Comparison and Alternatives 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^{o}C. But air cannot be stored in salt caverns above ~42^{o}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^{o}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 Reformation (SMR), i.e. cracking methane into hydrogen. However carbon dioxide is a natural by-product of the reaction: $CH_4 + 0_2 = 2H_2 + CO_2$. 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 ~40ºC. 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 ~40bar 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 (~63.5% at 40MW, rising to ~70% at 500MW), buildable with existing technologies, cost-effective and validated by numerous multinational engineering 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:

Comparison of CAES Technologies										
	Storelectric TES CAES					Storelectric CCGT CAES				
Compared with…	Efficiency (ave. life)	Capital $/MWh	Emissions (operational)	Plant Lifetime	Locations	Efficiency (ave. life)	Capital $/MWh	Emissions (operational)	Plant Lifetime	Locations
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, $800m. 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,

- Mining is exceedingly expensive in comparison with solution mining;
- 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.

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 compressions 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 CO_2 storage, promoted by Energy Dome, is a variant of LAES using CO_2 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 -78ºC rather than -196ºC) 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 CO_2 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.

Alternatives to CAES

Alternatives to CAES for provision of arbitrage, balancing, ancillary, stability and other services come from power stations, pumped hydro-electric stations, batteries, Demand Side Response (DSR), interconnectors and ignorance.

	Capex nth /MW	LCOS £/MWh	Emissions	Plant Life	Lifetime deterioration	Synergies with renewables	Locations	Inertia
Storelectric								
CCGT CAES - CH_4		42.58						
CCGT CAES - H_2								
TES CAES		60.80						
Traditional CAES		89-107						
Pumped Hydro		117-152						
LAES		294						
Batteries (Lithium)		157-229						

Capex nth /MW: capital cost for the 5th plant onwards, per megawatt, >100MW, duration 4 hours
LCOS: Levelised Cost of Storage, assuming 1st large plant, 1 x 5-hr cycle / day, 350 days p.a. for Storelectric
- For the 5th plant, expected: CCGT CAES 10% cheaper capex, £39.03/MWh LCOS; TES CAES 30% cheaper capex, £45.06/MWh LCOS
- LCOS = sum of non-energy fixed and variable O&M costs + finance cost of plant, 25-year life; no consideration of efficiency
- Sources: Batteries, Lazard 5.0 (2018); LAES, University of Birmingham 2018; traditional CAES and pumped hydro, Lazard 2.0 (2016)

Power Stations
Power stations are being closed at a rapid rate, making them increasingly unable to provide these services at all. In providing these services they have high greenhouse gas emissions and substantial other pollution.

Power Stations with CCUS
Carbon Capture and Storage (CCS) and Carbon Capture and Use (CCU) (collectively, CCUS) is being proposed to make power stations emissions-free. However CCUS has a number of draw-backs, including:

- High capital and operational costs;
- Imposing a ~30% efficiency penalty on the power station;
- CO_2 transportation and storage is hazardous.

CO_2 is invisible, odourless and heavier than air, so any leak from CO_2 pipes and other transportation would asphyxiate anyone in the area. A light wind would enable this cloud to migrate to asphyxiate population areas.

CCS carries enormous additional costs of the storage / injection installation – which remain high even if reduced somewhat by re-purposing exhausted oil and gas wells, sometimes with enhanced oil recovery "benefits" (though these involve pumping out more harmful hydrocarbons). If CO_2 were to be released by an earth tremor, the same hazards as for transportation would affect shipping. CCU merely delays the emissions until the breakdown of the "usage" products; only "permanent" uses / chemical changes of the greenhouse gases are of lasting benefit.

However there will always be industrial and chemical processes that yield greenhouse gases, whose emissions need to be captured and sequestered by either storage or permanent use. Because of the costs and hazards of doing so, this is likely to lead to clusters of such industries. In those places there is scope for power stations with CCUS to piggy-back on those clusters' infrastructure.

Batteries, Including Flow Batteries
Batteries use scarce lithium, cobalt etc. which need energy-intensive and destructive mining, refining and manufacture. There is insufficient lithium in the earth's crust to back up the world's electricity systems, OR to power all the world's vehicles, even without considering usage in portable devices[1] – and there's even less cobalt or rare-earth metals. Cell life is 6-8 years, with their claimed optimal usage case (fast-charging and -discharging) being exactly the way to accelerate such deterioration. By time of swap-out, they require three times as much cooling as on day 1, cooling and AC-DC-AC conversion reduce battery grid-to-grid performance by 20-30% from claimed performance which is usually quoted terminal-to-terminal. And the heart of a flow battery is two pools of concentrated acid dissolving rare metal compounds.

