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Gigawatt Scale Storage for Gigawatt Scale Renewables

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Abstract: Multi-GW renewables need multi-GW storage, or fossil fuelled power stations will be needed to balance for intermittency. For the same reason, such balancing must be able to last for an entire evening peak if renewables are not generating at the same time. Batteries and DSR (demand side response) make very useful contributions and there is a large market for both, but without large scale and long duration storage, they cannot do the job. Interconnectors also contribute to the solution, and storage will make them more profitable, but (taking a UK perspective) Ofgem identified that all our neighbours have similar generation capacity crunches and similar demand patters, so if we need the electricity when they do, we'll have to pay through the nose for it. Last winter's £ 1,500/MWh prices proved that—even with only 4 GW interconnection. Following exit from the single market, our neighbours will be able to say "our consumers are more important than yours at any price". We need UK-based storage at the right scale, to store UK-generated electricity for UK use and for export—otherwise we lose security of supply. CAES (compressed air energy storage) and pumped hydro are the only technologies currently able to deliver this scale and duration of storage. Pumped hydro is cost-effective in the long term but there are few sites, and it is (location dependent) over 3*x* the cost of CAES. Storelectric has 2 versions of CAES: one is a comparable price to existing CAES, but much more efficient (~70% v 50%) and zero emissions (existing CAES emits 50%-60% of the gas of an equivalent sized power station). The other is retro-fittable to suitable gas power stations, is more efficient (~60% v 50%), almost halves their emissions, adds storage-related revenue streams and is much cheaper. Both are new configurations of existing and well proven technologies, supported by engineering majors.

Key words: Electricity storage, CAES, compressed air energy storage, adiabatic, grid balancing, renewable.

1. Introduction

Many people have suggested that batteries, demand side response and interconnectors are a viable way forward for balancing a future renewable grid in general, and for grid-scale electricity storage in particular, and some have cast doubt on whether there is a role for CAES (compressed air energy storage) or increased amounts of PHES (pumped hydro energy storage).

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) The challenge;
(2) Power;
(3) Capacity;
(4) Response time, duty cycles, ancillary services.

There are also additional considerations, such as:

(1) Cost, lifetime and efficiency;
(2) Environmental considerations;
(3) Cost and performance summary;
(4) Global potential;
(5) Other analysts' views.

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

This paper analyses the issues from a UK perspective, but the lessons apply equally to grids globally as they de-carbonise.

2. The Challenge

While many countries are targeting 80% reductions in greenhouse gas emissions by 2050 as compared with 2010 levels [1] (the EU is targeting 80-95% reduction [2]), different sectors of the economy face different

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levels of difficulty in de-carbonising. Because ground-based power sector will find it easier to de-carbonise than (for example) aviation and shipping, the EU has identified that in order to achieve those targets across the entire economy, the power sector needs to de-carbonise completely [2]. Grids will simultaneously have to expand to support the de-carbonisation of other sectors, for example heating, transportation and manufacturing.

The challenge is to enable renewables to power an entire and growing grid, with or without nuclear. The difference that nuclear makes is how much baseload power renewables would supply—it is therefore a matter of quantity, not quality, so the following covers either case. The role of the balancing technologies is to enable intermittent generation to supply both variable and baseload demand.

The scenario on which most grid players (operators, regulators, generators, storage providers etc.) focus is to address the rapid ramp rates of renewables in (for example) gusty or intermittently cloudy weather (one aspect of the intermittency challenge), and also the similarly rapid ramp rates, both upwards and downwards, in demand (dispatchability). Batteries and DSR (demand side response) are well suited to this, over limited power ranges.

For longer term fluctuations the grid players rely on interconnectors. However this does not consider a number of factors, including:

(1) Energy flows through interconnectors are often contracted well in advance and to that extent cannot be varied according to shorter term conditions;

(2) Demand and supply are often highly correlated at both ends of an interconnector, so a shortfall at one end is matched with a shortfall at the other;

(3) Weather patterns can cover both ends of interconnectors, and wider regions, for up to a fortnight at a time;

(4) Where legally permissible (e.g. between nation states outside free trade pacts, such as post-Brexit Britain), each country would favour their own consumers' needs.

