SUPPLEMENTARY INFORMATION

S1: CAES - geological storage options, developments and restrictions

(reference numbering/citation relates to main paper and references in additional Supplementary Information listing; A[number])

Critical to the success of every CAES project is a repository for the safe and secure storage of large volumes of air at very high pressures, which typically represents the most important and expensive component of the system. Technologies behind current and future electrical energy storages based on compressed air, are largely those developed and proven for the long-term, safe storage of fuels (notably compressed natural gas), the origins of which can be traced back to 1915.[4,8] A number of underground (geological) storage options are available, including man-made voids (solution-mined salt caverns, abandoned mines, conventionally mined unlined salt and rock caverns [URC's] and lined rock caverns [LRC's]) and porous rock storage (depleted hydrocarbon fields and aquifers). Geological storages offer important advantages over surface storages including: high storage capacity due to large volumes and high operating pressures, protection against external influences (including natural catastrophes, during periods of war and acts of terrorism), a low surface footprint plus low environmental impacts, long operating lifetimes and low costs (relative to storage capacity).[4,A1] Whilst investigations into many of the CAES technologies date back to the 1960s, with studies also having included the feasibility of using storage caverns excavated by nuclear explosives,[A2] the last 15-20 years has seen significant research into CAES, with ever more efficient and novel CAES operating systems (Supplementary Appendix 1, Tables A1-A6).

Salt cavern storage

Thick, deeply buried (>250 m) massively bedded or domal halite deposits exist in many countries[A3] and are hosts to important solution-mined salt cavern gas storage facilities, which in 2014, ranked third globally, accounting for 6% of storage, but providing more rapid cycle storages.[4] Being the host to the only three operational CAES facilities that prove CAES to be a commercially viable, mature and cost-competitive technology to meet bulk, grid-scale storage requirements, they are also associated with the largest number of CAES assessments (Supplementary Appendix 1, Table A1). In 1969, the need for storage capacity in northern Germany triggered the decision by the utility Nordwest-deutsche Kraftwerke (NKW) to develop the world's first conventional DCAES facility at Huntorf, construction of which commenced in 1974 with commissioning in 1978.[9] The Huntorf plant, currently operated by E.ON Kraftwerke GmbH, remains operational over forty years after commissioning, employing two air caverns 150 m in height, with a third cavern storing gas required to reheat the air during generation.[9] Originally providing rapid 'black start' capability required by the north German grid it today primarily provides the power grid with minute reserves, balancing-out shortfalls between day-ahead-forecasts for wind power and actual production.[9] Initially rated at 290 MW output capacity, upgrades in 2006 raised this to ~321 MW, achieved within 6-9 minutes. Expectations were high, then and at times since, that CAES would gain utility acceptance.[7,A4]

However, there was not the take-up or development expected for both conventional DCAES and second generation ACAES or ICAES technologies. Despite advanced designs for DCAES plants with heat recuperation, such as the Soyland Power Cooperative Inc. 220 MW plant in 1982, further developments for advanced designs was linked to successful implementation of DCAES, which did not occur until 1991 with the 100 MW, 10 hour McIntosh plant in Alabama,[5,10] following which market and economic drivers changed unfavourably. Commissioned in 1991 and operated by PowerSouth Energy Cooperative, the DCAES plant at McIntosh Alabama was, and remains, the world's second operational facility. It utilises one 263 m high, cigar-shaped cavern[A5] and has an output of 110 MW, available within 14 minutes. It differs to Huntorf in that a recuperator captures waste heat from the turbine power plant to heat the withdrawn air, raising plant efficiency.[A6] In late 2019, the Goderich facility (Ontario, Canada) became the world's third salt cavern-hosted and first commercially operational, utility-scale ACAES plant, with a 2.2 MW charge rating, providing 1.75 MW of peak power output and 10+ MWh of storage capacity.[11,A7,A8] A small (2MW) isothermal test facility linked to wind generation also operated briefly between 2012 and 2016 at Gaines, Texas.[25,26] Interest in salt cavern-hosted CAES continued through the 1980s into the 1990s, with most studies in the US, but including in halites of Tertiary age in Israel[A10] (Supplementary Appendix 1, Table A1). Considerable interest in salt cavern-hosted CAES has been shown since the mid-2000s, particularly linked to renewable generation and support. Most assessments or proposed developments are in the US and Europe, including Germany, Austria, Spain, Denmark, The Netherlands and the UK, but they include projects in China and Canada (Supplementary Appendix 1, Table A1).

