Grid-scale electricity storage
using an innovative form of
Compressed Air Energy Storage

CAES or Batteries?

Many people have suggested that batteries are a viable way forward for grid-scale electricity storage, and some have cast doubt on whether there is a role for Compressed Air Energy Storage (CAES).

However CAES, batteries and the other storage technologies are very different technologies, for different scales, durations and duty cycles. There is a role for all of them, with each having its optimal niches. Therefore we consider them under the following headings, which are the headings of this report:

1. Power
2. Capacity
3. Response Time, Duty Cycles, Ancillary Services

There are also additional considerations, such as:

4. Cost, Efficiency and Lifetime
5. Environmental Considerations
6. Cost and Performance Summary
7. Global Potential
8. Other Analysts' Views

The final section looks at the quantity of storage required, and how the different technologies fit together.

Power

Energy storage is required at a number of different scales. We divide them into five bands, as follows:

Scale	Power	Technologies Best Suited
Domestic	<100 kW	Batteries, supercapacitors, flywheels
Local	<1 MW	Batteries, supercapacitors, flywheels, cryogenic
Area	<10 MW	Cryogenic, heat, large batteries, flow batteries, CAES
Regional	<100 MW	CAES, pumped hydro, poss. heat
Grid	>100 MW	CAES, pumped hydro, future hydrogen

The largest battery currently installed anywhere (or, to our knowledge, planned anywhere) is 65MW. These are used to alleviate local and domestic line capacity constraints, and to provide a small amount of time-shifting of energy, i.e. making it available at a time other than when it was generated.

It is possible to increase batteries' rated power cheaply, though this would entail reducing their capacity (duration of output at full power) proportionately. Thus a 20MWh battery could produce 10MW for 2 hours or 40MW for 30 minutes, assuming that the electrical circuits and signal conditioning can take it.

Although there have been start-ups offering small-scale CAES, Storelectric and most other CAES companies believe that it is best suited to large-scale applications, of 100MW or more. Storelectric offers efficient solutions rated above 100MW, with the potential for smaller ratings either in the future or with decreasing efficiency and cost-effectiveness. Power is determined by the design, specification and cost of all the surface systems, and is therefore the main driver behind the cost of a CAES plant – though the cost per MW of power decreases rapidly as size increases. A good rule of thumb is that whereas batteries increase in cost by ~85% when doubling either their power rating (at constant duration) or their duration, Storelectric's CAES increases by ~1/3.

Capacity

Energy storage is required at a number of different scales, which we define thus:

Scale	Capacity	Technologies Best Suited
Domestic	<250 kWh	Batteries, supercapacitors, flywheels
Local	<5 MWh	Batteries, supercapacitors, cryogenic
Area	<50 MWh	Cryogenic, heat, large batteries, flow batteries, CAES
Regional	<500 MWh	CAES, pumped hydro, poss. heat
Grid	>500 MWh	CAES, pumped hydro, future hydrogen

All grid-connected batteries to date have had a storage capacity of between 1 and 2 hours' output at full rated power. Therefore they are best suited to application that require such durations of output, or (better) less: if less, then they can produce output on multiple occasions between charges.

Doubling the capacity of a grid-connected battery costs at least 80% of the original cost, as twice the number of batteries is needed, and other system elements (such as air conditioning) need to be (approximately) doubled. Capacity is the main cost driver for batteries.

The total output of Tesla's Gigafactory (under construction) is 35GWh p.a. by 2020. A single CAES plant could have this capacity.

Although there have been start-ups offering CAES storing energy in cylinders, Storelectric believes that such technologies are unlikely to be cost-effective in the near future. Geological storage is much larger scale and cheaper.

Storelectric can store its air in salt caverns now. Salt caverns are solution mined, a slow but relatively cheap process, depending on geology and geography: the geology must offer salt and mudstone strata sufficiently deep, and the geography must offer a source of water, and a destination (either industry or the sea) for brine. With these caveats, the cost of capacity is ~$6/kWh, or $6m/GWh, to use the same surface equipment.

Notably, there are salt basins across the world; in Europe there are sufficient to store a week's worth of the continent's total energy demand; similar amounts could also be stored in North America, North Africa, the Middle East and elsewhere.

In future it will be able to store air in six other geologies, which would open up virtually the entire plant to CAES. Most of these are in porous rock (e.g. aquifers, depleted hydrocarbon wells) and therefore offer much larger scale storage, much more cheaply.

Response Time, Duty Cycles, Ancillary Services

Response Time

Batteries have a very rapid response time: they can usually be operational and synchronised with the grid within a second. They can also remain on standby with low energy consumption. Only supercapacitors and flywheels are faster, and these have much lower capacity (duration). The "virtual storage" derived from Demand Side Response can also match it, provided permission is not required before use.

CAES and Pumped Hydro are rather slower. They can respond with 30 seconds, though a smaller plant (of either type) optimised for speed of response could respond within 10 seconds if kept spinning and synchronised: CAES would do this using the generator (without load) as a motor, and therefore consuming little power.

Duty Cycles

Batteries are best suited to duty cycles that last from minutes to half an hour or more, repeating in order to provide levelling for intermittent generation, and to satisfy demand spikes without burdening the remainder of the grid.

