Energy Briefing Sheet: Energy Storage

Introduction

Electricity storage will play an increasingly important role in supply and distribution.

This paper is a summary of the relevance of electricity storage at 'utility level' and 'grid level' (say 10 to 1000 MW), the technologies, the potential costs and benefits, and some issues to do with facilitating implementation.

Roles and benefits of electricity storage

In the context of large-scale storage of electricity (from say 10 MW upwards), two main roles and their benefits are considered here.

- **Ancillary services:** until recently, the UK electricity system was characterised by a relatively small number of massive rotating generators feeding power 'one way' to consumers via the transmission and distribution networks. The diverse and highly distributed nature of renewable generation, often using power electronics, can result in power flows and fluctuations at variance with the original designs of networks. Electricity storage can help maintain stability and optimise use of networks.
- **'Time-shifting':** outputs from wind and solar generation are variable and/or unpredictable and cannot be adjusted to match demand. As demand increases at peak times, increasingly expensive and inefficient fossil-fuelled generators are called. Low carbon energy stored at off-peak times could 'fill the gaps' in intermittent renewable generation and displace peaking plant, reducing costs, helping to meet carbon reduction targets and increasing capacity margins.
  Both the above may help postpone or avoid enhancement or replacement of existing infrastructure.

Electricity storage can generally respond to changes in demand more quickly than generation, whether storing or exporting. Comparing some sources of electricity generation and storage: the output from nuclear power stations tends to be varied slowly and is used to serve 'base load'; coal-fired stations can ramp up or down by about 5% of their installed capacity per minute; gas turbine power stations can respond more quickly; Dinorwig pumped storage station can take up 1,320 MW of load in 12 seconds if synchronised in 'spinning reserve'; batteries can respond to load fluctuations within say 1 second. Keep in mind that installed capacities of thermal generation are typically up to 2,000 MW; the biggest battery installation at November 2017 is 100 MW[1].

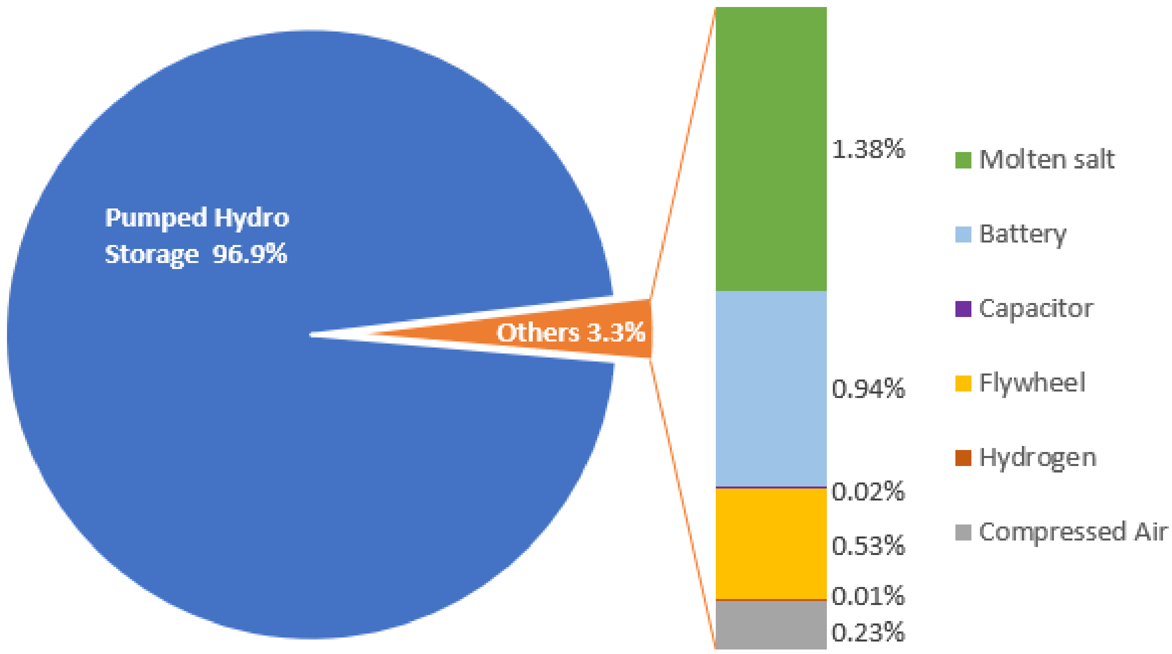
[1] Government of South Australia, 2017, http://ourenergyplan.sa.gov.au/battery.html

Therefore, well designed and implemented electricity storage systems may help address the energy 'trilemma', that is the simultaneous achievement of decarbonisation, security of supply and affordability.

