

Comparison of CAES Technologies

When discussing adiabatic CAES, such as that proposed by Storelectric, it is important to know about the different types of CAES – essentially, Traditional, Isothermal and Adiabatic, and variants on these. They are very different in nature, and in particular adiabatic CAES is frequently confused with isothermal CAES such as that proposed by Lightsail, SustainX and General Compression. In fact, the two are fundamentally different.

Note that all efficiencies are cited grid-to-grid and lifetime, unlike batteries which normally quote terminal-to-terminal [ignoring ancillary loads] and day 1 [ignoring degradation]. Note too that batteries tend to quote costs for the installation without land, grid connections, development costs etc. which are all included in all Storelectric's estimates makes.

CAES

Compressed Air Energy Storage (CAES) uses excess or cheap energy (e.g. from an electricity grid, or from renewable generation) to compress air to high pressure – 70bar is typical. When the energy is needed again, the air is released to power (or help power) a turbine which regenerates the electricity. Because compressed air is not very energy-dense, it needs large volumes and therefore geological storage is used; existing CAES uses salt caverns, which are well-known technology currently used for large amounts of storage of natural gas and other hydrocarbons, hazardous waste etc. Although almost 1/3 of Europe's natural gas stocks are in salt caverns, there has never been a collapse of such caverns. Salt caverns are man-made within salt basins, which can be found world-wide.

Traditional CAES

When compressing air to 70bar, it heats up to ~650°C. But air cannot be stored in salt caverns above ~42°C, or the cavern will deteriorate. So traditional CAES wastes the heat of compression in a cooling tower. However expansion from 70bar at roughly ambient temperature cools down the air to ~-150°C. This would freeze not only the environment but also the equipment, destroying it, so the heat needs to be put back in. Traditional CAES puts in the heat of expansion by burning gas. The method used by both Huntorf and McIntosh is to feed the compressed air into a gas turbine, thereby making the turbine more fuel efficient. But it still burns 50-60% of the gas of an equivalent sized power station (for McIntosh; Huntorf is 60-70%), and its round trip efficiency (all energy out:in) is, at best, 50% (Huntorf 42%) though more modern equipment aspires to ~54%. Because the expansion is through specially modified turbines, traditional CAES is only available in fixed sizes.

Storelectric's CCGT CAES is traditional ("CCGT" because it's based on the design of a Combined Cycle Power Station), but with benefits:

1. 60% efficient;
2. Retro-fittable to existing power stations (other versions are new build only), saving substantial capex by re-use of existing plant and buildings;
3. Any turbine frame size (other versions need specially approved / accredited frames, usually of one size only)

Traditional CAES with Hydrogen

Some turbines can be fired using 80-100% hydrogen rather than all methane. To this extent they have the potential to have reduced or zero emissions. Storelectric's CCGT CAES is dual-fuel and can operate on 100% methane, 100% hydrogen or any mix between the two.

This runs into the issue of where the hydrogen comes from. The only currently-available source at suitable scale is “black hydrogen” made from Steam Methane Reforming (SMR), i.e. cracking methane into hydrogen. However carbon dioxide is a natural by-product of the reaction: $\text{CH}_4 + \text{O}_2 = 2\text{H}_2 + \text{CO}_2$. 85-90% of this can be captured expensively (“brown hydrogen”), while imposing inefficiencies on the reformation process: the higher the percentage captured, the higher the penalties of capital and revenue costs and inefficiency.

The alternative is electrolysis (“green hydrogen”), the majority of which is currently done by Proton Exchange Membrane (PEM) systems which are naturally small-scale; membranes are expensive consumables; green hydrogen is 2-3 times dearer than black hydrogen. About half the energy of electrolysis goes into the oxygen which is expelled. But there is potential to develop non-membrane technologies to suitable scales, efficiencies and cost thresholds – therefore this is a promising technology for the future. It is to be noted that using such hydrogen in CAES is potentially commercially beneficial as it uses its combustion as a catalyst for storage; making hydrogen to burn directly in power stations will never be more than 40% round trip efficiency and much dearer (both capital and revenue costs) than CAES.

Isothermal CAES

Isothermal CAES (Lightsail, SustainX, General Compression) realises that the most efficient way to compress air is at constant, low temperature. Therefore they invented novel types of compressor that extract the heat at $\sim 40^\circ\text{C}$. However this only considers half the cycle: the extracted heat is not usable within the system, so it is wasted. This leaves the same expansion problem as traditional CAES, which they claimed to solve by scavenging heat from the environment: the temperature is low enough for (for example) heat pumps or waste heat from industry to provide it. But the sheer quantity of heat required would overwhelm any such scavenging in anything other than very special locations, e.g. using waste heat from a smelter. And the novel expanders have not been perfected; and the novelty of the compressors does not maximise efficiency, cost-effectiveness or reliability.