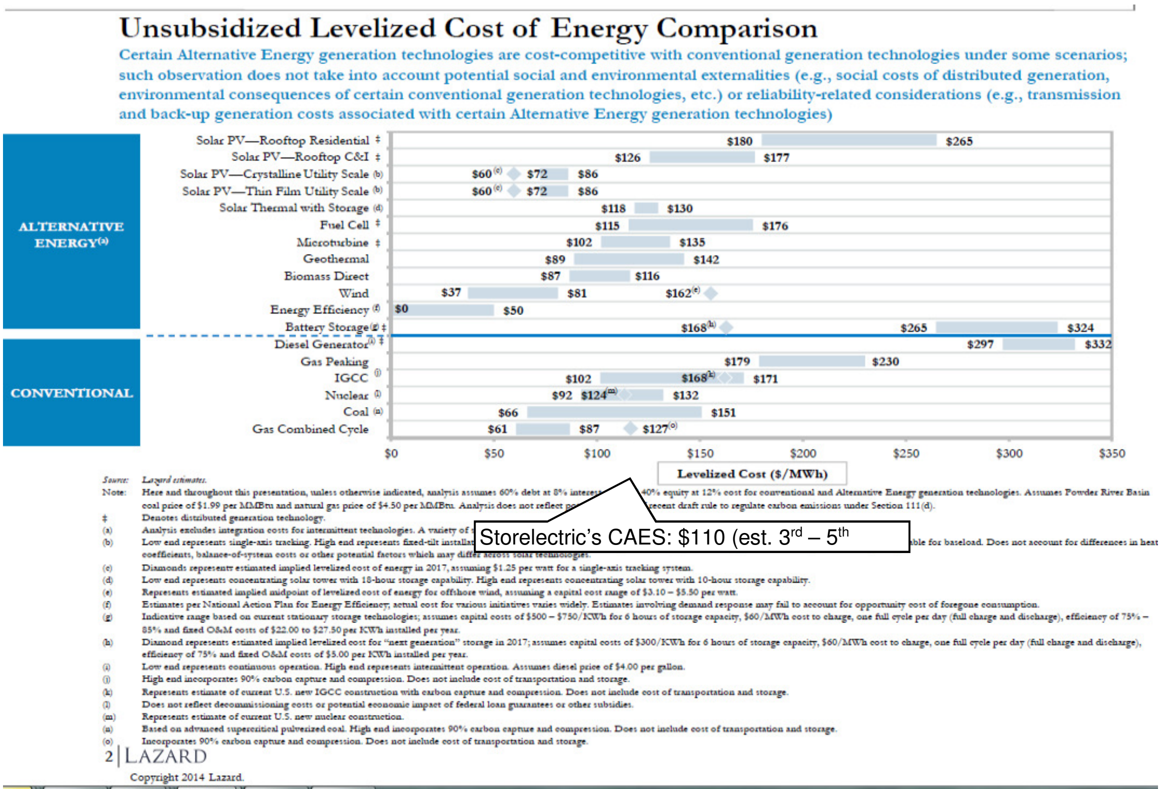
CAES is best suited to duty cycles from minutes to entire peak periods or even days, though can be optimised for quicker response times. This provides (with zero or very low emissions) the system back-up and resilience that is currently being provided by gas-fired peaking plants at great cost and with substantial emissions.

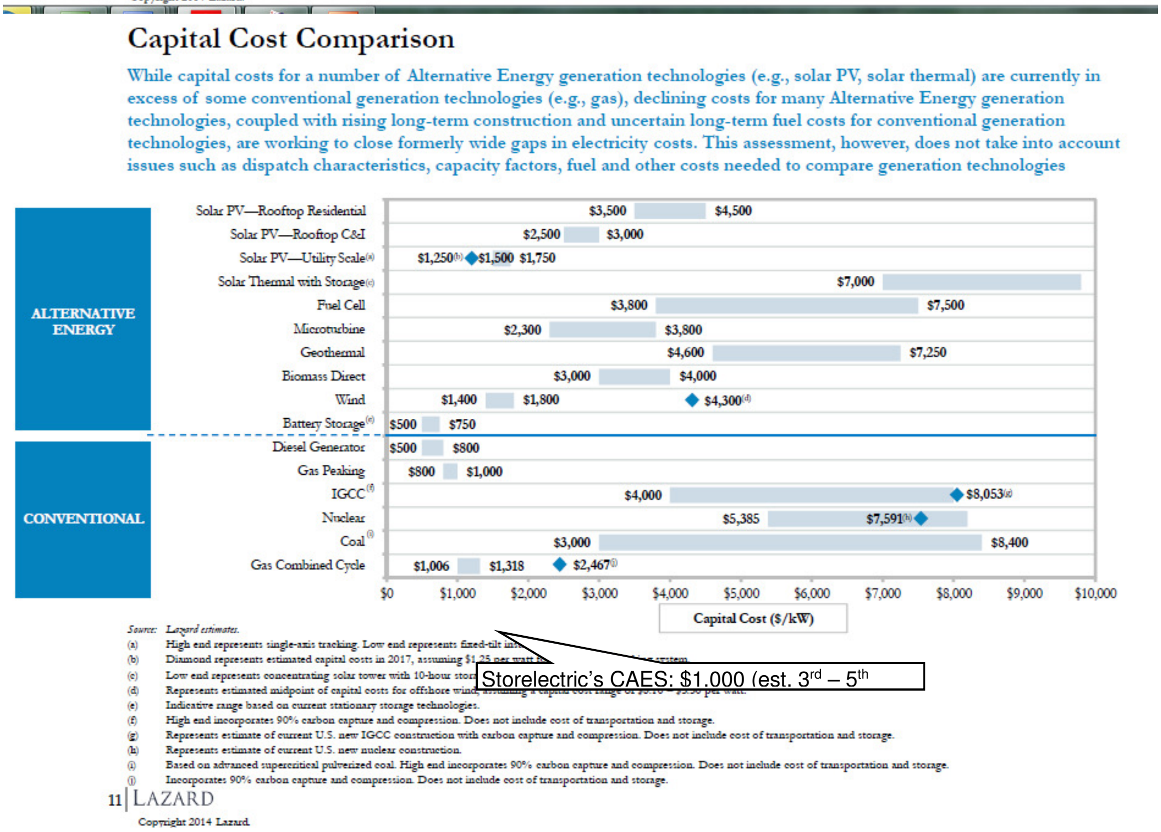
Other Ancillary Services

CAES, Pumped Hydro and flywheels offer another valuable service that batteries and supercapacitors cannot: inertia to increase loss-of-infeed tolerance and short circuit level. This is the immediate inertial response of a system to rapid faults, which grid operators value very highly. Indeed, if they deem there to be insufficient inertia on the system (for example, excessive proportions of power coming from non-synchronous sources such as wind turbines, solar panels and interconnectors), they will invest millions to build plants solely to provide inertia. They also offer reactive load, and can help suppress voltage dips and harmonics.

Cost, Efficiency and Lifetime

Cost





According to Lazards' analysis (www.lazard.com/insights), comparing the costs of various power sources in America (where planning, construction, gas and coal prices are all cheap), CAES is much cheaper per MWh of power than batteries. Indeed, Storelectric's CAES is cheaper than an equivalent sized gas-fired peaking plant (OCGT), based on a plant generating 500MW and a capacity of 6-21GWh.

Note that there is no comparison of storage capacity. For batteries, a storage capacity of 1-2 hours' duration at peak load is assumed. The figures for CAES are for between 12 and 42 hours' duration.