Storage offers further particular benefits; see 'Further reading' below.

Storage technologies

In practice, electricity is converted to potential, kinetic or chemical energy from which it is converted back to electricity on demand. Technologies are listed in roughly decreasing level of maturity and scale.

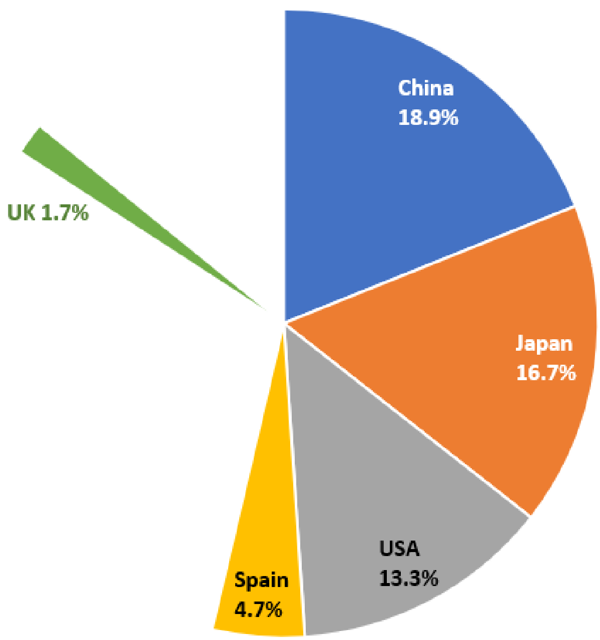


Worldwide Total Electricity Storage by Technology
Source of data: DOE (USA) Global energy storage database (Dec-17)
http://www.energystorageexchange.org/

Pumped hydroelectric storage (PHS)

PHS consists of upper and lower reservoirs connected by a waterway with a power house close to the lower level. Motors and pumps are used to pump the water up to the higher reservoir when there is a surplus of low-cost electricity available; at times of peak demand the water is discharged through turbine-generator sets back to the lower reservoir to generate electricity. The motor-pump and turbine-generator sets are often the same (reversible) plant. Further information is available in the ICE briefing sheet on hydropower.

PHS is the only technology providing 'grid scale' storage at present, constituting 96.7% of total worldwide energy storage. Worldwide capacity in 2017 was 169 GW with 3 to 6 GW added in 2016 and significant additional capacity under construction.[2] The UK has 2,744 MW of installed capacity which generated 2,959 GWh (using 4,014 GWh for pumping) in 2016.[3] SSE has consent for a further 600 MW at Coire Glas.[4]



Pumped Hydroelectric Storage by Country
Source of data: DOE (USA) Global energy storage database (Dec-17)
http://www.energystorageexchange.org/

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[2] DOE (USA) Global energy storage database (Dec-17) http://www.energystorageexchange.org/
[3] GTM Research/ESA U.S. Energy Storage Monitor
[4] AES press release, 17 February 2016

Molten salt

Salt is heated in a solar furnace to store surplus energy during the day. The heat thus stored is used later to generate steam from which electricity is generated using a steam turbine. Worldwide installed capacity in 2017 was 2.4 GW. The largest is 360 MW, in Spain.

Batteries

There are several technologies under this heading which could be considered individually but, for brevity, are treated here together. They include lead-acid, nickel-cadmium, lithium-ion, metal-air, high temperature (sodium-sulphur, sodium-nickel halide), and flow. With their varied attributes, these technologies have a wide range of potential applications. At present, lithium-ion, flow and high temperature batteries offer the best prospects for large-scale storage. Lithium-ion dominates existing installations; the rate of installation is increasing as unit costs come down.