This leaves three scenarios that are not catered for by grid players' current plans: winter evening peaks, widespread shortfalls and widespread weather patterns.

2.1 Winter Evening Peaks Scenario

When the sun goes down on a windless winter afternoon, a long period of peak demand is in prospect with negligible renewable generation. The duration of this peak vastly exceeds the power and duration capabilities of batteries and DSR, and are likely to exceed the available (un-contracted) capacity of interconnectors.

2.2 Widespread Shortfalls Scenario

In May 2017, two-thirds of French nuclear power generation was down for a mix of planned and unplanned outages [3]. This caused knock-on effects throughout Western Europe despite the currently restricted sizes of the interconnectors with France. Imbalance prices shot up in the UK to over £ 1,500/MWh, against typical normal prices of £ 40-50/MWh.

2.3 Widespread Weather Patterns Scenario

Weather patterns often do not just cover one country, they can cover large proportions of a continent, and can do so for many days at a time—as they did at the end of February and early March this year [4]. Over such extended periods and geographies, most countries within a network of interconnectors are affected similarly, so the interconnectors do not help. And they are affected for a long time, so batteries and DSR do not stand a chance.

3. Power

Energy storage is required at a number of different scales. We divide them into five bands, as Table 1.

The largest battery currently installed anywhere is 100 MW, with 1 hour duration [5]. These are used to alleviate local and domestic line capacity constraints, and to provide a small amount of time-shifting of

Table 1 Scales of storage: size.

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

Table 2 Scales of storage: capacity.

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

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 20 MWh battery could produce 10 MW for 2 hours or 40 MW 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 100 MW or more. Storelectric offers efficient solutions rated from 40 MW to GW, 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 (at constant rating), Storelectric's CAES increases by ~1/3.

4. Capacity

Energy storage is required at a number of different scales, which we define thus as Table 2.

All grid-connected batteries to date have had a storage capacity of between 0.25 and 2 hours' output at full rated power. Therefore they are best suited to applications 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 are 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 35 GWh 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 \$6 m/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 planet 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.

5. Response Time, Duty Cycles, Ancillary Services

5.1 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.

5.2 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 and pumped hydro are 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 are currently being provided by gas-fired peaking plants at great cost and with substantial emissions.

5.3 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, and stabilise the grid in other ways. 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.

6. Cost, Lifetime and Efficiency

6.1 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 500 MW and a capacity of 6-21 GWh.

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.

6.2 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 or pumped hydro 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 received a mid-life upgrade in 2006, aged 28 years, and is still operating—at a higher capacity (321 MW vs. 290 MW as first built) than originally.

6.3 Efficiency

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

- Huntorf (traditional OCGT-based CAES): 42%;
- McIntosh (traditional CCGT-based CAES): 50%;
- Dresser Rand's Smart CAES (an evolution of McIntosh): up to 54%;
- 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 [6], shown in Table 3.

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 new 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.

Table 3 Quoted and actual battery efficiencies, actual costs.

	2.5 kVA, 5 MWh	100 kVA, 200 kWh	50 kVA, 100 kWh
Costexcl. installation	£ 3.76 m	£ 406 k	£ 331 k
£/MWh	£ 752 k	£ 2,030 k	£ 3,310 k
Costinc. installation	£ 4.62 m	£ 490 k	£ 422 k
£/MWh	£ 924 k	£ 2,450 k	£ 4,110 k
Nominal efficiency	83.2%	83.2%	83.2%
Measured efficiency	69.0%	56.3%	41.2%
Average parasiticload	29.5 kW	29.5 kW	29.5 kW

7. Cost and Performance Summary

The various technologies can be summarised (excluding durations) in Table 4:

Table 4 Comparing electricity storage technologies.

		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 minutes.

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 Ltd., based on a 500 MW, 6 GWh plant after the first 3-5 plants when CAPEX costs will have stabilised.