Efficiency

CAES has various quoted levels of efficiency. Storelectric's is much better:

- Huntorf (traditional OCGT-based CAES): 42%
- McIntosh (traditional CCGT-based CAES): 54%
- Dresser Rand's SmartCAES (an evolution of McIntosh): up to 60%
- Storelectric, with thermal energy storage: 68-70%

Battery advocates often quote efficiencies of 85%-97%, but these are battery-only performances with small-scale installations. Large installations require huge parasitic / ancillary loads, especially air conditioning. Northern Power Grid's Customer-Led Network Revolution, which concluded in December 2014, measured the actual round trip efficiency of battery systems at the beginning of their life[1]:

	2.5kVA, 5MWh	**100kVA, 200kWh**	**50kVA, 100kWh**
Cost excl. installation	£3.76m	£406k	£331k
£/MWh	*£752k*	*£2,030k*	*£3,310k*
Cost inc. Installation	£4.62m	£490k	£422k
£/MWh	*£924k*	*£2,450k*	*£4,110k*
Nominal efficiency	83.2%	86.4%	83.6%
Measured efficiency	69.0%	56.3%	41.2%
Average parasitic load	29.5 kW	29.5 kW	29.5 kW

In a recent public presentation, a senior manager of Belectric stated "it is well known that" a 5-year-old grid connected battery requires three times as much air conditioning load as an otherwise identical 1-year-old installation, due to the rate of deterioration of the battery. However there is little literature on this because the rate of deterioration depends on the temperatures and duty (load) cycles to which a battery is subjected.

The Danish Technical Institute's Forskel project (2016)[2] also analysed actual battery performance. The Executive Summary:

> "Generally, the batteries themselves have efficiencies above 95%, but auxiliary systems and losses in inverters and transformers can reduce the overall system efficiency to below 50% in low load operation."

[1] http://www.networkrevolution.co.uk/project-library/electrical-energy-storage-cost-analysis/ table p6

[2] https://www.energiforskning.dk/sites/energiteknologi.dk/files/slutrapporter/bess_final_report_forskel_10731.pdf

In 5.2.5 (p36), the table shows the difference in efficiency η between battery efficiency (right-hand column) and system efficiency (middle column):

	Delivered energy [kWh]	Consumed energy [kWh]	η System [%]	η Ex. Aux. [%]	η Battery [%]
Peak (1/3 C)	53,3	66,3	80,3	85,3	98,2
Init. cycles 1/3C	54,2	95,6	56,8	66,5	93,9
Accelerated Avg. Day	201,9	263,6	76,3	82,6	96,3
Avg. Day	34,3	75,9	45,2	56,4	95,9

There is no comment about the additional cooling requirements or cell efficiency reduction of batteries (or of the compounding of these two factors) as they degrade; however Belectric informed the author verbally that the cooling requirements for an end-of-life (i.e. 80% capacity) battery are three times that on day one. This is because the reduction in capacity is mirrored by efficiency losses, which manifest themselves as additional heat output.

Cost and Performance Summary

The various technologies can be summarised (excluding durations) as follows:

		Size (up to)				Grid Support				Efficiency	LCOE	Capex	
Technology	**Type**	10 MW	100 MW	1 GW	>1 GW	FFR	FR	SU	LT	%	$ /MWh	$k /kW	$ /kWh
Storelectric	CAES									68-70	100	1	116
Dresser Rand[1]	CAES									54 [1]	125	4.7	586
Pumped Hydro	PHES									75-82	185	5.8	725
Highview	Cryogenic									65?	210	1.36	340
Li-ion	Battery									41-75	125	6	5454
Va Redox[2]	Flow Batt.									60-70	460	6.5	1300
Flywheels	Flywheels						3			85-95	380	4.2	1700

Notes
1. Dresser Rand has 50-60% of the natural gas burn (and emissions) of an equivalent sized CCGT
2. Vanadium Redox flow battery
3. Flywheels' normal duration is 5-15 mins

Key: Grid Support
FFR Fast frequency response
FR Frequency Response
SU Start-up (e.g. back-up to wind)
LT Long term (weekly or more)

Data sources for costs:
Storelectric Storelectric Ltd, based on a 500MW, 6GWh plant after the first 3-5 plants when capex costs will have stabilised
Dresser Rand DoE (American Department of Energy) www.sandia.gov/ess/publications/SAND2013-5131.pdf Brayton installations
Highview Highview Power Cost Estimator, http://www.highview-power.com/market/#calc-jumper using their default values (100MW, 4 hours, standalone system). Levelised cost from http://cleanhorizon.com/images/slides/20140916_CleanHorizon_white_paper_3.pdf
Pumped Hydro DoE (American Department of Energy) www.sandia.gov/ess/publications/SAND2013-5131.pdf
Lithium Ion Costs: DoE (American Department of Energy) www.sandia.gov/ess/publications/SAND2013-5131.pdf, taking the three batteries with duration >1 hour (the remainder had durations of 0.25 hours), averaging them at $6000/kWh for a 1.1 hr battery

Lithium Ion Efficiencies: http://www.networkrevolution.co.uk/project-library/electrical-energy-storage-cost-analysis/. Best efficiency is 69% including parasitic loads (bottom of p6) for a 5MW system; the figures in the table assume that efficiencies increase with size.
Va Redox DoE (American Department of Energy) www.sandia.gov/ess/publications/SAND2013-5131.pdf
Flywheels DoE (American Department of Energy) www.sandia.gov/ess/publications/SAND2013-5131.pdf

Lifetime

Depending on the temperatures and duty (load) cycles to which a battery is subjected, the average lifetime of a grid-connected battery is usually quoted as 5-8 years, Lithium chemistries being 5 years and lead-acid 8 years.

In contrast, the lifetime of a CAES installation is expected to be 40 years for the top-side equipment (with a mid-life overhaul) and over 100 years for the caverns. Huntorf was upgraded in 2006, aged 38 years, and is still operating – at a higher capacity (321MW versus 290MW as first built) than originally.

The Danish Technical Institute's Forskel project also analysed actual battery lifetime under various conditions. 5.3.7 p43-44 states that lifetime (defined as 20% degradation of capacity) is, in cycles:

Temp	Dis rate	DoD	SoC	Lifetime
25°C	0.5C	30%	50%	5500
45°C	2C	95%	95%	330
5°C	2C	95%	95%	170
25°C	0.3C	100%	100%	990

Table 21: Calculated degradation by model with estimated lifetime measured in equivalent full cycles

C = duration in hours (strictly, capacity MWh divided by power rating MW)
DoD = Depth of Discharge
SoC = Minimum State of Charge in operation

Studying the results in Table 21 it becomes obvious that the operation conditions have a huge impact on the battery lifetime and thus the investment pay back. It demonstrates how difficult it is for the battery supplier to specify a lifetime in the datasheet as well. The manufacturer guarantees least 1000 100% cycles at 0.3C and 25℃. Simulating this test in the model results in 990 cycles as shown in the fourth row in Table 21.
Note that for daily cycling (with maintenance periods) 360 discharge cycles per annum would be expected. Therefore in the parameters of this table lifetime varies between half a year and 15 years.