The RWE led 'ADELE' project was to develop at Stassfurt (Germany) the world's first ACAES plant,[A12] feasibility studies for which started in 2007 with construction planned in 2016. The TES system was progressed[A13] but the 360MW project is halted indefinitely. In the UK, Storelectric and Gaelectric were progressing projects that have received EU-funding as part of developing energy infrastructure. Most advanced was Gaelectric's application to construct a 200-300 MW plant at Larne in Northern Ireland (EU 'Project 1010').[43] With caverns at depths in excess of 1500 m, this would be the deepest CAES facility constructed. However, the collapse of the Gaelectric group of companies in 2018 means the future of the various projects are unclear, with the exception of that in the Netherlands, owned subsequently by Corre Energy BV.[A14] Storelectric Limited was assessing various CAES proposals including retro-fittable CCGT CAES plant technology (EU 'Project 1023') and a TES system (EU 'Project 1022 - 'CARES'') with development in two stages: a 40 MW test facility followed by a 540 MW plant.[A15]

Despite this interest, to date, the salt cavern storages at Huntorft, McIntosh and most recently Goderich, represent the only currently operational and commercial CAES facilities providing bulk energy storage.

Porous rock storage – depleted fields

Gas storages in porous rocks provide the greatest volumes with, worldwide, depleted fields being volumetrically and numerically the largest (around 81% of 2014 stored natural gas

volume) and aquifers second (around 13% of 2014 global storage capacity).[4] Porous rock storages, due to size and requiring numerous wells and limited by porosity/permeability of the reservoir, generally represent longer-term, seasonal storages. CAES in porous rock storages has been considered for many decades, in both depleted fields and aquifers, particularly in the US (Supplementary Appendix 1, Tables A2&A3) and follows the same principal as natural gas storage. Matrix (pore) porosity is most common, but fracture porosity has been considered, particularly in aquifers as in the Pacific Northwest in eastern Washington and Oregon states.[A16]

Depleted field CAES has been considered since the 1970s (Supplementary Appendix 1, Table A2),[13,14] however, although a number of assessments and feasibility studies have been undertaken in the 2010s, no CAES in depleted oil or gas fields exists to date. Between 2012 and 2015, depleted field studies were under investigation for CAES by KPC&L, NPPD, NYPA, NYSERDA, PG&E, SMUD, Tri-state and Xcel, with support from NETL and EPRI.[A17,A18] Significant among these were the PG&E-led investigations in California, particularly an advanced 300 MW, 10-h CAES plant using a depleted gas reservoir, which received significant funding from the ARRA 2009 Energy Smart Grid Demonstrations Program (specifically for advanced CAES demonstration projects),[A17] California Public Utilities Commission (CPUC), and the California Energy Commission (CEC), with the hope a commercial plant could on-line by 2020-2021. An early PG&E & EPRI interest thought to have good potential and capable of supporting a 110 MW, 37-hour CAES plant, was the Dunnigan Hills depleted gasfield, NW of Sacramento, northern California.[A19] Interest, however, lay to the south and a tie-up with the 4500 MW Tehachapi Wind Project in southern California with both depleted field and aquifer storage considered.[A19] From over 120 sites considered three top sites in late 2012 were chosen for further study,[A20] plus the Bakersfield saline aquifer site (see below). By February 2013 all permits and approvals required to begin site preparation, borehole drilling, core retrieval and to develop a CAES facility at two sites were obtained: at King Island and East Island, San Joaquin County.[A21,A22] The first phase of the feasibility study was completed in June 2013 with the collection of core samples at the two sites, which were sent for laboratory analysis to determine permeability, porosity and sample mineralogy.[A21,A22] King Island was selected as the preferred site for an Air Injection Test (AIT), with a reservoir model constructed based on 3D seismic reflection data and the engineering, procurement, and site preparation completed for the AIT involving a series of pressure tests.[A22] The project demonstrated the technical feasibility of using the abandoned King Island natural gas reservoir for storing high-pressure compressed air for a 300MW, 10-hour CAES facility. The reservoir proved capable of accommodating the flow rates and pressures required for the operation of the facility. However, the current status is of the project is unclear, but seems stalled due in part to the high cost of a CAES facility relative to alternative energy storage technologies.[27]

Depleted field CAES has continued to attract attention around the world (Supplementary Appendix 1, Table A2), including in Portland (Australia),[A23] Nebraska Public Power District (NPPD) using the Big Springs gas fields in western Dakota[A24] and the Sacramento Municipal Utility District (SMUD) assessment for sites in Sacramento, California.[A25] However, depleted

field storages carry increased risks, specifically compressed air introducing oxygen into a depleted natural gas reservoir with residual hydrocarbons presents a situation where an ignition and explosion potential exist. This could be both underground in the reservoir or in the wellbore and during discharge due to residual hydrocarbons in the depleted formation.[28] These authors suggest that underground fire or explosion could occur with the heat or ignition source provided via a variety of potential mechanisms: the heat of compression energy generated as the air is compressed prior to injection into the underground storage reservoir by friction and movement generated within the formation during compressed air charging or discharge, piezoelectric discharge from material within the formation, static electricity discharge, surface lightning strike etc.