Dresser Rand: DoE (American Department of Energy) http://www.sandia.gov/ess/publications/SAND2015-1002.pdf. Brayton installations;
Highview: Highview Power Cost Estimator, http://www.highview-power.com/market/#calc-jumper using their default values (100 MW, 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) http://www.sandia.gov/ess/publications/SAND2015-1002.pdf;
Lithium Ion: Costs: DoE (American Department of Energy) http://www.sandia.gov/ess/publications/SAND2015-1002.pdf, taking the three batteries with duration >1 hour (the remainder had durations of 0.25 hours), averaging them at $6,000/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 *p*6) for a 5 MW system; the figures in the table assume that efficiencies increase with size;
Va Redox: DoE (American Department of Energy) http://www.sandia.gov/ess/publications/SAND2015-1002.pdf;
Flywheels: DoE (American Department of Energy) http://www.sandia.gov/ess/publications/SAND2015-1002.pdf.

8. 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), which 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. Such topologies are also usually remote from both generation and major demand, requiring long transmission line spurs.

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 (with an outstanding safety record world-wide) in these same geologies at the same pressures.

9. Global Potential

According to the late David Mackay's book "Sustainable Energy—Without the Hot Air" [7] (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 were (until recently) dropping is because extraction technologies and volumes are still improving faster than demand: if demand was to grow to such global levels, scarcity pricing would soon start.

According to information from the economist, vehicles alone would exhaust the world's stock of lithium in 2-10 years for the number of battery vehicles forecast in 2040 [8][1]. This leaves nothing available for portable devices or grid applications.

And batteries require other, scarcer, materials too, such as cobalt and, somewhat less scarce, nickel.

In contrast, salt basins alone offer enormous potential for CAES, referring to Fig. 1.

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: it is not normal to seek salt basins, they are found 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.

However storing air in these geologies is not straightforward and needs to be analysed carefully; therefore salt caverns are the quick, safe and simple way forward initially.

10. 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 [9].

The following four graphs (Figs. 2-5) 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

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

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, 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
	2040 OPEC	5.8	years, just for vehicles
	2040 ExxonMobil	9.7	years, just for vehicles