Their conclusion that one can only discharge it very slowly and on 100% cycles to reach 1,000 (or 990) cycles = 3 years' life on daily cycles suggests that they must be treated very tenderly and used for balancing operations rather than ancillary services which tend to be briefer and faster discharges. In the bullets below the table,

- The discharge rate has much more impact on degradation than the charge rate.
- Full discharge degrades only the battery half as much as if the battery is discharges to lower DoD.

- Cycling the battery between 25% and 75% SoC degrades the battery more than, if the battery is cycled between 0% SoC and 100% SoC.

Storing batteries without use also makes them deteriorate, annex 4.2.6 p110:

Temperature: Vary
SoC 70%

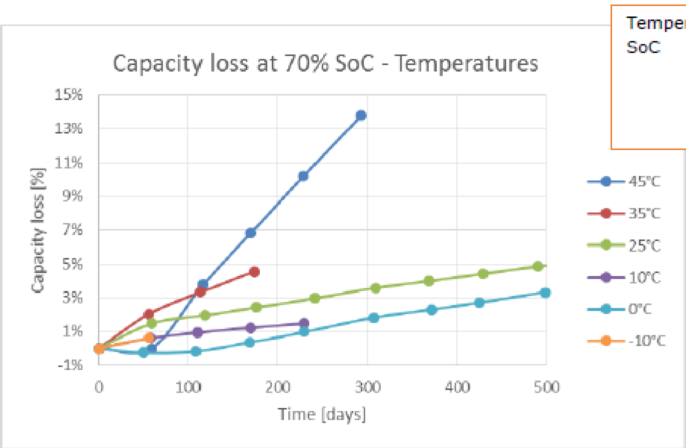


Figure 97: Capacity loss during storage at 70% SoC - different temperatures

And storing them at lower state of charge reduces losses - but does not help the standby capacity of the grid.

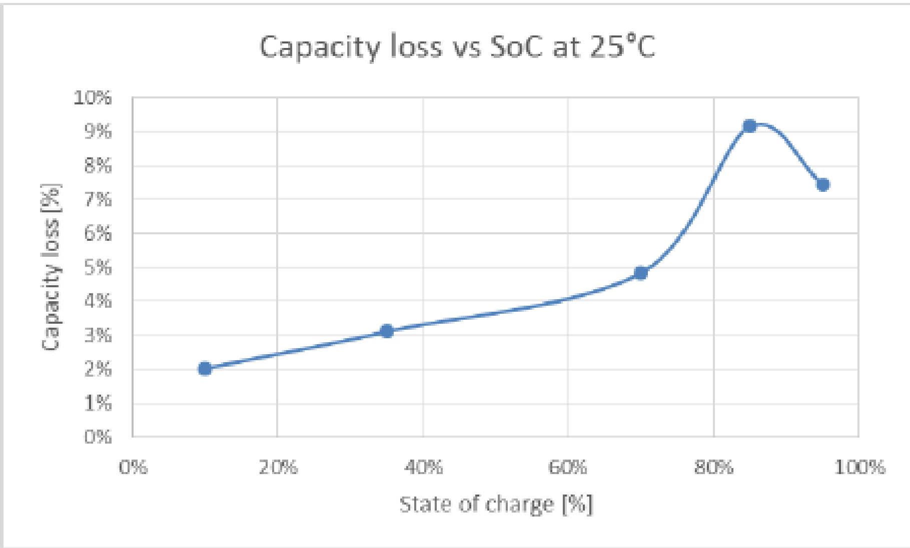


Figure 100: Capacity loss during storage versus state of charge at 25°C

Environmental Considerations

Batteries need to be mined, refined, transported, manufactured, replaced every 5-8 years, and then recycled or disposed of. They all use elements and compounds that are toxic, explosive or both, and most use raw materials of which there would be a major shortage if exploited for global grid balancing (see next section).

Pumped hydro-electric schemes flood two valleys (unless using the sea, a lake or a river as the lower reservoir, an unusual set-up), are usually remote from major generation and consumption (hence require very long transmission lines, with their losses and visual blight) and are open to large-scale evaporation (and are therefore not suited to hot climates). They also require a very special topography, which is not common – and even less so if one excludes areas of outstanding natural beauty or environmental importance.

Storelectric stores its power underground, invisibly. Its surface footprint is comparable with a gas-fired power station of equivalent size, and its subterranean footprint is of the order of a square kilometre per plant. The caverns are so deep that many activities (especially farming) can continue above them. The pressure at which the air is stored is determined by the weight of the rock above, which is therefore not in tension but is being kept in balance by the air pressure within. And air is benign, almost completely safe to store and to use, unlike the natural gas that is currently stored in these same geologies at the same pressures.

Global Potential

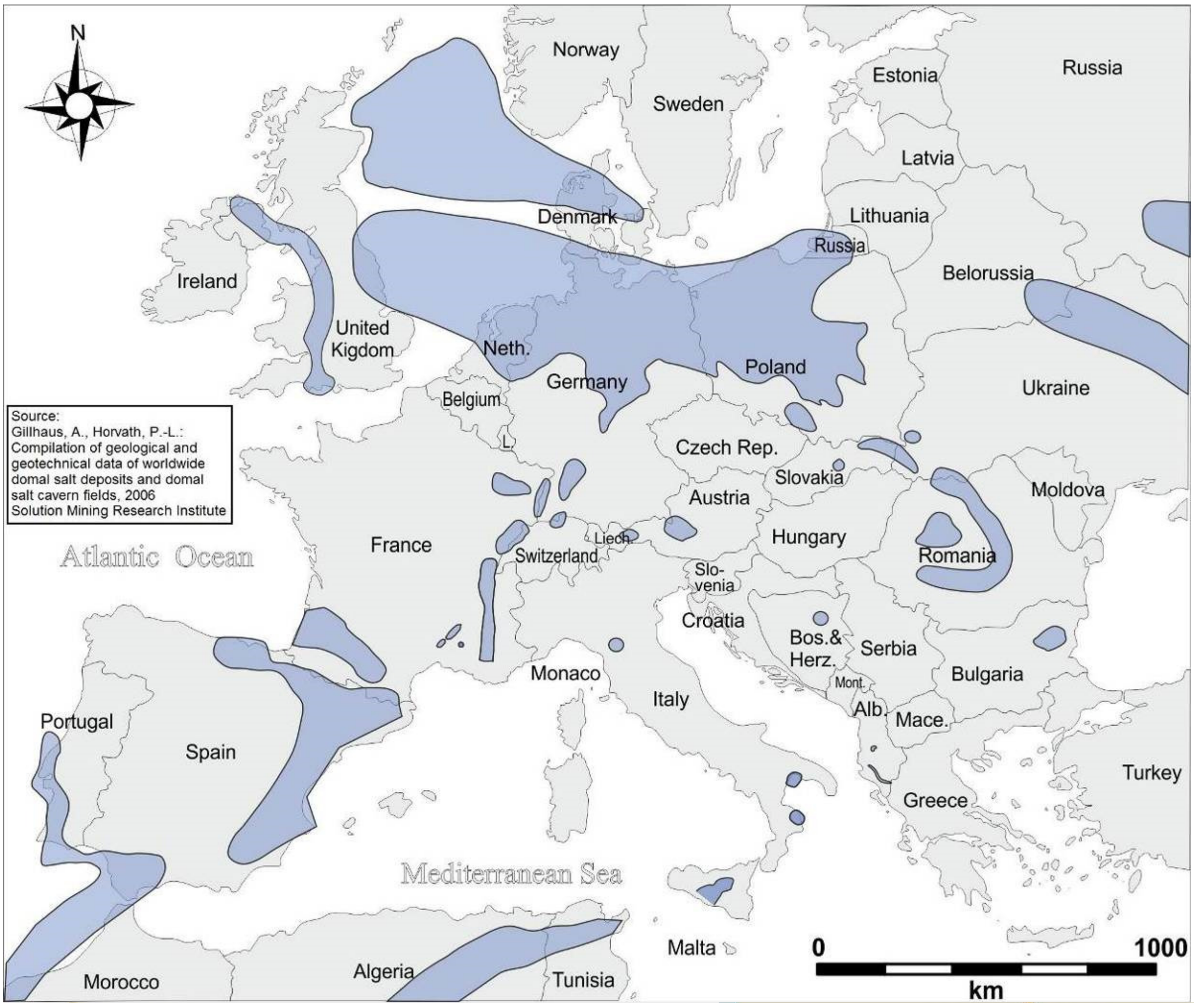
According to the late David Mackay's book "Sustainable Energy – Without the Hot Air"[3] (David was Chief Scientific Officer for the British Government's Department of Energy and Climate Change), there is enough lithium in the ground (excluding the very low-grade stocks in the sea) globally to power either the world's cars or the world's grids – and that's without the world's portable devices. And this assumes that:

1. We use lithium twice as efficiently as today, per MWh of storage;
2. We can extract it all cost-effectively;
3. There are no other uses for Lithium;
4. Every battery lasts forever, whereas their true life is 5 years;
5. No battery is ever wasted or destroyed, anywhere;
6. Only today's number of vehicle-miles are driven, and only today's amounts of electricity are consumed, which disadvantages developing countries as well as preventing the electrification of heating (e.g. by heat pumps), industry and transportation;
7. We ignore the scarcity of the other elements (manganese, cobalt, nickel, and alloying metals) that form an essential part of a modern lithium battery.

Clearly none of these assumptions is remotely sustainable, except the first which may be achievable in 10-20 years. The only reason why lithium prices are dropping is because extraction technologies are still improving faster than demand: if demand were to grow to such global levels, scarcity pricing would soon start.

In contrast, salt basins alone offer enormous potential for CAES:

[3] http://www.withouthotair.com/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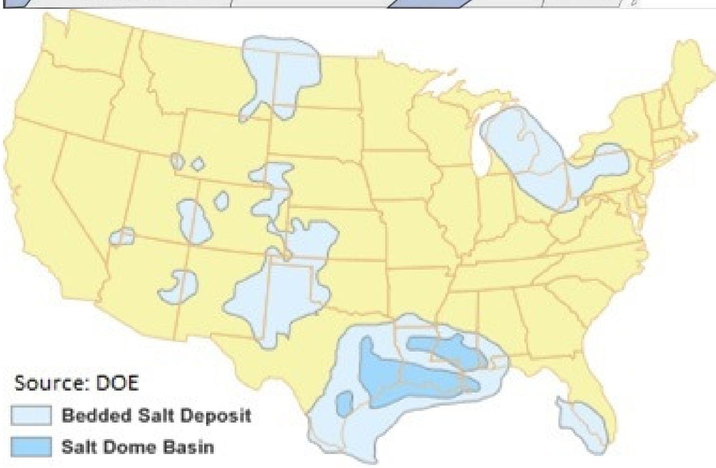
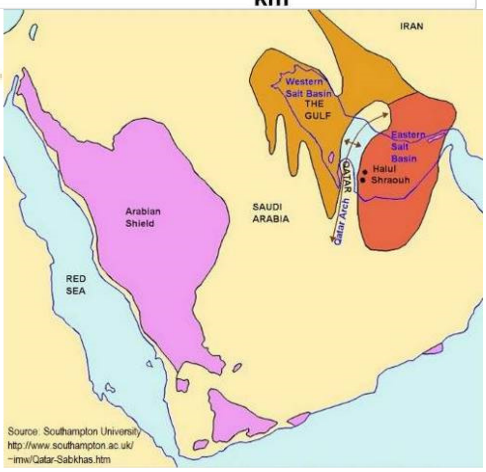
Source:
Gillhaus, A., Horvath, P.-L.:
Compilation of geological and
geotechnical data of worldwide
domal salt deposits and domal
salt cavern fields, 2006
Solution Mining Research Institute


Source: DOE
Bedded Salt Deposit
Salt Dome Basin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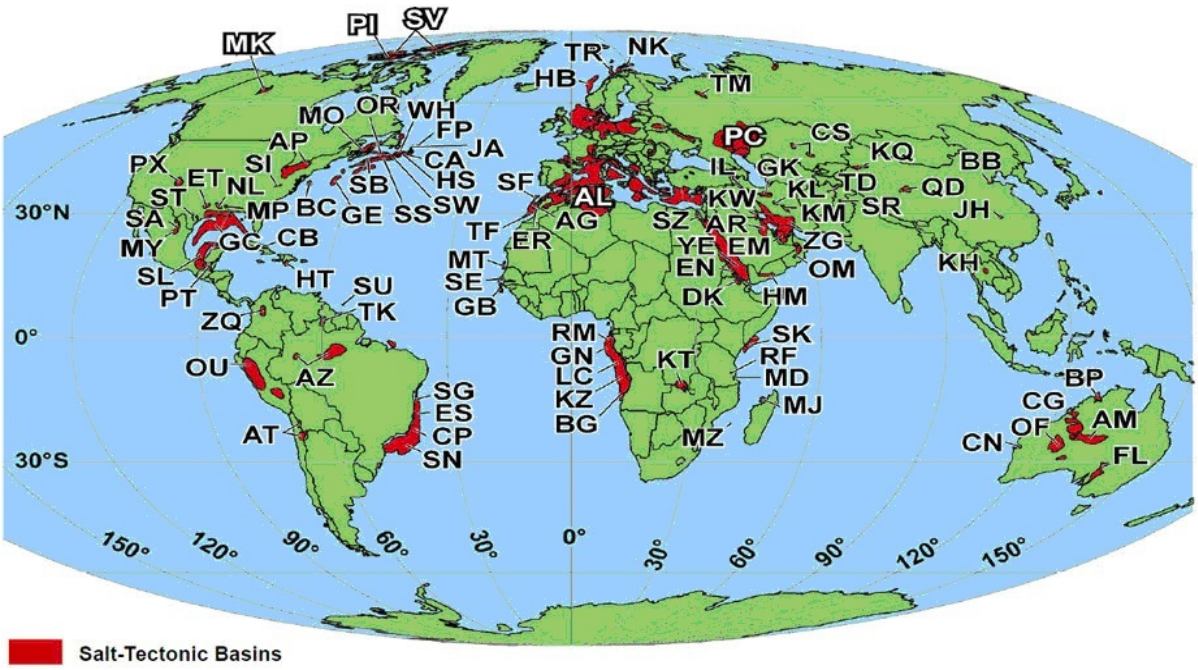
Source: Southampton University
http://www.southampton.ac.uk/
~imw/Qatar-Sabkhas.htm