In late 2017 some 50 projects of 10 MW or more were operating, the largest of which is 100 MW in South Australia, commissioned in November 2017. The total worldwide capacity in late 2017 is recorded as 1.65 GW, just less than 1% of worldwide energy storage capacity, of which more than 700 MW is in the USA[5]. There is an additional unknown capacity of 'behind the meter' installations, that is within industrial customers' systems. The rate of installation (around 15 to 20% per annum in recent years) is forecast to increase significantly.[6] The largest installations in the UK are the AES Advancion® energy storage array at Kilroot, Northern Ireland[7] and the 6 MW (10 MWh) UK Power Networks trial project at Leighton Buzzard[8]. Amongst numerous other projects, National Grid awarded contracts in August 2016 for a total of 200 MW of battery storage for enhanced frequency response, due to be operational by March 2018.[9]

A plausible scenario is the use of multiple, widely distributed, battery systems to overcome stability issues and distribution capacity constraints, responding to local peaks in demand. They could also be used for 'time-shifting' solar and wind generation to times of peak demand. A further consideration is the demand from charging electric vehicle batteries and their possible use for off-setting peak demand in homes.

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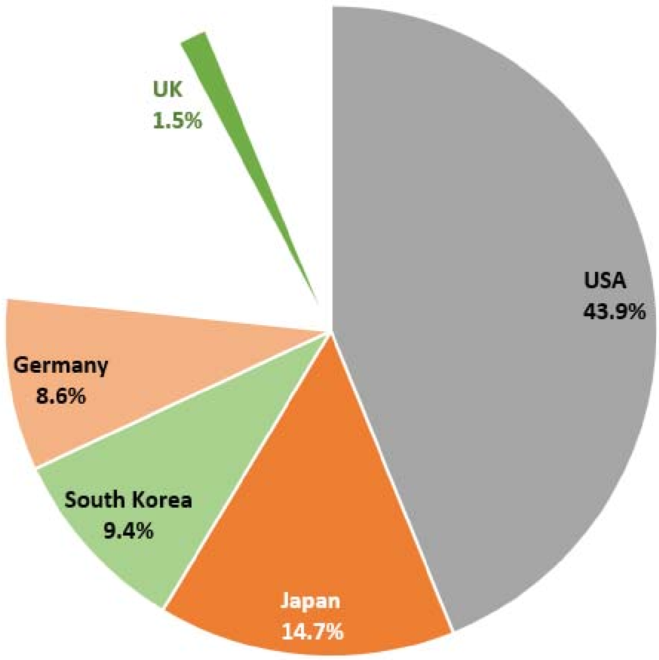
[5] DOE (USA) Global energy storage database (Dec-17) http://www.energystorageexchange.org/
[6] GTM Research/ESA U.S. Energy Storage Monitor
[7] AES press release, 17 February 2016
[8] Smarter Network Storage, UK Power Networks, September 2015; web page and report
[9] National Grid brings forward new technology with Enhanced Frequency Response contracts **http://media.nationalgrid.com/press-releases/uk-press-releases/corporate-news/national-grid-brings-forward-new-technology-with-enhanced-frequency-response-contracts/**



Battery Storage by Country
Source of data: DOE (USA) Global energy storage database (Dec-17)
http://www.energystorageexchange.org/

Compressed air energy storage (CAES)

Air is compressed into a cavern (typically salt caverns) when surplus low-cost electricity is available, and released through turbines to meet peak demands. Projects can be more compact than PHS, certainly in terms of surface installations, but the compressibility of the gas introduces heat issues. The heat of compression and cooling of de-pressurisation are addressed by various means. Two 'grid scale' plants are operating to date: at McIntosh, Alabama (110 MW, commissioned in 1991) and Huntorf, Germany (290 MW, commissioned in 1978). These two plants use the compressed air in gas turbines which, by omission of the compression stage, emit substantially less CO_2. However, they are both diabatic, so the heat generated on compression of the air is dissipated and the air has to be re-heated before it enters the turbine. The overall efficiency is less than a modern gas turbine combined cycle plant. Higher efficiencies can be achieved with adiabatic processes to extract the heat of compression to a separate store, using it to re-heat the expanding air. CAES may be regarded as offering the potential for 'utility scale' energy storage at present. Six small plants (80 to 2,000 kW) have been commissioned, mostly in USA and Canada, since 2012.

