Compressed Air Energy Storage: A simple idea but a difficult practice.

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In the mainstream there are two main branches of Compressed Air Energy Storage (CAES) - conventional and adiabatic.

1. Conventional CAES

Conventional (also known as *diabatic*) CAES plants are essentially gas turbines in which air is *pre-compressed using off-peak electricity*, rather than running a turbine and compressor simultaneously. In these plants, off-peak grid electricity is used to compress air which is stored, and then mixed with natural gas and combusted during expansion. Compression is staged and the majority of the compression heat wasted (although some may be stored in a recuperator to pre-heat the air before combustion). Currently there are two commercial CAES plants worldwide; the Huntorf plant in Germany and the McIntosh plant in Alabama.

- **Huntorf CAES plant**: Data from [1]. 310,000m^3 cavern at a depth of 600m, pressure tolerance between 50 - 70 bar, converted from a solution mined salt dome. Daily charging cycle of 8h, output of 290MW for 2 hours. 0.8kWh of electricity and 1.6kWh of gas required to produce 1kWh of electricity. Notably, built when the price of gas turbines was historically high.
- **McIntosh CAES plant**: Data from [2]. 538,000m^3 salt cavern at a depth of 450m, pressure tolerance between 45-76 bar. Originally it provided an output of 110MW for 26 hours but in 1998 two extra generators were added and its total output capacity is now 226MW. 0.69kWh of electricity and 1.17kWh of gas to produce 1kWh of electricity.

Both plants are commercially viable and still running in their respective markets!

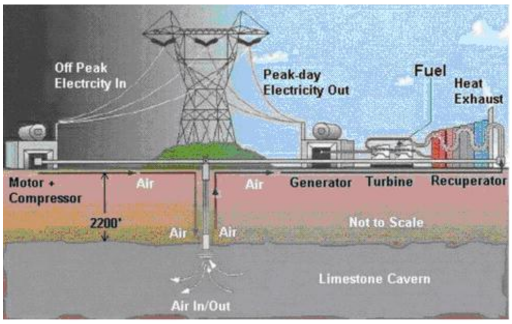

Figure 1: Schematic of *diabatic* CAES system.

As with Pumped Hydro Storage (PHS), CAES also requires favourable geography to provide the underground air storage caverns. However there are many more suitable sites worldwide than for PHS, although the costs are highly site specific. The costs of mining a suitable underground cavern where suitable geology doesn't exist or creating an above-ground equivalent storage container are potentially prohibitive, whereas alternatively a naturally occurring cavern or somewhere easily minable may offer a very attractive price of storage in terms of $/kWh (or dollars per metre cubed of air storage).

Caverns can be created in salt geology (typically using salt solution mining techniques) or existing caverns can be exploited provided that they are capable of housing the desired pressure. Geological formations such as aquifers and salt formations (bedded salt and domal salt) offer potential locations. Costs can also be reduced if existing well infrastructure is in place from previous underground drilling operations. While specific geology is required, this geology is relatively widespread. For example, the EPRI suggests that up to 80% of the US could have favourable geology [3] (see Figure 2).