Augwind: [Air Battery](#) is a small-scale isothermal CAES operating at $\sim 40\text{bar}$ pressure in inflatable balloons 13m long x 2.4m diameter = 255m^3 (patented) buried 4m deep. Its business case is balancing renewable generation, but its scale is multi-MW ([biggest announced](#) is 120 MWh) and its use of balloons suggests short durations: we estimate 4-8 balloons per MWh. Being isothermal, it can only scavenge heat from the environment, which also greatly limits its scale even in a hot country. Their claim to be the world’s first isothermal CAES ignores Lightsail, General Compression and SustainX.

Adiabatic CAES

Adiabatic CAES balances the heat over the whole cycle of compression and expansion, storing the heat of compression to re-use during expansion. The principles are shown in [RWE's defunct Adele proposal](#) (2'39" video) which proposes to store the heat of compression in ceramic storage riddled with capillaries to diffuse the heat through the ceramic. Bricks are ceramic. This is effectively two night-storage heaters (renowned for being unresponsive and difficult to regulate), each the size of a tower block, which would expand and contract, rubbing itself to dust (thereby clogging any channels it can enter) and crushing the capillaries, leading to very high maintenance costs and frequent long outages to re-build the storage. Building and insulating such vessels would be prohibitively expensive.

[Storelectric's](#) TES CAES (TES = Thermal Energy Storage) is a proprietary adiabatic technology that is highly efficient ($\sim 63.5\%$ at 40MW, rising to $\sim 70\%$ at 500MW), buildable with existing technologies, cost-effective and validated by numerous multinational engineering

Grid-scale electricity storage

enabling renewables to power grids affordably, reliably and resiliently



companies including Costain, Fortum, Siemens, Mitsubishi Hitachi Power Systems, Arup and Mott MacDonald. Because it uses “off-the-shelf” compressors and expanders, it is reliable and can be built at almost any size for which such compressors and expanders can be found.

Other Adiabatic CAES

Adiabatic CAES is currently being promoted by Hydrostor and AlaCAES. In summary:

Compared with...	Comparison of CAES Technologies							
	Storelectric TES CAES				Storelectric CCGT CAES			
	Efficiency (ave. life)	Capital \$/MWh	Emissions (operational)	Plant Lifetime	Efficiency (ave. life)	Capital \$/MWh	Emissions (operational)	Plant Lifetime
Huntorf CAES	*				*			*
McIntosh CAES	*				*			*
Hydrostor CAES	*				*			*
AlaCAES	**		***	*	**		***	*
Batteries	*				*			*

Storelectric is: Over 50% better Over 20% better Over 10% better Equivalent Worse

* For salt caverns. When Storelectric develops other geologies, plants will be much more widespread.

** If using existing vacant tunnels / mines; otherwise AlaCAES is much more expensive

*** Marked as equivalent, but lining susceptible to damage by earth tremors

Hydrostor: A Canadian CAES company, Hydrostor, is building a small 6MW CAES project in South Australia. They are very secretive about both technology and costs, so comparisons are difficult; we're open about costs and less secretive about technology. However, from what little they permit into the public domain ([here](#) and [here](#)) it appears that their thermal storage means is intrinsically vastly expensive in comparison with ours, and their plant sizes are also an order of magnitude smaller. For example,

- ◆ Mining is exceedingly expensive in comparison with solution mining;
- ◆ Hydrostatic pressure is typically ~55% of salt cavern pressures at the same depth;
- ◆ Open lakes in dry countries, with very high evaporation, is not a particularly good idea;
- ◆ They are not using a salt basin, which raises big questions about the hermeticity (i.e. how airtight it is) of their air stores over time - they have to line it, and linings are costly and subject to degradation over time (from the erosion due to air/water flows) and with the earth tremors that occur everywhere.
- ◆ Their thermal storage technology is (like Storelectric's) confidential, so no comment.

They have two projects in California using disused mines for air storage, which is highly risky (economic risk from air loss, not health-and-safety risk) in a very seismically active region. The [Pecho Energy Storage Center](#) in San Luis Obispo County is 400MW, 3.2Wh, at undisclosed cost. The [Kern County plant \(GEM A-CAES\)](#) is 500MW, 4GWh, and has a \$975m budget, about 1.5 times the expected cost of our first-of-a-kind large adiabatic plant, and ~2x our estimated costs for our 5th. Both projects involve large surface reservoirs in a region with longstanding water shortages and high rates of evaporation.