Cryogenic energy storage or liquid air energy storage (LAES)

In this process, air, nitrogen or hydrogen is cooled (using cheap off-peak electricity) until it liquefies so it can be stored in an insulated container at atmospheric pressure. (Air liquefies at about -195°C; the volume ratio is 700:1). The liquid gas is then pressurised, evaporated and heated to ambient temperature to drive a turbine. All component technologies are mature though to date their combined use for this purpose remains in the development stage. A 350 kW LAES pilot project ran from 2011 to 2014 at the University of Birmingham, UK, and a 5 MW demonstration plant in Manchester, UK, is due to be commissioned in early 2018.[10]

Flywheels

An electric motor is used to rotate a flywheel when surplus or low-cost electricity is available. The kinetic energy thus obtained can generate electricity on demand instantly. Rotors operating in a vacuum with near-frictionless magnetic bearings achieve high efficiency. Carbon fibre is used to achieve very high rotational speed, the kinetic energy being proportional to the square of the speed of rotation. Flywheels can be used in vehicles, and track-side on electrified railways, for regenerative braking; multiple units can be used at the utility power supply level. Two flywheel generators of 400 MW output (for 20 seconds) have been in operation at the Joint European Torus project in Oxfordshire, UK, since the 1980s.[11] Worldwide capacity is about 930 MW, 0.5% of worldwide energy storage capacity.

Super-capacitors

Capacitors are possibly the only technology that store electricity directly, that is as electric charge rather than converting electricity to some other form of energy. Super-capacitors provide short term storage which, responding instantly to demand, are applicable to voltage and frequency regulation, uninterruptible power supply and 'appliance' (for example regenerative braking) applications. To date, capacity falls short of grid or utility-scale but present development may lead to viable installations. Worldwide installed capacity is about 31 MW (mostly in South Korea), 0.02% of worldwide energy storage capacity.[12]

Hydrogen

Hydrogen can be used directly in gas turbines and internal combustion engines, injected into gas distribution networks, stored underground in large volumes, and transported, so offers various synergies with renewable energy. Hydrogen cell powered vehicles promise greater range than electric vehicles. However, the 'round-trip' efficiency (making, transporting, compressing, converting back to electricity, etc) is comparatively low and hydrogen is hazardous (as are most other technologies in various ways). To date, most hydrogen is produced from steam reforming from fossil fuels but can also be made by electrolysis of

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[10] Highview Power Storage, Projects http://www.highview-power.com/projects/
[11] Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, May 1986. JET Flywheel Generators http://journals.sagepub.com/doi/abs/10.1243/PIME_PROC_1986_200_013_02
[12] DOE (USA) Global energy storage database (Dec-17) http://www.energystorageexchange.org/

water; there are no electrolysis plants of significant size to date but there are several small-scale pilot and demonstration projects.[13] Hydrogen storage schemes comprise about 0.01% of worldwide energy storage capacity at present (2017). There is a significantly polarised debate comparing hydrogen and batteries for vehicles.

Other technologies

There is a growing list of ways in which energy might be stored. These are some.