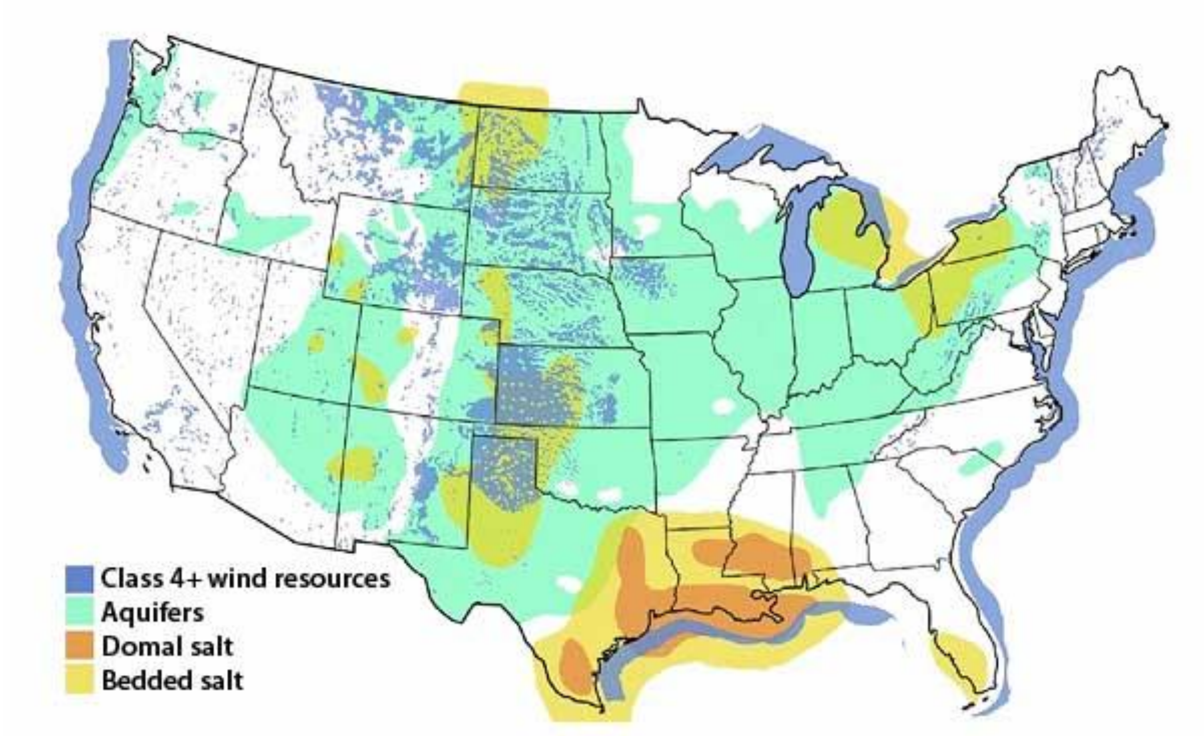

Figure 2: US geology for compressed air caverns. Regions with high wind resources are also indicated with the idea that CAES sites and wind turbines could be co-located [4].

Estimates for the costs of cavern mining can be as low as $1/kWh of storage capacity if solution mining techniques can be used [5]. In solution mining, fresh water is pumped in a salt deposit, becomes saturated with salt and is then removed. One problem however is that disposal of this brine can cause environmental issues.

1.1 CAES Performance Characteristics and Applications

CAES systems have traditionally been designed as centralised storage facilities which are intended to cycle on a daily basis and to operate efficiently during partial load conditions. This design approach allows CAES units to swing quickly from generation to compression modes and means that they are well suited to ancillary services markets, providing frequency regulation. Their ability to operate on a (intra) daily cycles means that they are also useful for load-following/peak shaving. The air storage caverns can also be very large, allowing for multiple days worth of electricity storage.

It should be noted that the inlet pressure (45-76 bar) for the CAES high pressure turbine is much higher than the equivalent for a typical gas turbine (about 11 bar) so a typical gas turbine can only be used as the low pressure expander. The high pressure turbine at Huntorf is based on a small-intermediate steam turbine design.

1.2 Table of Cost Estimates

Typical Capacity	Typical Power	Efficiency	Storage Duration	$/kWh	$/kW	Lifespan	Cycling capacity
500MWh – 2.5GWh	50 – 300MW	n/a	Hours – days	4-7 [6], 2-50 [7], 60 - 120 [8]	300-600 [6], 400-800 [7], 1000-1250 [8]	20-40 years	High

Table 1: CAES cost characteristics

2. Adiabatic CAES

Adiabatic CAES is an energy storage concept that *removes the natural gas combustion* from conventional diabatic CAES. In adiabatic CAES the heat generated by the compression of air (the charging process) is stored in a Thermal Energy Store (TES) which is separate from the ambient temperature high pressure air store. When the system is discharged the high pressure air is reheated using this stored heat and then expanded. Without the stored heat, the process has an unacceptably low efficiency - this is because significant exergy is stored in the heat as well as the cool high pressure air. When the heat is recovered, the expected *practical* efficiency of these systems is debated – though the second law of thermodynamics does not pose a ceiling on the efficiency as for heat engine – it just means that the real process has to be *less than 100% efficient*. Pragmatic estimates of the real efficiencies of this type of system are debated; most of the academic literature estimates *practical efficiencies in the range of 60-75%* [9,10]. If a plant could be constructed with no inefficiencies in any process - the theoretical efficiency would approach 100%.

2.1 Status

As no demonstration plant has ever been successfully constructed, Adiabatic CAES must be considered as an unproven technology. It does however have significant promise for use with renewables integration, energy management, peak shaving and grid reserves. The largest planned demonstration ACAES facility is a 290 MW adiabatic CAES project based in Germany called project ADELE [11]. It is a consortium between German utilities RWE and GE, the German Aerospace Center DLR, construction company Zublin, the Fraunhofer IOSB and the Unversity of Magdeburg.