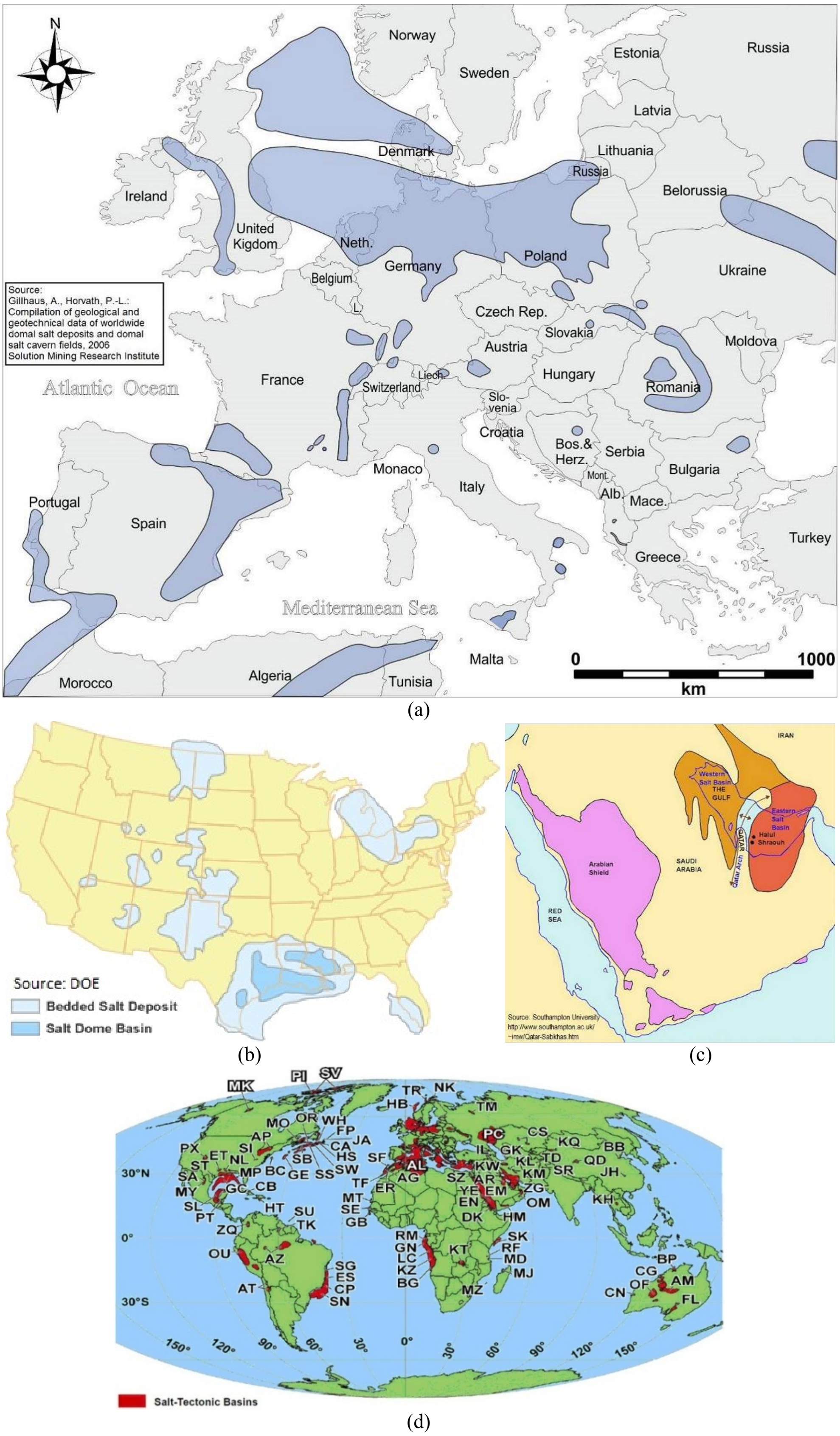

Fig. 1 Maps of salt basins in Europe, North America, the Middle East, and the world.

Table 5 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	0.5-2,700
Pumped hydro	> 10	> 600	20,000	> 70	4.3	10 s-4 min	300-1,800
Flywheel	300-25,000	280-360	0.0002-500	90-93	7.5	< 1 s	0.001-1
Superconducting Magnet	500-72,000	300	0.0002-100	95	1	< 1 s	0.001-2
Battery storage	1-15	500-1,500	0.0002-2	59	-	< 1 s	0.01-3