Demand Side Response (DSR)
DSR is the best-value means of providing for short, sudden peaks and troughs in generation and/or demand. However it is necessarily limited in both volume (to a fraction of what is controllable) and duration. The volume limitation was evaluated in 2015 by National Grid as 5% of peak demand[2] excluding DSR from future vehicle-to-

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[1] https://www.economist.com/news/briefing/21726069-no-need-subsidies-higher-volumes-and-betterchemistry-
are-causing-costs-plummet-after -

Electric Vehicles, 2016		25 GWh	750,000 vehicles
Mid-range:	2040 Bloomberg	15,500 GWh	465,000,000 vehicles
	2040 OPEC	5,000 GWh	150,000,000 vehicles
	2040 ExxonMobil	3,000 GWh	90,000,000 vehicles

Total lithium mined, 2016		180,000 tonnes in one year
	2040 Bloomberg	111,600,000 tonnes in one year, just for vehicles
	2040 OPEC	36,000,000 tonnes in one year, just for vehicles
	2040 ExxonMobil	21,600,000 tonnes in one year, just for vehicles

Total available lithium in planet 210,000,000 tonnes
Years' output: 2040 Bloomberg 1.9 years, just for vehicles

[2] http://fes.nationalgrid.com/media/1295/2015-fes.pdf See figure 46 p94 (Acrobat p96)

grid (V2G) availability. But DSR cannot be called upon more than once in a period, so the maximum volume available needs to be divided by the number of occasions on which it may be called during the period. For example, refrigerators can be turned off for no more than 15 minutes during an evening peak; 5 “calls” during that peak mean that the total MW volume of refrigerators need to be divided by 5 to determine how much is available for any specific call.

Duration of batteries is optimally 20-60 minutes; for DSR 15-30 minutes: after sunset on a windless winter evening, how is the peak and overnight demand powered after these are exhausted by 6pm? Or if adverse weather patterns extend such periods for days or even weeks? In Western Europe, the worst-case scenario for this is a fortnight’s weather pattern called (in German) the *kalte dunkel Flaute* (cold dark doldrums) which settles over most of the continent for up to a fortnight, on average every couple of years; narrowing the geographical remit to a few countries and/or the timescale to few days, such patterns are frequent.

Vehicle to Grid Storage (V2G)
V2G is supposed to be the “magic bullet” that balances the grid, operating as a mix of battery storage and DSR: the charging of batteries can be displaced to low-demand and/or high-generation periods, while the energy stored in the batteries can also be called upon to support the grid. But vehicles demand about the same energy as the entire electricity grid. Electric vehicles are estimated to be about 5x more efficient at using energy, which reduces available battery capacity to 20% of grid demand. On average, EV batteries will only be half-charged; indeed, as they’ll mostly be called upon at the end of a day’s use, one can only expect them to be quarter-charged on average, reducing battery capacity to 5% of grid demand. And people won’t be happy if their batteries are flat in case they wish/need to pop out in their vehicle, so at least half that charge needs to remain, reducing effective capacity to 2.5% of grid demand. And that assumes that all vehicles will be battery powered, no hydrogen-powered fuel cells: the global shortage of lithium means that no more than one-third of vehicles will be battery powered, and these will be of smaller size and shorter range than the fuel cell vehicles, so the effective capacity is 0.5% of grid demand. No magic bullet.

Thermal Storage
Thermal storage is good for storing heat for re-use as heat. When storing electricity for use as heat, it has some potential, but begs the question: why would use electricity (high-grade energy) to create heat (lowest-possible-grade energy) directly? Because of the high-grade nature of electricity it can be used in other processes such as heat pumps which are much more efficient, though they provide no storage.

But storing energy thermally to regenerate directly into electricity is a hugely inefficient process its theoretical maximum efficiency in the thirties percent. Moreover, proposals to do so in concrete (e.g. Energy Nest and molten salt methods including the developmental “binary molten salt” improvement) claim environmental efficiency while ignoring that the creation of cement to form that concrete is one of the most environmentally damaging processes of all: not only is a huge amount of heat (from what sources?) required to turn limestone into lime, but that process is in its very nature the chemical extraction of carbon dioxide from calcium carbonate: what then happens to this CO_2? Moreover, concrete (and ceramic, i.e. bricks) suffers a number of problems, including:

- Lack of controllability: difficult to get heat in and out on demand, so ramp rates are slow, giving it some potential for baseload but making it unsuitable for balancing actions or demand following;
- Expansion and contraction: the storage will create cracks and rub against adjacent blocks (and against the medium for carrying the heat in and out, whether they be capillary tubing or iron bars), so destroying the plant and making containment costly;
- Low specific heat capacity (for concrete and ceramics; salt is better), thereby requiring huge volumes of storage per unit of energy stored;
- Low thermal conductivity, leading not only to the lack of controllability above but also to inefficiencies and slow cycle times in absorbing and re-emitting the heat;
- High temperature requirements for electricity generation, meaning that a large amount of waste “cushion” energy needs to be input to get the system up to operational temperatures;
- For molten salt, further issues include –
  - The inability to let it cool below its melting point, owing to the difficulties (including of low thermal conductivity) of re-melting it),
  - Its corrosiveness of the plant itself, and
  - The high cost of plant to take temperatures suited to molten salt – justifiable for Concentrated Solar Power [CSP] due to the savings in using mirrors rather than photovoltaic cells, but not as easily justifiable in other contexts.
- Therefore their claimed “low energy losses” and “low carbon footprint” apply to the heat stored, not to the total process and system.

Pumped Hydro

Pumped hydro is exceedingly expensive (over 3x the capital cost of adiabatic CAES), remote from both supply and demand (requiring huge transmission lines) and flood two valleys. The number of acceptable potential locations that have not yet been used is very low, especially in the developed world. And hot countries have too-high evaporation and often too little water for pumped hydro to be practical.

Interconnectors

Interconnectors are the standard fall-back position of most grids, on the rash assumption that if renewables aren’t generating “here”, they are “there”. But the sun sets on half the world at a time, stopping all solar generation overnight. Weather patterns last for hours to weeks, often affecting all neighbouring grids, so the neighbours have no surplus to export – the French and Germans cite a regular weather pattern called the *kalte Dunkelflaute* (Cold Dark Doldrums)[3]. Therefore interconnectors cannot be relied upon, unless reliable storage of sufficient scale is contracted with at the other end, for example Germany or Denmark contracting exclusive use of Norwegian pumped hydro – which is not itself unlimited.

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[3] https://www.dw.com/en/what-happens-with-german-renewables-in-the-dead-of-winter/a-37462540

Ignorance

Ignorance is the final “alternative”. This is a blithe reliance on “the markets” to ensure that sufficient energy and other services are available. It is this that powered the development of overt subsidies such as the Capacity Market in the UK (£1bn p.a. by 2017 without catalysing the construction of a single new power station) and covert subsidies such as the tremendous growth in total balancing and ancillary services in the UK (also £1bn p.a. by 2017 as compared with delivering very similar amounts of energy in 2010, without enhancing the energy supply), not to mention the hidden subsidies such as the under-pricing of pollution (carbon prices are nowhere near the $177-805/tonne (most likely $417) estimated cost of the total harm of emissions[4]). Thus ignorance adds enormously to costs while failing to address the challenges.

[4] https://www.theguardian.com/environment/climate-consensus-97-per-cent/2018/oct/01/new-study-finds-incredibly-high-carbon-pollution-costs-especially-for-the-us-and-india citing the study https://www.nature.com/articles/s41558-018-0282-y?utm_source=Nature_community&utm_medium=Social_media_advertisingCommunity_sites&utm_content=BenJoh-Nature-MultiJournal-Social_Sciences-Global&utm_campaign=MultipleJournals_USG_SOCIAL

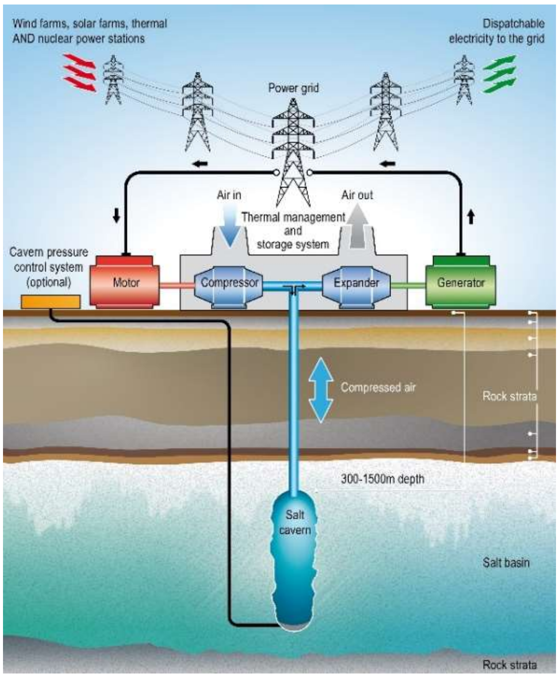
Grid-scale electricity storage
enabling renewables to power grids
affordably, reliably and resiliently

Storelectric

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 world-wide. 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.