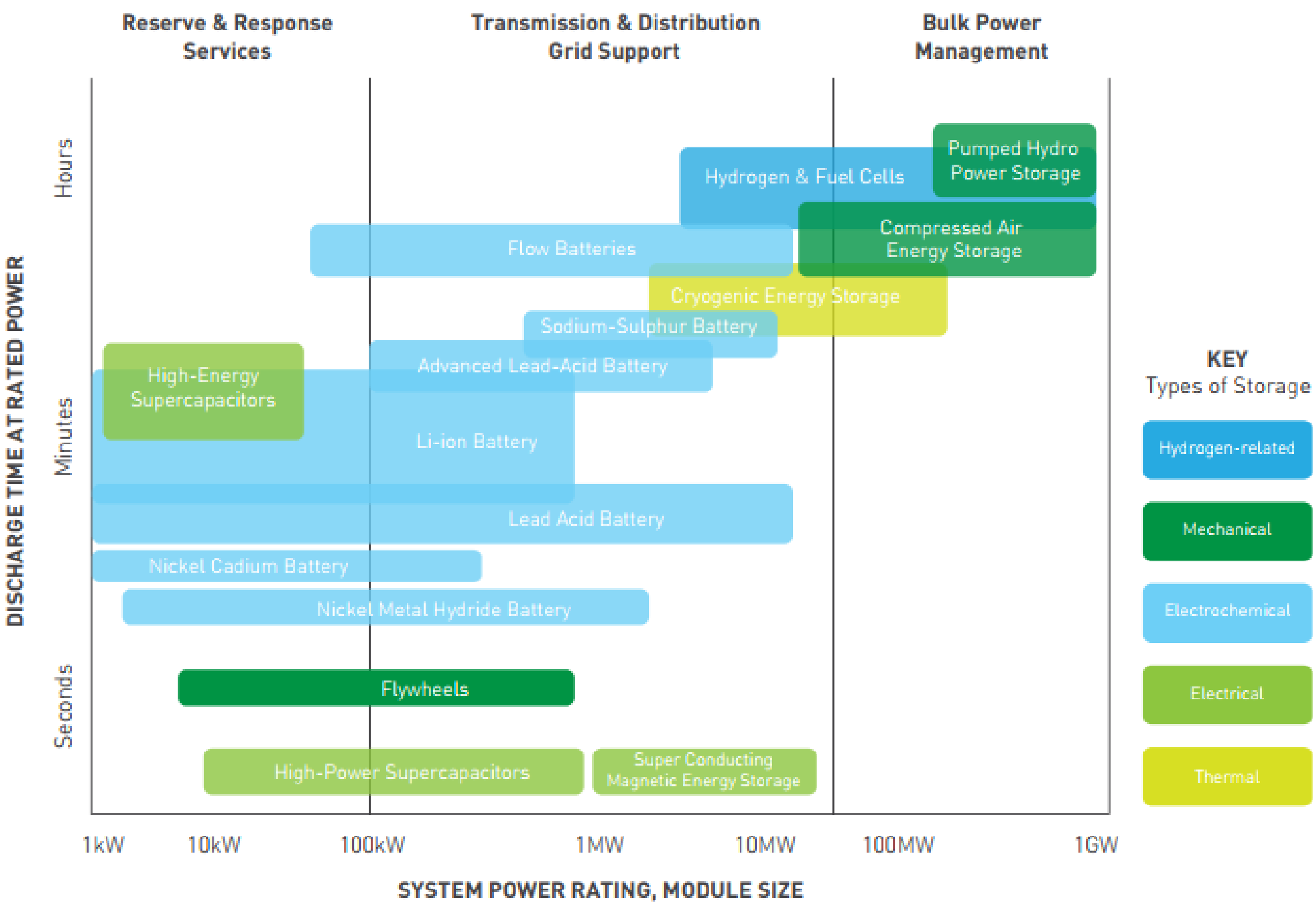
Pumped heat: electricity is used to compress a gas such as argon, pumping it downward through a tank filled with aggregate; the gas cools to ambient temperature as it passes downward. The gas leaving the bottom of the hot tank is expanded, cooling as it does so, and is passed upwards through another aggregate filled tank, cooling the aggregate and warming the gas back to ambient temperature. Energy is recovered by reversing the cycle. A round trip efficiency of up to 80% is claimed.

Mountain railway: rocks or concrete blocks are transported uphill on railway wagons using off-peak electricity and use regenerative braking on the way back down.

Montmorillonite clays have been found to have electrostatic properties that can be used to store an electric charge. It can also be used as a medium for containing paraffin whose phase change latent heat properties are used to store heat. The latter could be effective for heating and cooling of buildings.

Applications of technologies: the chart below illustrates the approximate ranges of power and energy available from different electricity storage technologies. They are also compared in the following table.

