume of 538,000 m^3 at a depth of 450 m. This plant has the capability of producing 226 MW for 26 hours following an upgrade in 1998. Using a heat recuperator fed from the gas turbine plant, 0.69 kWh of electricity and 1.17 kWh of gas the plant can give an output of 1 kWh of electricity under diabatic conditions [29] [20].

In 2013, the *ADELE* 290 MW project was proposed as the first adiabatic demonstration land-based plant in Germany, where the compression heat was proposed to be stored having a thermal energy store (TES) which is separate from the ambient temperature high pressure air store. The main challenge of this plant is to have high performance compressors for operating temperatures and pressures up to 600°C at 100 bar respectively, with high efficiency heat storage containers. To date, this project has been delayed [23] [24] [30].

In 2012, the *Fraunhofer Institute* proposed a multi-stage setup using radial compressors and expanders. This design is an adiabatic CAES working at low temperatures and is seen to have efficiencies in the range of 58 - 67%. This arrangement is proposed to be superior to the ADELE concept due to its capability to integrate in fast start ups, whilst also having a part-load capability across a wide range. To date, this concept exists only at an academic level and there are no identified manufacturers and suppliers who could provide data through feasibility studies [23] [31].

Storelectric Ltd. is a UK-based company which this year have proposed a power system with options that can eliminate the need for gas re-heating, making it 100% renewable and having round trip efficiencies ranging between 60 to 70%. The company markets the idea as costing very near to a gas fired peaking plant [32].

Gailectric from Northern Ireland has submitted a CAES proposal under the European scheme for projects of common interest (PCI) in 2013. The project is designed to adopt CAES technology generating up to 330 MW for periods of up to 6 hours duration [33].

ALACAES of Lugano, Switzerland, is planning the world's first high pressure AA-CAES plant. This proposed 100 bar plant follows the successful implementation of a 600 kW plant with a capacity of 1 MWh operating at 7 bar plant in 2016 [34].

In the USA, the *Pacific Gas & Electric Co.* have been working on a 300 MW adiabatic plant which was scheduled for completion in 2016 [35]. The company *SustainX* had proposed an isothermal process having a water-in-air heat-transfer process within pneumatic cylinders. The plant achieves the isothermal characteristics by spraying water in the air which is being compressed in the compression chamber. This design allows heat to be transferred from water to air during expansion or from air to water during compression. Since the same power unit provides both isothermal compression and expansion, the cost of separate compressor and expander subsystems is avoided [36] [37] [38]. *Apex*, a Texas based company, have proposed the Bethel project being a 317 MW CAES facility with a storage capacity of 30,000 MWh that is enough to energise more than 300,000 homes [39].

Another isothermal design has been suggested by *LightSail* in California involving spraying water droplets during the compression cycle to absorb the heat of compression and limit the temperature increase in the compression chamber. The warm water is stored and eventually reintroduced during the expansion process as droplets [19] [40].

4.2 Offshore CAES Projects – Current Research and Development

A number of works have examined the feasibility of using compressed air as an underwater energy storage technology for offshore use. Storage options could be through rigid containers or through energy bags; these being bags fabricated out of specially reinforced fabric. Both options would need the respective pneumatic and electrical piping and cabling and the compression and expansion machinery which could be located as a combined platform with the energy generating plant or as a standalone floating platform. These could also be on land depending on the distance from land and the environmental constraints of the area [18] [41].

4.2.1 Rigid storage containers

Rigid containers have been researched at the *University of California* (UOC) using compressed air to pump out water when there is an energy surplus. This compressed air is released when energy is needed to drive the expansion equipment. This research proposes a 230 MW installation with a storage capacity of 10 hours and operating pressures of 60 bar in pipework at a depth of 650 m.

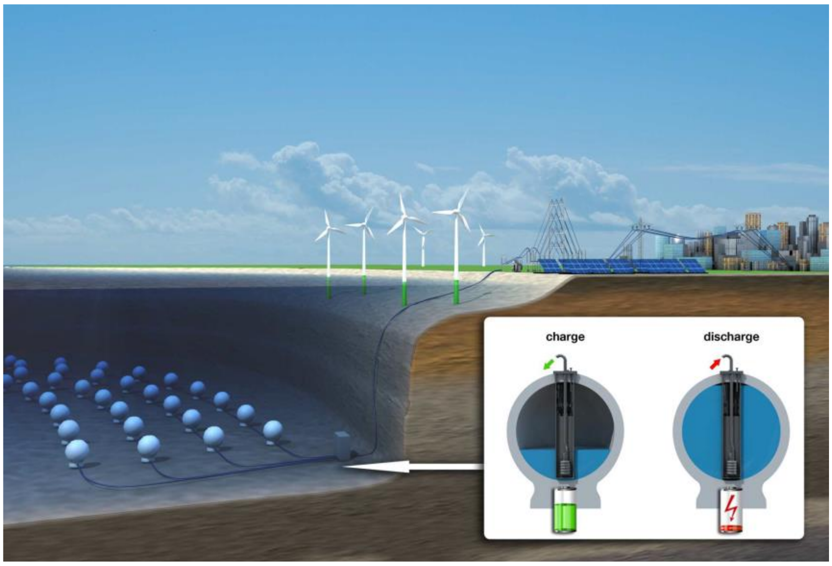

Figure 1 – STENSEA stored energy in the sea [42]