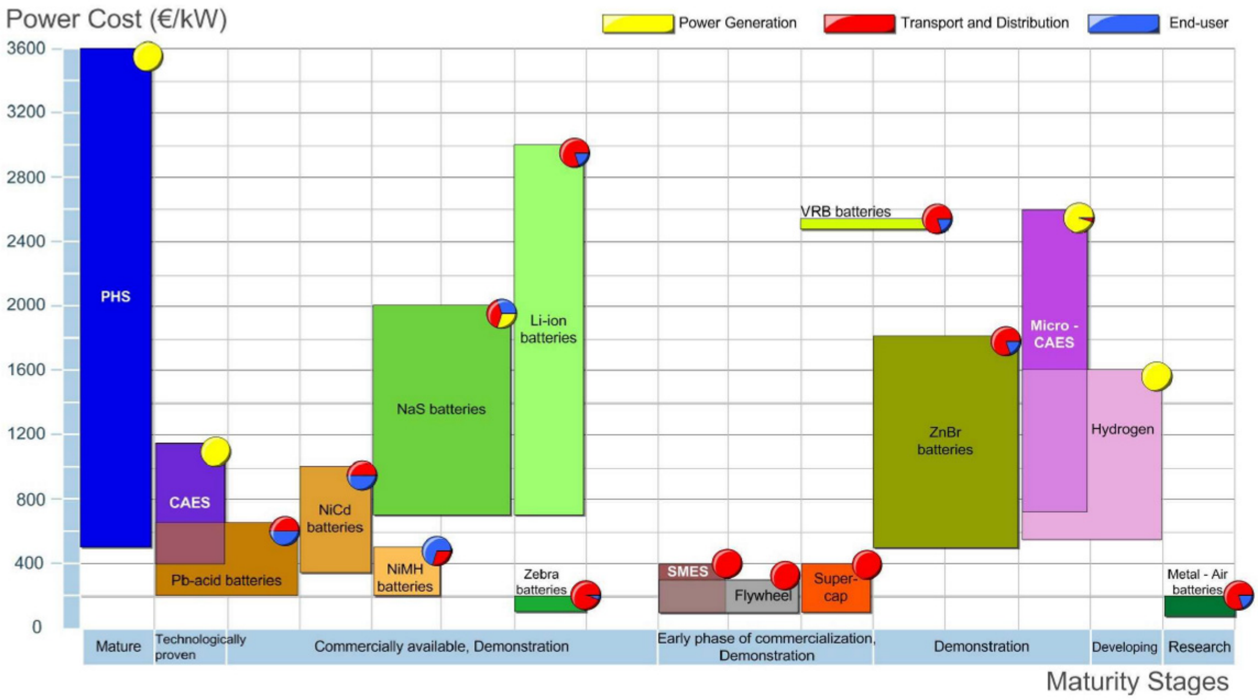

Fig. 2 Types of storage, by cost and technology maturity [11].

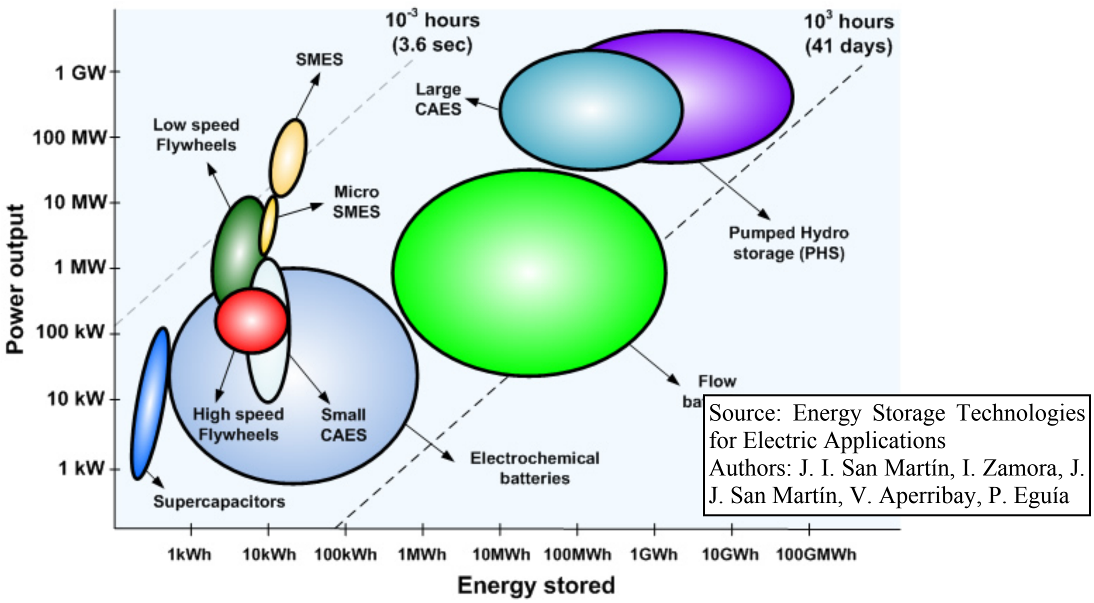

Fig. 3 Types of storage, by power output and energy stored.