Reviewing [their patents](#), their “hydrostatically compensated compressed gas energy storage system” contains variable amounts of both fluid (water) and air in horizontal tunnels, kept at constant pressure by a large water-filled vertical shaft. There is an additional air pipe into the top part of the horizontal tunnel, for air injection and extraction. This is of benefit because all the air in the cavity can be used, and the top-side equipment is operating at constant air pressure. However it reduces the pressure as lithostatic pressure is ~1.8 x hydrostatic pressure (depending on the rock). Put another way, the mine has to be 1.8x deeper to achieve the same air pressure. It also prevents them using salt caverns, which are cheap to make and

naturally hermetic, confining them to mines which are seldom hermetic. It does get round the challenge of pressure-sealing mine shafts (which are of very large diameter in comparison with salt cavern boreholes), but most mines have alternative entrances which also have to be sealed, and few are airtight; moreover, seismic activity is likely to cause cracks which break hermeticity. Their design includes thermal storage, suggesting “a cascade” of stores each with different phase change materials that change phases, at different temperatures, citing 150-175, 175-200 and 200-250°C temperature ranges for the stores.

It is difficult to see how claims 1-3 of their “*Thermal Storage Apparatus*” patent has been granted, as it greatly resembles published state of the art.

Their “*variable-buoyancy assembly and non-collapsible fluid-line assembly for use with fluid-processing plant*” applies to their early prototype built in Lake Ontario. The air volumes and pressures involved are so low that both scale and efficiency will be severely compromised. Perhaps this is why the patent was withdrawn from the European phase of its application; it appears that only the Canadian patent is granted, and this has been assigned as collateral.

AlaCAES: A Swiss CAES company, AlaCAES, has built a small 1MW adiabatic CAES project in a disused transportation tunnel in Switzerland. They say that they have achieved 72% round trip efficiency, though without saying whether that is gross (terminal to terminal) or net (grid to grid) efficiency. They are very secretive about their costs, so comparisons are difficult; we're open about costs. However, from what they permit say on [their website](#) it appears that their air storage means is intrinsically vastly expensive in comparison with ours, and their plant sizes are also an order of magnitude smaller. For example,

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Liquid Piston Compression CAES: [This compresses air](#) by pumping water into a cylinder, based on the observations that (a) pumping water is cheaper and more efficient than pumping air, and (b) the heat of compression is absorbed by the water, ready for reversing the heat flow during expansion. It is promoted by Sherwood Power in the UK.

- ◆ Because air storage is in cylinders, there is no geological restriction on locations.
- ◆ It is appropriate for small scales – the research paper states “a few MW”.
- ◆ As the heat is kept to below the boiling point of water, compression ratios are no more than a factor of 2, leading to relatively low efficiencies and small MWh capacities.
- ◆ Internal designs to maximise air/water heat transfer are still subject to research.
- ◆ Because the cylinders need to contain the air at pre-compression pressures, they need to be very large in comparison with the air storage cylinders, or alternatively to be subject to numerous stages of compression.

LiGE Air Battery / Leaper Qube: [Claiming](#) to be 65% efficient, this is an isothermal CAES technology with all the relevant issues (see above). The heat is cooled via absorbers (hence at low temperature; the technology and efficiency of absorbers are unknown) stored in a “heat battery” at temperatures between -35°C and +100°C, restricting its scale to kilowatts, to be put back in during expansion – which is an adiabatic process rather than the claimed isothermal one. The low temperature of this stored heat reduces the efficiency of the heat cycle and expands the thermal storage volume required. It uses piston compressors and expanders,

limiting size. Nor is there any mention of how the air is stored: if in cylinders, then it is again intrinsically small-scale. Indeed, the picture shows equipment that may be smaller than that. The inventor envisages [a 5MW / 5MWh system](#), i.e. 1 hour duration, though also for delivering renewable energy during demand peaks; the given range is “from 200Kwh to many MWh” and therefore about three orders of magnitude smaller than Storelectric’s CAES, and is therefore targeted at domestic and commercial scale, not grid scale.

It claims to produce usable clean water (a very substantial volume of over 25,000 litres per day for a 5MWh system) that it extracts from the air. While it is true that compression and cooling will precipitate air, the amounts will vary according to climate and weather; if this is an intrinsic part of the process, then the plant’s efficiency and capability will vary greatly with climate, seasons and weather. It is [patented](#) in South Africa, pending elsewhere.