Salt-Tectonic Basins

Note that global salt basins are:

- On a scale that only shows one of the 10 UK basins;
- Only shown in countries that divulge their geology publicly; and
- Coincident with areas explored for petrochemicals: nobody seeks salt basins, they find them by accident.
- Therefore there are many more, often undiscovered as yet: we know of one three times the size of the Cheshire basin located west of New Delhi, India, and another in Queensland, Australia.

Moreover, the other six geologies in which CAES can be built (following minor R&D) extend potential areas globally, without necessarily having any impact on resources that people would otherwise use. These geologies are all currently used safely for storing methane:

- Saline and sweet water aquifers (deeper than used for drinking water);
- Depleted oil fields;
- Depleted gas fields;
- Chalk;
- Gypsum;
- Limestone.

Other Analysts' Views

We select a small number from among the hundreds of reports that have analysed a variety of storage technologies for their "sweet spots". Almost without exception, they support the above analysis. Note that none of them was aware of Storelectic's particularly high-potential technology when undertaking these analyses, and therefore base all their evaluations on Huntorf and McIntosh.

Chinese paper on combined pumped hydro and CAES[4]

Table 1. Capital cost of installed storage plants.

Type	Storage Capital Cost ($/kWh)	Plant Capital Cost ($/kW)	Storage Capital (MWh)	Efficiency (%)	Operation and maintenance cost ($/kW/yr)	Hours (full power)	Power (MW)
CAES	>3	>425	5–100,000	>70	1.35	1–10 min	0.5–2700
Pumped Hydro	>10	>600	>20,000	>70	4.3	10 s–4 min	300–1800
Flywheel	300–25,000	280–360	0.0002–500	90–93	7.5	<1s	0.001–1
Superconducting Magnet	500–72,000	300	0.0002–100	95	1	<1s	0.001–2
Battery Storage	1–15	500–1500	0.0002–2	59	-	<1s	0.01–3

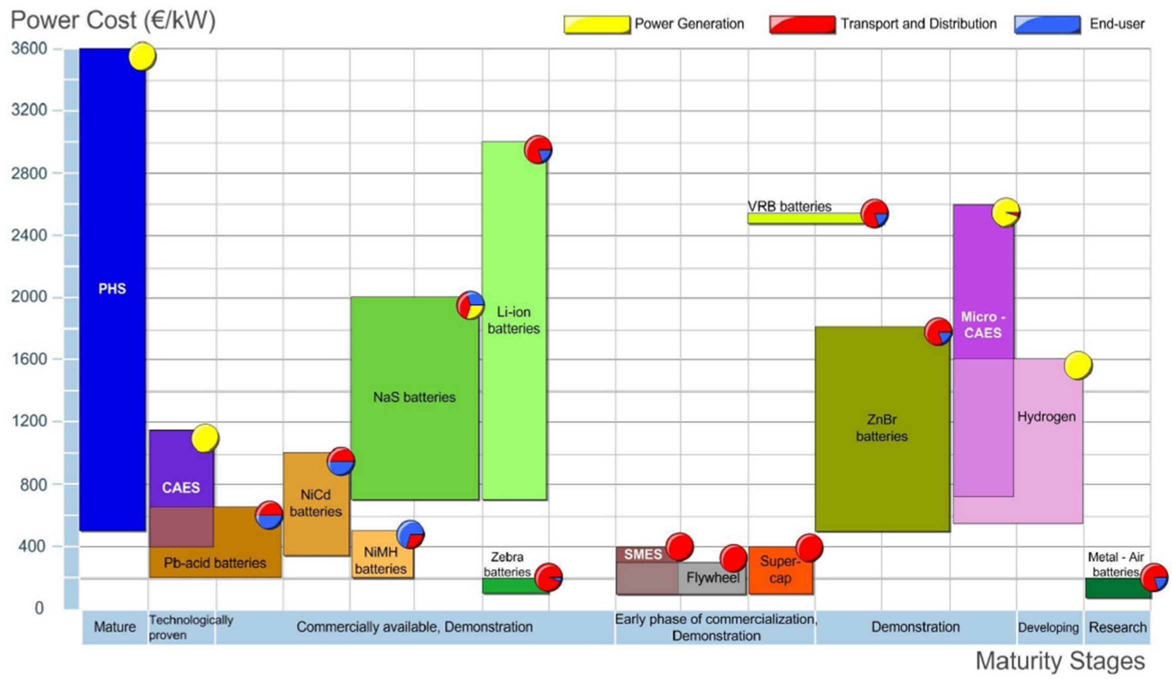
The following four graphs provide different ways of looking at storage:

1. By cost and technology maturity;
2. By power output and energy stored;
3. By power rating and discharge time (another view of the previous graph);
4. By capital cost per unit energy.