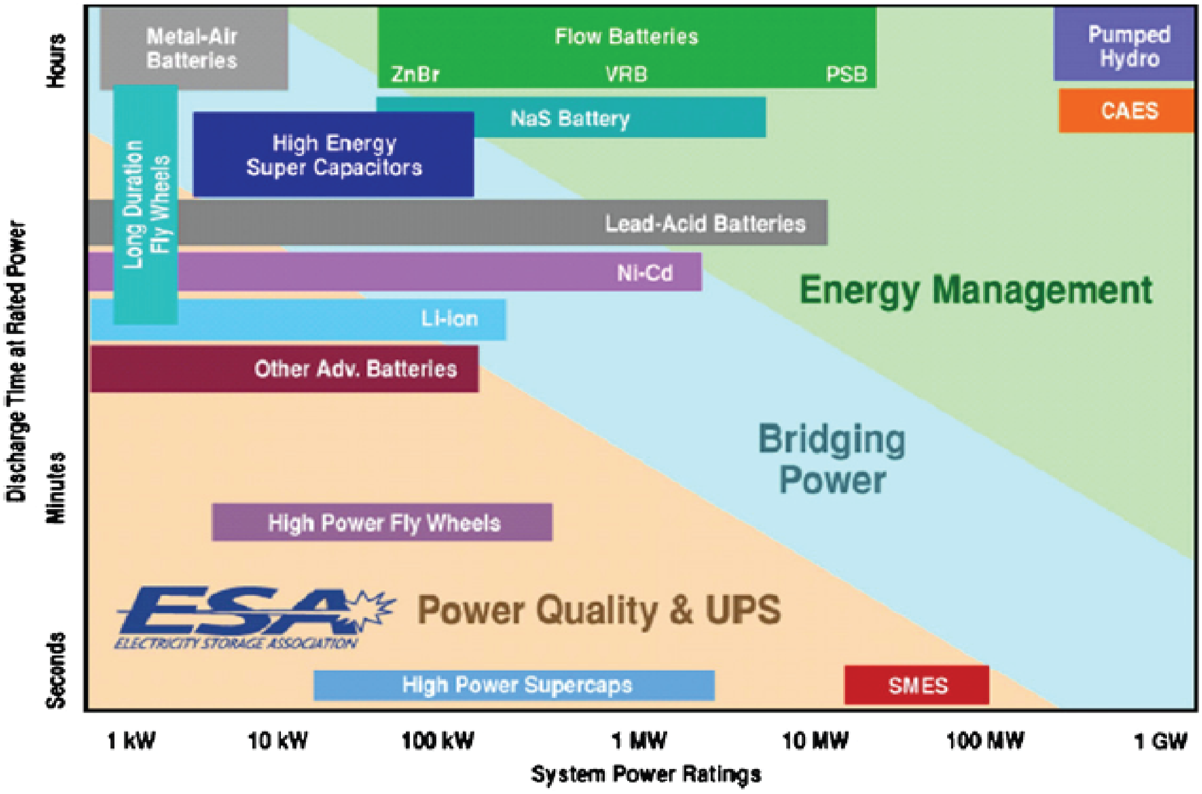

Fig. 4 Types of storage, by power rating and discharge time (another view of the previous graph).

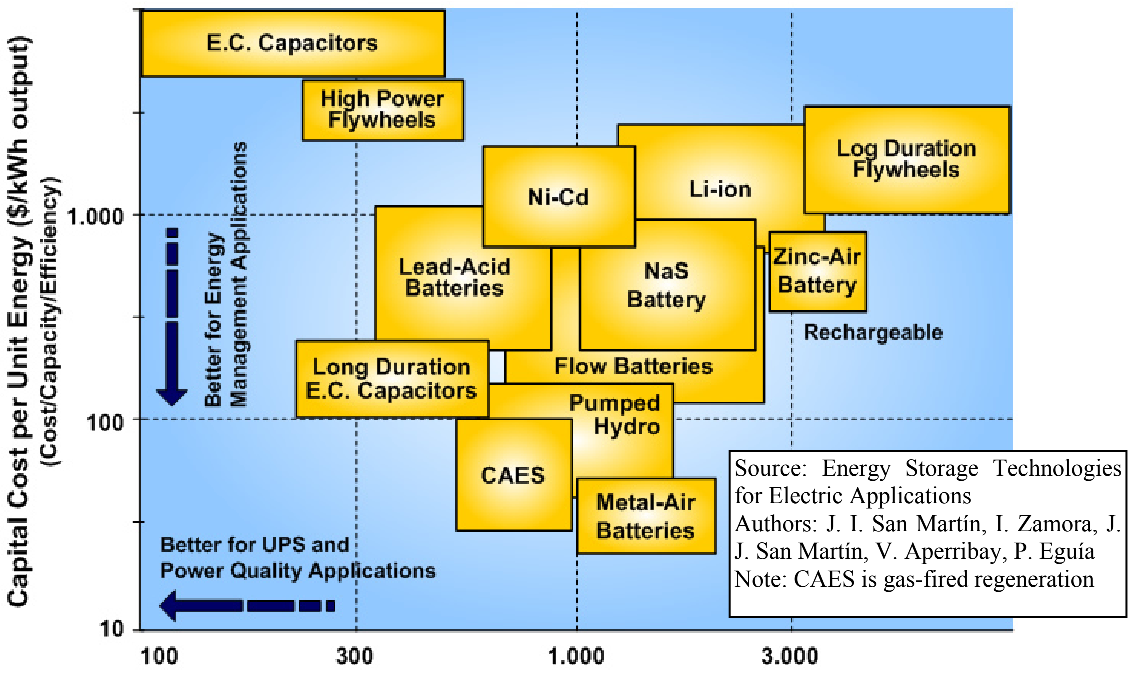

Fig. 5 Types of storage, by capital cost per unit energy.

electricity supply and demand, topography/geology, and environmental footprint as well as capital and revenue costs (c.f. Table 5).