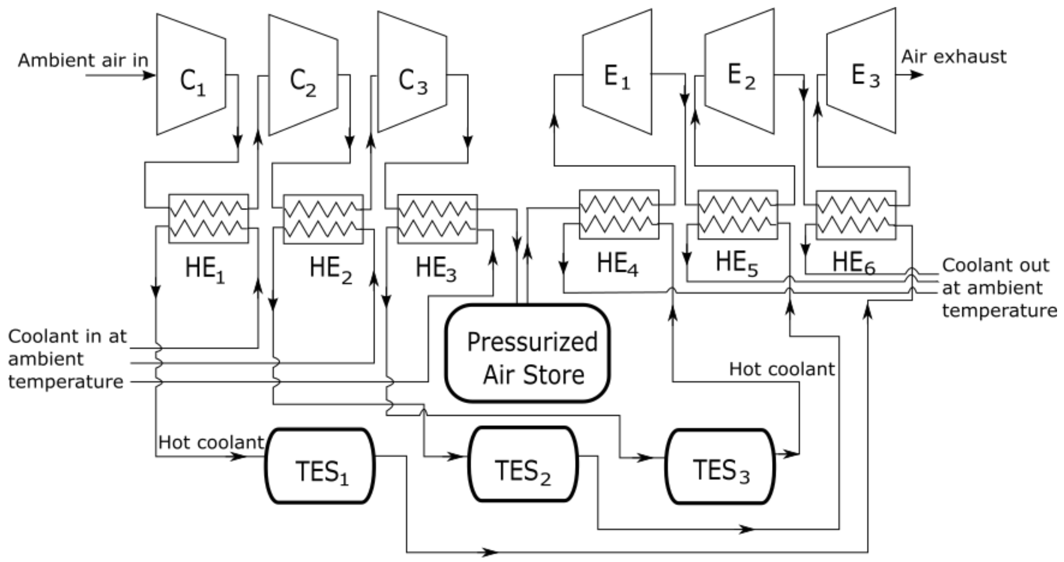

Figure 3: A simple schematic of an ACAES configuration. There is a thermal store for each compression stage.

A schematic diagram of an ACAES system is shown Figure 3. In this configuration, air is compressed and then cooled using counter-current heat exchangers that transfer the heat from the air into a thermal fluid. This thermal fluid could then be stored in an insulated tank and used to reheat the air prior to each expansion stage. Several people have also suggested the use of Packed Bed regenerators to store the compression heat in the air.

2.2 Underwater CAES

Underwater CAES is a sub-type of ACAES which exploits an underwater Compressed Air Store at a *depth of typically around 400m*. The ambient pressure at this depth is approximately 40 times the atmospheric pressure, and the air store is either a flexible bag or a dome structure open at the bottom. As air is pumped into the storage container it displaces water and thus the store can operate at a constant pressure. This idea was pioneered by Prof Seamus Garvey and Dr Andrew Pimm at the University of Nottingham, as well as by researchers at the University of Windsor Ontario and Canadian startup Hydrostor (whose work is ongoing at the time of writing).

2.3 Fuelless CAES

The usage of the term "adiabatic CAES" is also somewhat ambiguous, as the term "adiabatic" is sometimes used to refer to the compressions and sometimes to refer to the overall process - *i.e.* the energy storage process aims to be adiabatic in the sense that ideally, it would exchange negligible heat with the surroundings. Therefore some authors therefore prefer the use of the *umbrella term* Fuelless CAES. This then clearly encompasses all compressed air processes which aim to store and return energy without the use of fossil fuels. This includes systems which have typically been labelled as isothermal CAES.

2.4 Isothermal CAES

In isothermal CAES the compressions aim to be ***isothermal and reversible***. This is theoretically achieved by minimising the temperature differences which drive heat flow from the compressors to the environment (which is at a lower temperature). A huge challenge here is to make an isothermal compression process which operates sufficiently quickly to be of practical industrial importance but which is still slow enough to maintain the *small temperature differences* required for high reversibility. One idea for near-isothermal compression which has been suggested by LightSail (a start-up company in California) involves a water spray into the compression chamber of a specially designed reciprocating compressor/expander unit (see Figure 4). The water droplets absorb the heat of compression and their high specific heat capacity causes the temperature increase in the compression chamber to be much smaller. This warm water is then stored and on discharge is re-injected as a mist into the reciprocating machine which now acts as an expander.