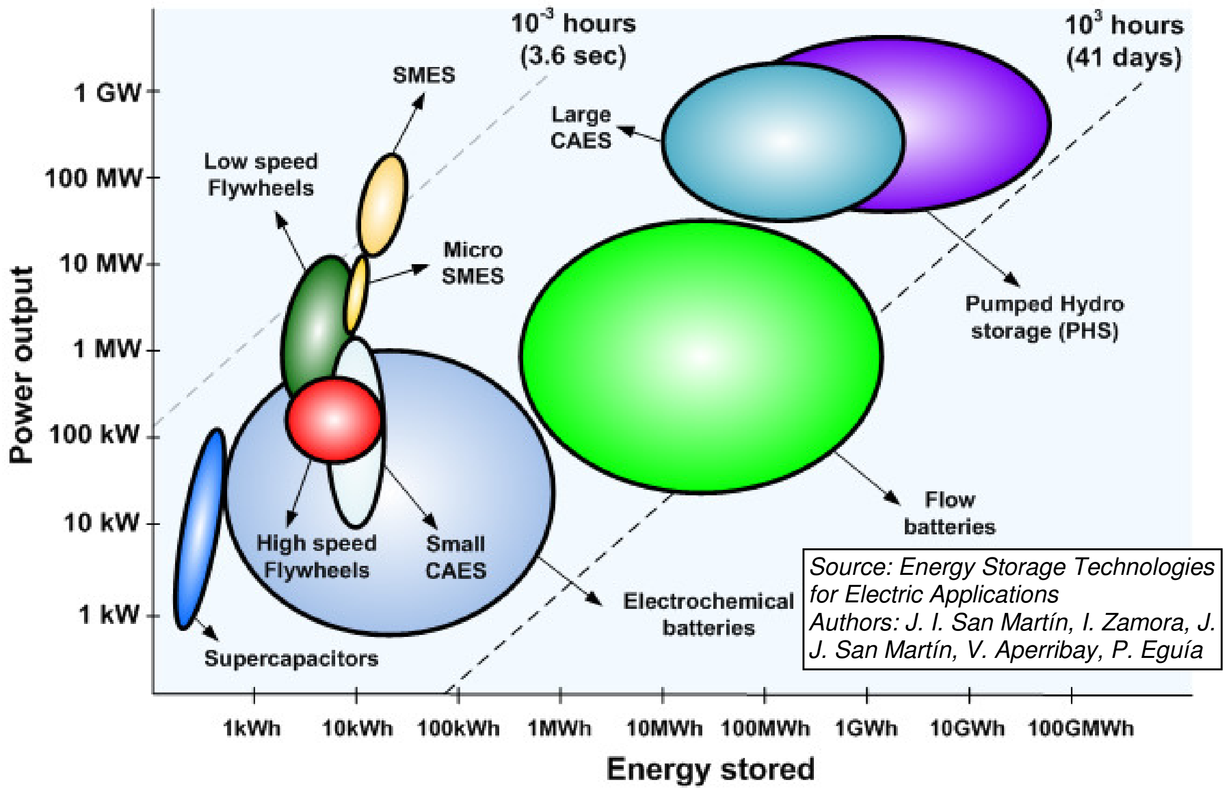
All four show CAES comparable with pumped hydro, fulfilling similar functions, and therefore not competing with the other technologies. To compare with pumped hydro, one must consider proximity to electricity supply and demand, topography / geology, and environmental footprint as well as capital and revenue costs.

KIC InnoEnergy, Thematic Field: Smart Grids and Electric Storage, Strategy and Roadmap 2014 [KIC = Knowledge and Innovation Community.][5]
"Electricity storage is identified as a key technology priority in the development of the European power system, in line with the 2020 and 2050 EU energy targets. Power storage has gained high political interest in the light of the development of renewables and distributed generation, as a way to reduce carbon emissions, to improve grid stability and to control the fluctuations of variable resources."

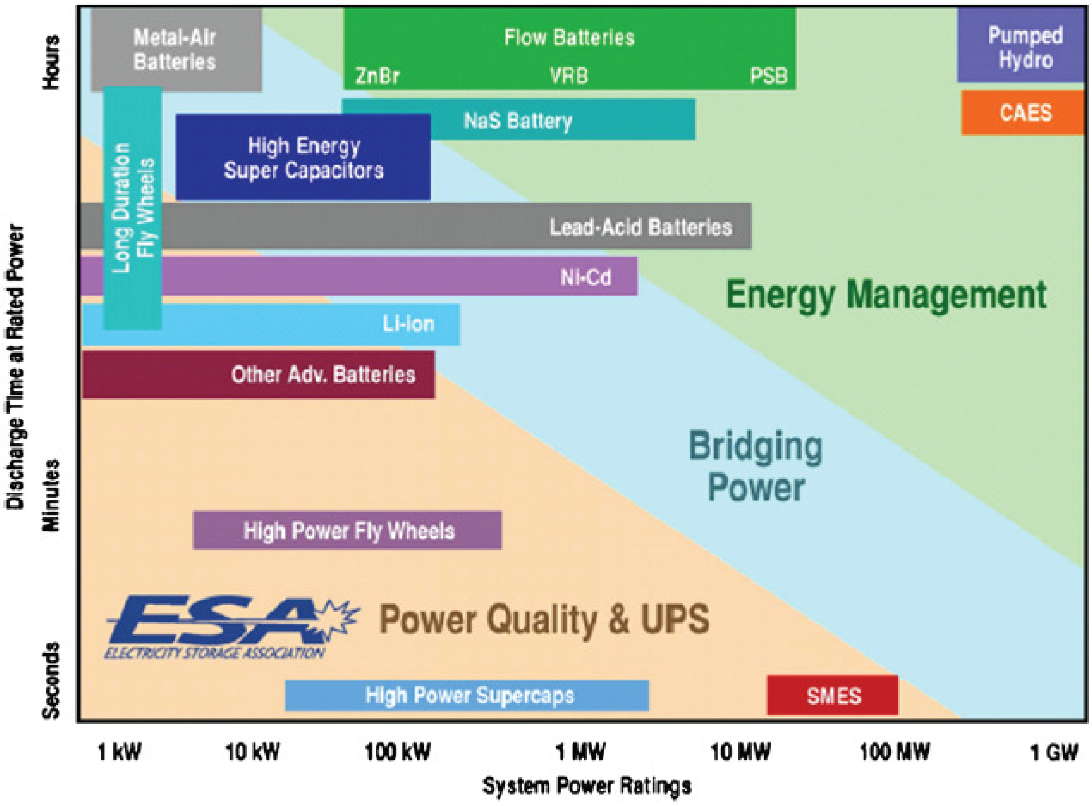
[4] http://www.mdpi.com/1996-1073/6/3/1554 linking to https://www.mdpi.com/1996-1073/6/3/1554/pdf
[5] http://cip2014.kic-innoenergy.com/thematic-roadmaps/



(Next graph[6])