[13] ITM Power Projects https://thinkrcg.com/energy-storage-opportunities-challenges/ , ITM Power hydrogen refinery project Rhineland http://www.itm-power.com/news-item/10mw-refinery-hydrogen-project-with-shell



Applications of energy storage technologies

Source: Pathways for energy storage in the UK, Centre for Low Carbon Futures, 2012. http://www.lowcarbonfutures.org/sites/default/files/Pathways%20for%20Energy%20Storage%20in%20the%20UK.pdf

Technology	Worldwide installed capacity	Largest installation	Typical discharge duration	$/MWh levelised cost	Example applications	Response time	Round trip efficiency
Pumped storage	169 GW [14] 150 GW [15]	3,003 MW [16]	~ 6 - 12 hours	152 – 198 [17]	Frequency & voltage response; diurnal **balancing**	From ~ 10 seconds	70 - 85%
Compressed air	405 MW [18]	290 MW	~ 24 hours	116 – 140 [19]	Diurnal balancing	~ 15 minutes	Diabatic: 42 - 55% Adiabatic: ~ 70%
Batteries	1.5 GW	40 MW [20]	minutes	267 - 561 [21]	Frequency & voltage response; diurnal balancing	< 1 second	60 – 75%
Cryogenic	5 MW	15 MWh	~3-6 hours	150 – 250 [22]			50 – 70% [23]
Capacitors	69 MW	15 MW	Minutes	180 – 350 [24]	Frequency response	< 50 ms	~ 90%
Flywheels	931 MW (of which 857 MW is for nuclear fusion research sites)	400 MW (JET, Oxfordshire, UK)	20 seconds	342 – 555 [25]	Frequency response Power quality High bursts of power UPS		~ 90%
		20 MW 5 MWh [26]	15 minutes				

[14] DOE [Dept. of Energy, USA] Global energy storage database, Sandia National Laboratories, downloaded Dec-17
[15] International Hydropower Association web site
[16] Bath County pumped storage station https://www.dominionenergy.com/about-us/making-energy/renewables/water/bath-county-pumped-storage-station
[17] Unsubsidized Levelized Cost of Storage Comparison, Lazard, 2016 https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf
[18] DOE [Dept. of Energy, USA] Global energy storage database, Sandia National Laboratories, downloaded Dec-17
[19] Unsubsidized Levelized Cost of Storage Comparison, Lazard, 2016 https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf
[20] Government of South Australia, 2017, http://ourenergyplan.sa.gov.au/battery.html
[21] Unsubsidized Levelized Cost of Storage Comparison, Lazard, 2016 https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf
[22] Liquid Air Energy Storage (LAES) – Highview Power Storage, Highview Enterprises Ltd, 2015 file:///D:/Downloads/12.%20Grid%20Scale%20Liquid%20Air%20Energy%20Storage-Dr.%20Gareth%20Brett,%20Highview%20Power%20(3).pdf
[23] Cryogenic energy storage plant could provide valuable back-up, article from The Engineer, February 2011 https://www.theengineer.co.uk/issues/28-february-2011/cryogenic-energy-storage-plant-could-provide-valuable-back-up/
[24] E-storage: Shifting from cost to value, World Energy Resources, 2016 https://www.worldenergy.org/wp-content/uploads/2016/03/Resources-E-storage-report-
[25] Unsubsidized Levelized Cost of Storage Comparison, Lazard, 2016 https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf
[26] Grid-scale flywheel energy storage plant, Beacon Power, October 2012

Indicative statistics for energy storage technologies
The data come from a variety of sources of different dates, may be out of date, varies with application and assumptions, etc; use with caution!

Relevance to civil engineering: the technology involving the greatest civil engineering input is clearly PHS, followed perhaps by compressed air storage. The other technologies mostly involve simple foundations and buildings in so far as the civil engineering input is concerned. Especially given the context of carbon reduction targets, whole-life carbon emissions associated with all infrastructure projects must be minimised. The guidance in PAS 2080: Carbon Management in Infrastructure should be used to evaluate and manage whole life carbon emissions. In doing so, the maintenance, use and decommissioning of assets must be considered. And, given the potential hazards of stored energy in its various forms, health and safety issues must also be fully addressed.