The *STENSEA Project* as shown in Figure 1 is also a concept for offshore storage of electrical energy using the principle of conventional pumped storage units. A concrete sphere of the order of 30 m with

2.7 m thick walls would include a pump-turbine which charges the sphere when there is a surplus of electrical energy by pumping the water out and then discharges the sphere through the turbine returning the electrical energy when required by allowing the water back in. This size of sphere would have a power of the order of 5 MW delivering 20 MWh per sphere. Underwater farms of 80 or more spheres are conceivable. Costs of € 1,200 to € 1,300 are foreseen.

At the *Massachusetts Institute of Technology* (MIT), the concept of rigid storage is being researched through concrete spheres, where again the flow of water in and out of the reservoir is used in synchronisation with the compression and release of the water. This concept introduces also the idea of using the reservoirs as anchorage for energy platforms such as wind turbines. Other concepts of underwater storage using rigid containers have also been investigated using the surrounding bedrock as the thermal reservoir for the compression heat [41].

4.2.2 Flexible storage containers

Figure 2 – Energy bags in a water tank [41]

Seabed storage through underwater installations where hydrostatic outer pressure would counteract the pressure of the air inside the storage vessel is another option for which there is a lot of research and commercial interest. Flexible storage concepts need to take into account the optimal depth where the air flow through hoses during the cycling of air is not degraded due to friction losses. Typical installations for flexible storage systems would be the tubular bags as shown in Figure 2 and as noted in [13] [43] or spherical bags. A 40 meter diameter bag at a sea depth of 500 meters can store up to 370 MWh if adiabatic compression is used. Experimental bags are shown in Figure 2 [41].

The *University of Nottingham* has been studying various shapes and cost models for energy bags since 2007. Energy bags studied at this university considered an adiabatic process. The compression heat is contained within a multi-layer of the energy bag. The bags have three innermost layers with molten salt in a porous bed of rock fragments to act as a heat transfer medium. The bag has a middle section made up of three layers containing mineral oil as a heat transfer fluid with a capacity to handle temperatures of 250°C. The three outermost layers are made up mainly of sea water, catering for temperatures of up to 100°C.

The Canadian company *Hydrostor*, together with a number of universities, propose spherical containers as energy bags for underwater storage, using the hydrostatic pressure of the surrounding water to push the compressed air out of the bags when it is needed to drive the turbo machinery. Their system in Lake Ontario is noted as the world's first grid connected underwater energy storage facility [41] [44] [45] [46].