KIC InnoEnergy, Thematic Field: Smart Grids and Electric Storage, Strategy and Roadmap 2014 (KIC = Knowledge and Innovation Community) [10].

"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."

11. How Much from Each Technology?

According to the UK Government's TINA (Technology Innovation Needs Assessment) 2015 main projection, by 2050 the UK needs 27.4 GW, 128 GWh storage [12]. This is in a range of needs that extends to 59.2 GW, 286 GWh. It is notable that dividing the GWh figure by the GW figure, the government assesses that the average duration of storage needed is 5 hours, which cannot be delivered cost-effectively by solid state batteries. And this report only analyses the storage required to turn renewable generation into dispatchable electricity ("peak smoothing"), without considering delivering baseload or supporting the de-carbonisation of heating, industry and transportation.

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[2]—and certainly the only one to meet it cost-effectively and minimising environmental effects.

12. Conclusions

Electricity grids need to de-carbonise completely in order to enable economies to achieve their necessary carbon reduction targets. In order to do so, not only must all energy be generated renewable (with or without nuclear, depending on viewpoint), but also it needs to be backed up renewably too. Current plans revolve around interconnectors, grid-connected batteries and Demand Side Response. These are all part of the solution. However none of these will deal with all scenarios, for example weather patterns that cover whole regions, or multi-hour peak demand during low renewable generation periods. The big missing element in these plans is large scale long duration storage at the same scale as their renewable generation—i.e. at the scale of multi-GW and ranging

[2] Basis of these figures:
Pumped Hydro: 2,828 MW, 9 GWh current storage capacity. Total current projects: 1,960 MW. Therefore 6 GW, 12 GWh 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:	60 MW conversion from hydro-electric
CoireGlas:	600 MW
Balmacaan:	600 MW
Cruachan:	600 MW increase from current 440 MW
Glyn Rhonwy:	100 MW

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 4-6 GW (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. Note: National Grid in FES 2015 estimated maximum DSR capability at ~5% of peak demand, http://nationalgridconnecting.com/2015-uk-future-energy-scenarios-published/ fig. 46 (not updated since).

from tens of GWh to multi-TWh depending on the country. There are currently only two technologies able to deliver such scales of storage: pumped hydro and Compressed Air Energy Storage. Traditional CAES still has emissions and low levels of round trip efficiency, but adiabatic CAES, such as that proposed by Storelectric, is almost as efficient as pumped hydro, a third of the cost and geographically much more widely implementable. Therefore grids, governments and industry should be developing large numbers of such projects in order to provide the energy the world needs, cost-effectively, cleanly and securely.

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About Storelectric

Storelectric (www.storelectric.com) is developing truly grid-scale energy storage using an innovative form of CAES. This is TES CAES (TES = thermal energy storage), licensed from TES CAES Technology Ltd. which is mostly owned by the same shareholders. It uses existing, off-the-shelf equipment to create installations of 500 MW, 6-21 GWh with zero or low emissions, operating at 68-70% round trip efficiency, at a cost of £ 350 m (€ 500 m) (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/MWh; similar to 10-year target prices of batteries per MW and less than 1/1,000 th/MWh. There is sufficient geological 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. Returns on capital are expected to be of the order of 15% in today's market—and the market is improving each year.

Storelectric has a second technology, CCGT CAES, which uniquely is retro-fittable to either OCGT or CCGT power stations if over a suitable geology. The cost of conversion depends on what is there, but a new-build CCGT CAES would cost about 10-15% more than a CCGT power station and have very similar returns on capital to TES CAES.

The next stage is to build a 40 MW, > 100 MWh pilot plant with over 62% 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 large-scale plant a further 3-4 years. The consortium includes global multinationals who cover all the technologies involved, their installation, financial and legal aspects.