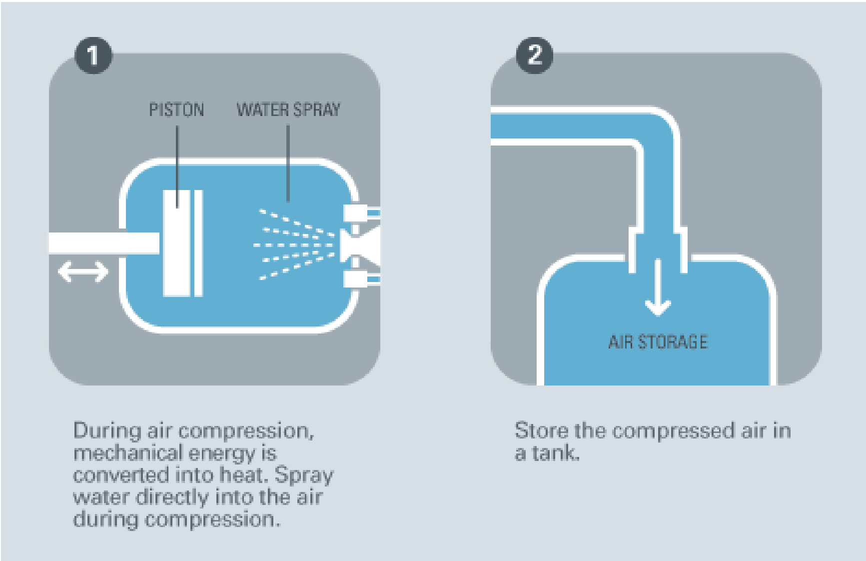

Figure 4: Illustrating a near-isothermal CAES concept [12]

Isothermal CAES was also being pioneered by SustainX, however this company has ceased operations citing spiralling system costs. Lightsail Energy and SustainX had a similar goal of an efficiency above 60% for their first generation of machines and believe that 75% is achievable in the long term. The SustainX prototype was a 1.5 MW machine.

2.5 ACAES Challenges

There are several challenges which must be overcome before adiabatic CAES can become a viable energy storage technology option.

- ***Specialised compressor equipment*** must be developed, in which the heat generated during the compression procedure is stored in a highly reversible manner. This process seems most likely to consist of a series of adiabatic compressions in which heat losses from the compressor to the surroundings are *minimised*. The compressors must also operate with much higher compression ratios than current compressors which do not involve cooling during the compression. Each of the compressions is then followed by a cooling stage which aims to *reversibly* extract the compression heat. Possible options for heat extraction include packed bed regenerators or counter-current indirect contact air-to-fluid heat exchangers. This type of compression equipment is fundamentally different to industrial many industrial compressors. **Why?** Because the vast majority of compressors are designed to *minimise* the work required to achieve air at a given pressure. Most industrial compressions then typically involve trying to shed as much heat as possible from the compression process - as hot air takes more work to compress. The ACAES process is fundamentally different as **reversibility** should be maximised rather than *work minimised*. In fact, *the greater the reversible work is per cubic metre of compressed air the higher the energy density of the storage system*.

- ***Specialised expansion equipment*** must also be developed. Air turbines which provide highly isentropic expansions and operate within the desired pressure ratios are required. The expansion process of an Adiabatic CAES system should aim to mirror as closely as possible the reverse compression process. Therefore it should include the same number of expansion stages and heating stages, and expansion stages must aim to minimise heat gain and return all heat reversibly during the heating stages. While these turbines do not currently exist on the industrial market, it is anticipated that their design can learn much from the current generation of gas turbines for power generation. The pressure ratios will likely be smaller than most current gas turbines. One specific advantage is that the material demands will be much less (in terms of temperature tolerance) than current gas turbines which operate with inlet temperatures up to 2200K.
- ***Sliding pressures.*** Unless the system can be operated between constant operational pressures, both the compression and expansion machinery must operate at maximum efficiency over a *range of pressure ratios*. A single constant high pressure air storage is a primary advantage of UnderWater CAES.
- ***High pressure air storage.*** Depending on the chosen method of storage high pressure, air storage tanks must be developed which have minimum cost. This has apparently been a problem area both for SustainX and LightSail, however LightSail have released statements which hint that they may have found a method of lowering the costs.
- ***highly reversible heat exchangers*** will also be required which can minimise the temperature difference between the working fluid and the thermal storage medium while introducing minimal pressure drops.

2.6 Notable experimental ACAES development

Lightsail (California) - startup. http://www.lightsail.com/

Hydrostor (Ontario) - startup. https://hydrostor.ca/

SustainX (Massachusetts) - startup (liquidated)

Project Adele (Ongoing utility/academic collaboration - big unexplained delays??)

University of Windsor - Prof. Rupp Carriveau and Dr. David Ting

University of Nottingham - Prof Seamus Garvey and Dr Andrew Pimm

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