4.3 Offshore Hybrid Projects

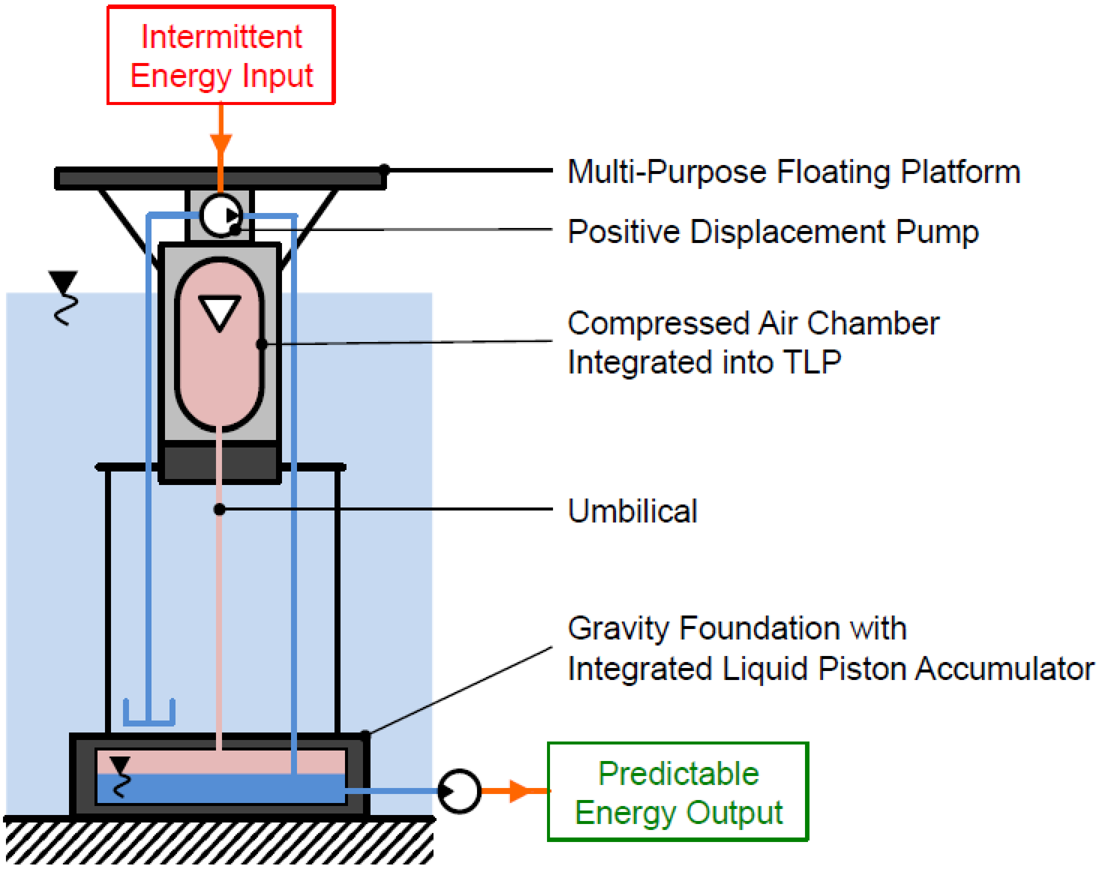

Figure 3– FLASC A floating platform with integrated energy storage [47]

Other ongoing studies and research in offshore energy storage involve hybrid technologies. The University of Malta is currently developing a CAES integrated into a floating platform that can support a number of offshore systems including wind turbines. The proposed design consists of

a floating liquid piston accumulator using seawater under compression (FLASC) as shown in Figure 3. The innovative feature of this design is the use of a dual chamber for compression. This design detail is intended to eliminate wide pressure and temperature fluctuations [47].

To note that this review may not be exhaustive due to ongoing work and patent registrations at the time of writing.

4.4 Offshore CAES Challenges

Although CAES is eligible as a bulk energy storage technology, there are still a number of opportunities to be investigated to arrive at a stage where this technology can be introduced in an economically justifiable manner in offshore environments.

The energy storage containers and the compression and expansion equipment have to be located near the RE generators' location offshore for a number of reasons, amongst which is the fact that the transmission system of the RE installation does not have to be designed for peak conditions. Another important aspect is the minimisation of friction losses in the movement of compressed air through the system. Long distances imply losses which may not justify the installation. These considerations imply the study of the technical and economic criteria of the platform needed to house the storage equipment in respect of the marine conditions of the location. Research and analysis of the technical and economic criteria is important to ensure that the right equipment is installed on an optimised support platform. If the energy is stored first, then all of the transmission equipment, in particular the electric generators of the respective wind turbines, can be downsized to accommodate the average quantity of generated electricity as opposed to the peak generation. For an offshore wind farm, where the transmission system is of the order of 15% of the total cost, these could be reduced if the average power is transmitted as opposed to the peak power.

To date, CAES systems have been mostly seen in the light of bulk storage for daily peak shifting. Further study is however needed to consider this technology for seasonal storage where, during periods of high winds or highly active water bodies, the collected energy is stored for long periods and eventually released slowly as the need arises. This aspect implies the use of strong containment to minimise self-discharge which, for CAES, could still be of the order of 10%.

The other area which also needs to be studied is the other end of the spectrum for energy storage involving fast response times of the order of seconds to make good for grid stability. This poses serious challenges since the rapid expansion of compressed air has to cater for the cooling aspect. Again, the use of adiabatic and isothermal processes is important, whilst keeping in mind the same challenges which need to be overcome due to high temperatures and pressures similar to those of land based systems [48] [49].

Conventional CAES processes where the energy of compression is not stored to be reintroduced in the expansion phase lack the efficiency which would justify offshore commercial installations. The technology needs to be researched further and improved to introduce adiabatic or isothermal processes so that during the expansion stages there will not be the need to use the combustion of fossil fuels to raise the temperature.

Another area which still merits research and further study is the review of offshore renewable energy CAES technologies through life cycle analyses. Research to date has focused a lot of effort on the various technologies and respective parts of the overall process. A detailed study of the whole life cycle of the project could yield technical and economic improvements.

To date, some prototyping has been carried out. The next challenge is now a financial one in order to scale up the systems and maximize efficiency. However, at this point there is a dearth of operational data that addresses risks from a commercial perspective.

5. Conclusions

Compressed air energy storage facilities can be very large and are therefore very well suited to applications which require high power and energy ratings. Self-discharge losses can be considered low and energy can be stored for more than a year. The start-up time is of the order of 10 minutes, which can be considered to be faster than that of conventional generation plants. The main drawbacks of the containment and the heat of compression processes can be said to be the two areas undergoing research both for terrestrial and offshore facilities. Once these are overcome, this technology would be a commercially viable choice for offshore energy storage and for wider scale RE grid integration.

The objectives of this paper were to highlight the latest updates on offshore CAES technology for bulk energy storage. The literature which was reviewed clearly shows an increase in research being carried out in this area and similarly a growing interest from the commercial sector. The authors believe that CAES, or variants of this technology, can be a solution for offshore electrical energy storage. However, the choice of EES would depend heavily on the operational scenario.

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