Challenges

Intuitively, storage of energy is appealing; it appears ideally complementary to the intermittency of renewable generation. However, there are several reasons why it may not be as attractive as at first it seems.

First, to reduce carbon emissions, the electricity must come from a low-carbon source and be used to displace fossil-fuelled generation. Further, it uses electricity; typical 'round-trip' efficiency is around 70 to 95%, depending on the technology used; some technologies are much less efficient than that.

Next is cost. There are typical ranges of costs for some of the energy storage technologies in the table above. Without going into detail, clearly the cost of storage is not trivial and is additional to all other costs of generating and delivering electricity. Energy storage only makes commercial sense when exploiting a significant difference between the purchase and selling prices of electricity (arbitrage).

Then there is the capacity. PHS provides easily the largest power and energy capacity of any form of storage to date. But even the largest schemes can only provide of the order of say 1,000 MW for a few hours. That is sufficient for rescheduling the output of solar energy within one day (in fine summer weather) but is well short of being able to store grid-scale energy from wind over a few days for use in a subsequent period of high pressure and light winds.

Another, possibly contentious, measure is the ratio of 'energy returned on invested', EROI.[27], [28], [29] Energy invested includes all energy required to source materials and build a plant, to obtain the fuel and operate the plant through its life, and to decommission it. EROI must be at least 1 if a plant is to yield more energy than is invested but a ratio of about 7 may be considered an economically viable minimum. Fossil-fuelled, nuclear and hydroelectric generating stations have EROIs of around 30 to 100. Wind and solar PV may have values of about 20 and 10 respectively (2017). These figures are reduced of course if storage is added so the addition of storage may appear uneconomic if judged solely on this measure. However, the EROI for renewables is increasing as costs decrease, and the need to decarbonise coupled with arbitrage may override an EROI criterion except as a comparative measure.

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[27] Energy intensities, EROIs, and energy payback times of electricity generating power plants. Weiβach et al, Energy 52 (2013) 210. Reprint available here.
[28] Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response, Marco Raugei et al, Elsevier, March 2017. Available **here**.
[29] Energy returned on energy invested, Wikipedia https://en.wikipedia.org/wiki/Energy_returned_on_energy_invested (A web search will reveal many other references.)

The last issue considered here is policy, regulation and market framework. At present in the UK, the development of storage is hampered by regulatory constraints and lack of incentives for deployment of storage. For example, Transmission System Operators are forbidden from controlling energy storage, District Network Operators are only allowed 'small' amounts of storage, and flexible sources of generation are mostly cheaper than storage. The UK Government consulted on this issue in 2016 and may make changes that would favour deployment of storage. See ICE's report 'Realising the potential' for further information.

Conclusions

Decarbonisation is changing the way we generate, distribute and use electricity. Especially as some of the technologies are developed and get cheaper, the opportunities as well as the need for successful deployment of electricity storage will increase. Electricity storage will be able to help achieve decarbonisation targets provided that it is charged from surplus low-carbon electricity.

At present, pumped hydroelectric is the mature and dominant energy storage technology. Of many other technologies that have potential to make a significant contribution, battery technologies are advancing the most rapidly; costs are coming down and the rate of installation (mostly lithium-ion) is increasing quickly.

None of the challenges noted above should be regarded as reason to hold back on the deployment and growth of energy storage. The need for change is not confined to electricity. In all aspects of the built environment, engineers must seek to reduce whole-life greenhouse gas emissions in line with targets. See also ICE's briefing sheet on heat.

Further reading

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The rise of electricity storage: something for everybody, Brookings, 2015 http://www.brookings.edu/research/opinions/2015/05/08-electricity-storage-rise-banks

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Comparison of large-scale energy storage technologies, Energy 169 November 2016 Issue EN, ICE

Energy Storage: Opportunities & Challenges, AXIS and Renewables Consulting Group, August 2017 https://thinkrcg.com/energy-storage-opportunities-challenges/

Batteries, Exports, and Energy Security: The deployment of 12GW of battery storage, All Party Parliamentary Group (APPG) on Energy Storage and Renewable Energy Association, December 2017 http://www.r-e-a.net/upload/energy_storage_appg_report-_dec_2017_-_large_-_final.pdf