Hybrid CAES

Storelectric also (and uniquely) offers two versions of hybrid CAES:

1. CCGT CAES with thermal storage: increases overall efficiency substantially by greatly reducing gas consumption.
2. TES CAES with hydrogen: increases duration, potentially to 2-3 times as long; especially useful for providing emergency power such as for unusually challenging weather conditions (e.g. black start, or the *kalte Dunkelflaute* 2-week weather pattern in which renewable generation is very low over most of western Europe).

Liquid Air Energy Storage (LAES)

LAES is often considered a competitor to CAES, but is not. It has benefits inasmuch as it is not constrained to certain geologies. However it is intrinsically more expensive, being cryogenic equipment: at least £85m for 50MW / 250MWh (Storelectric’s TES CAES costs £50m for 40MW / 200MWh – both are costs for first plants, to diminish for later plants) to deliver a system with 60% maximum theoretical efficiency at large scale, terminal-to-terminal (Storelectric’s TES CAES is 63.5% at 40MW, rising to 70%+ at large scale, grid-to-grid i.e. including ancillary and power conversion loads). Their 350kW, 2.5MWh pilot plant achieved 9% terminal-to-terminal efficiency.

To improve this low efficiency they seek installations in conjunction with large amounts of externally supplied waste heat. But locations with such waste are few and far between, and are working on making their own systems more efficient (e.g. by recycling the heat within their process) which, over time, would reduce such waste heat.

Liquid Carbon Dioxide Storage

Liquid CO₂ storage, promoted by [Energy Dome](#), is a variant of LAES using CO₂ instead of air as its medium. While superficially attractive, CO₂ is a very hard material to handle as it alters phase irregularly, and its flow is both hard to control and highly corrosive. Leaks would be disastrous, not only for emissions but also because it would act as a cloud of asphyxiating gas about 50% heavier / denser (therefore slower to disperse) than World War 1 chlorine bombs, but (unlike chlorine) colourless, odourless and cannot be counteracted by measures as simple as breathing through a wet cloth.

The operating temperatures would be better than LAES (below -78°C rather than -196°C) but worse than Storelectric’s advanced adiabatic CAES (ambient), so its round-trip efficiency is likely to be between the two, 60% LAES and 68-70% AA-CAES; possibly 63-64%. But unlike both CAES and LAES it needs to contain its expanded gas: CAES and LAES just put the

expanded air back into the atmosphere, using the sky as the low-pressure vessel, whereas liquid CO₂ technologies will be very straitjacketed by the volume of their low-pressure vessel.

Pintail Power

Pintail Power have two technologies (liquid air and liquid salt) and hybrids of them. They (Bill Conlon, founder and President) stated verbally that their round trip efficiency (electricity out divided by all energy in) of 45-55%, and by our assessment their plant is much more expensive due to the extremely high / low temperatures involved. However they do have some advantages, principally that they are not geologically constrained for locations.

About Storelectric

Storelectric (www.storelectric.com) is developing transmission and distribution grid-scale energy storage to enable renewables to power grids reliably: the world's most cost-effective, widely implementable large-scale energy storage technology, turning locally generated renewable energy into dispatchable electricity, so...

enabling renewables to power grids cheaply, efficiently, reliably and resiliently.

- ◆ Innovative adiabatic Compressed Air Energy Storage (Green CAES) will have zero / low emissions, operate at 68-70% round trip efficiency, levelised cost significantly below that of gas-fired peaking plants, and use existing, off-the-shelf equipment.
- ◆ Hydrogen CAES technology converts & gives new economic life to gas-fired power stations, reducing emissions and adding storage revenues; hydrogen compatible.

Both technologies will operate at scales of 20MW to multi-GW and durations from 4 hours to multi-day. With the potential to store the entire continent's energy requirements for over a week, global potential is greater still. In the future, Storelectric will further develop both these and hybrid technologies, and other geologies for CAES, all of which will greatly improve storage cost, duration, efficiency and global potential.

About the Author



Mark Howitt is Chief Technical Officer, a founding director of Storelectric. He is also a United Nations expert advisor in energy transition technologies, economics, regulation and politics – [invitation here](#). Also advisor to the [IEA \(International Energy Agency\)](#) and [Renewable Energy Association](#). Regular consultee for UK government, regulator, and National Grid

A graduate in Physics with Electronics, he has 12 years' management and innovation consultancy experience worldwide. In a rail multinational, Mark transformed processes and developed 3 profitable and successful businesses: in commercialising a non-destructive technology he had innovated, in logistics (innovating services) and in equipment overhaul. In electronics manufacturing, he developed and introduced to the markets 5 product ranges and helped 2 businesses expand into new markets.

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