[6] http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html


Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
High Energy Super Capacitors
Long Duration Fly Wheels
Lead-Acid Batteries
Ni-Cd
Energy Management
Li-ion
Other Adv. Batteries
Bridging Power
High Power Fly Wheels
ESA
ELECTRICITY STORAGE ASSOCIATION
Power Quality & UPS
High Power Supercaps
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1 kW
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100 kW
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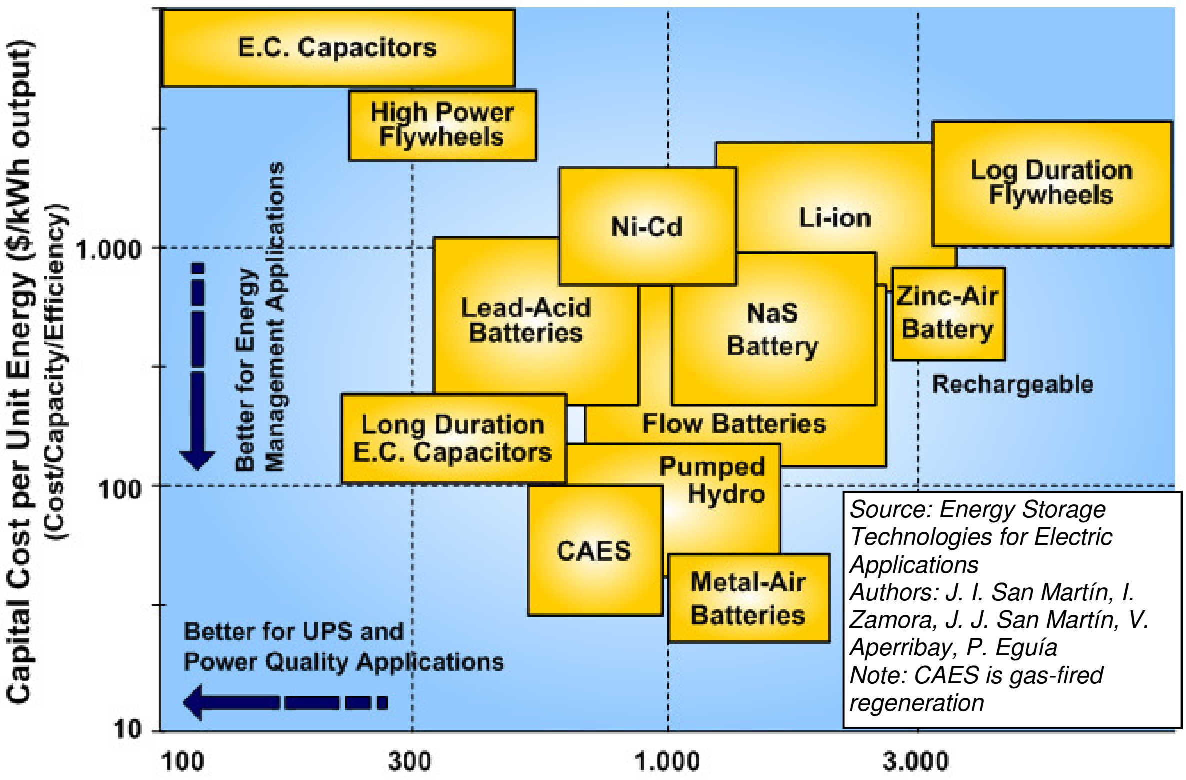
100 MW
1 GW
System Power Ratings


E.C. Capacitors
High Power Flywheels
Log Duration Flywheels
Ni-Cd
Li-ion
Lead-Acid Batteries
NaS Battery
Zinc-Air Battery
Rechargeable
Flow Batteries
Long Duration E.C. Capacitors
Pumped Hydro
CAES
Metal-Air Batteries
Better for Energy Management Applications
Better for UPS and Power Quality Applications
Capital Cost per Unit Energy ($/kWh output)
(Cost/Capacity/Efficiency)
1.000
100
10
100
300
1.000
3.000
Source: Energy Storage Technologies for Electric Applications
Authors: J. I. San Martín, I. Zamora, J. J. San Martín, V. Aperribay, P. Eguía
Note: CAES is gas-fired regeneration

How Much From Each Technology?

According to the UK Government's Technology Innovation Needs Assessment (TINA) 2015 main projection, by 2050 the UK needs 27.4GW, 128GWh storage[7]. This is in a range of needs that extends to 59.2 GW, 286 GWh.

Taking the main projection, these can be satisfied as follows, according to reasonable estimates of the potential of each:

Technology	Power (GW)	Capacity (GWh)
Pumped Hydro	2 GW	20 GWh
Batteries	2-3 GW	2-3 GWh
Interconnectors	8-12 GW	n/a
Demand Side Response	2-3 GW	2-3 GWh
Unmet need for storage	7.4-13.4 GW	102-104 GWh

Storelectric's CAES is one of the only technologies capable of meeting this unmet need[8] – and certainly the only one to meet it cost-effectively and minimising environmental effects.

[7] http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/electricity_networks_storage/

[8] Basis of these figures:

- **Pumped Hydro:** 2,828MW, 9GWh current storage capacity. Total current projects: 1,960MW. Therefore 6GW, 12GWh represents Storelectric's assessment of the reasonable maximum available in the UK, given that each installation floods two valleys. Current projects are (maximum sizes only):
  - Sloy 60MW conversion from hydro-electric
  - Coire Glas 600MW
  - Balmacaan 600MW
  - Cruachan 600MW increase from current 440MW
  - Glyn Rhonwy 100MW
- **Batteries:** assumes wide-scale roll-out of grid connected batteries with 1-2 hours' duration. Average size of current such batteries is under 1MW (ref. REA Energy Storage in the UK report 2016).
- Current **interconnectors** are 4GW, with projects in planning to increase this to 9GW. But this includes the Norwegian interconnector (~5x our cost per MW) and the Icelandic one (>10x) – and interconnectors cannot be relied upon to deliver power exactly when needed, at reasonable prices.
- **Demand Side Response:** Assumes that there are 4-6GW (6-10% of peak demand) available at any time, that each call on resources continues for 30 minutes, and that any given resource cannot be called upon twice in quick succession. Therefore for 1 hour's usage, only half the power rating can be used at any time.

About Storelectric

Storelectric (www.storelectric.com) is developing truly grid-scale energy storage using an innovative form of Compressed Air Energy Storage (CAES). This uses existing, off-the-shelf equipment to create installations of 500MW, 6-21GWh with zero or low emissions, operating at 68-70% round trip efficiency, at a cost of £350m (€500m) (estimated for 3rd – 5th plant), and a levelised cost cheaper than that of gas-fired peaking plants (OCGT). Capex is one-third that of pumped hydro per MW and 1/75th per MWh; similar to 10-year target prices of batteries per MW and less than 1/1,000th per MWh. There is potential in the UK to store the entire continent's energy requirements for over a week; potential in mainland Europe and the USA is greater still, with global roll-out planned.

The next stage is to build a 20MW, >100MWh pilot plant with over 60% efficiency, using scale versions of the same technology, for which Storelectric is currently raising funds. Construction will take 2-3 years from funding, and the first full-scale plant a further 3-4 years. The consortium includes global multinationals who cover all the technologies involved, their installation, financial and legal aspects.