Porous rock storage – saline aquifers

Early assessments of CAES also considered aquifers (Supplementary Appendix 1, Table A3), which continued through the 1990s, including in Israel[A10] and the Gippsland Basin in SE Australia,[A28] the 2000s and into the 2010s, including a UK offshore CAES aquifer assessment.[15] Amongst the earliest aquifer CAES studies was the development programme, jointly sponsored by the US DoE and EPRI and led by Public Service Company of Indiana (PSCI) during the 1970s in which CAES in Illinois and Indiana, where aquifer gas storages were already established in both sandstone and carbonate reef reservoirs, was assessed for an up to 1000-MW CAES facility.[14,A26,A27] The Calcutta-Carbon field (Indiana) with a reefal limestone reservoir, identified originally for gas storage and with reservoir and injection tests completed, was made available for CAES evaluation and development,[A26] but was not progressed. During the early-mid 1980s extended injection tests were conducted on sandstones in the Pittsfield 'dome' (Illinois), with DOE funding and led by Pacific Northwest Laboratory (PNL).[A19,A26] Selected from eleven candidate sites a comprehensive investigation into the practical feasibility for CAES in aquifers was undertaken between 1982 and mid-1984.[A26] A 25MW (2 MPa/290 psi/20 bar) mini-CAES test facility undertook injection and partial withdrawal of air over several years, providing operational data on aquifer performance in terms of air bubble growth, reservoir stability, water coning, particle production, geochemical reaction and thermal storage. A key finding was considerable oxygen depletion following storage due to the presence of pyrites in the reservoir. The Pittsfield aquifer test facility finally closed in 1985.

More recently, the Iowa Stored Energy Park (ISEP) project investigated a 270MW CAES plant linked to wind generation.[12] Investigations ceased in 2011 after detailed geological investigations determined the aquifer identified could not support the planned capacity with oxygen depletion a significant likely problem. Nevertheless, the project left a huge legacy in terms of the volume of data for future reference. Other aquifer sites assessed in the early 2010s have been those by PG&E under ARRA-funding ('Bakersfield' prospect)[A29] and by SMUD[A30] in their California service territories. Nothing was progressed. Two feasibility studies in Europe highlight current interest to support offshore wind energy generation. Estimates for UK offshore aquifer storage suggest the resource could offer considerable inter-seasonal storage capacity, equivalent to ~160% of the UK's electricity consumption for early 2017.[15] A CAES feasibility study of the Middle Cambrian Faludden sandstone reservoir

in several structures was undertaken on Gotland, Sweden.[A31] Estimates for energy storage capacity, based upon a plant with a power output of 70 MW for 18.5 h, suggest that industrial scale CAES is possible, with energy storage capacities up to 1300 MWh.

However, fundamental questions remain regarding the hydrological and energetic performance of CAES in porous rock and particularly aquifers. This is despite aquifer performance for CAES having been examined in numerous studies, including a large US government research and testing programme over 30 years ago, more recent testing of an aquifer site in Iowa, and modelling studies, all suggesting aquifer CAES is feasible.[A32,A33]

Abandoned mine storage

In many areas of the world, the extraction of natural resources such as coal, salt, metals/ores and limestone has left significant underground voids (workings), which depending upon local geological conditions and depth, may be utilised for the storage of liquids (e.g. water and hydrocarbons) and gases, including air. However, other than mine energy air storage schemes in Scandinavia and a number of CAES tests in worked areas of mines (Supplementary Appendix 1, Table A4), there has been no use of former mines in non-salt rocks for CAES. Investigations and assessments have appeared periodically since the mid-1970s and continued into the 21st Century, with a number of projects in the US, including in New York State[A34] and in Minnesota[A35] during the mid-2010s. Use of former mines for CAES was assessed in Germany in 2010.[A36] However, the most significant CAES project proposed in such storage was a 2700 MW CAES plant in a former limestone mine at Norton, Ohio (USA). First considered in the 1980s, most recent interests started in 2000,[A37] with investigations having continued through until 2013, when the project was suspended.[A38]

Unlined, conventionally mined rock caverns

In regions lacking cheaper alternative geological storage options, URC's have been constructed for liquid and gaseous hydrocarbon storage. Despite this and small rock cavern compressed air storage schemes operating in association with mines and PHS plants, URC's have not been deployed for CAES purposes. However, supported by the Swedish firm Stal-Laval, a number of feasibility studies and assessments were undertaken in Sweden, dating back to the late 1940s (Supplementary Appendix 1, Table A5), but mostly the late 1960s-1970s.[A39,A40,A41] In the UK, the Central Electricity Generating Board (CEGB) considered introducing CAES to the grid in England and Wales in the 1960s, conducting preliminary pressurisation tests of an unlined, test gallery at the Ffestiniog PHS site in North Wales.[13] It was not progressed due to the existing PHS plant and a lack of suitable rock type locations.

Interest continued through the 1970s to early 1980s with a number of regional assessments and technical feasibility studies into water-compensated URC storage undertaken in Illinois, California, Kansas, New York State, Maryland, New Jersey and Washington D.C.[13] One significant project involved Soyland Power Cooperative Inc. and a planned 220 MW DCAES plant using a water-compensated URC and heat recuperation to support a coal-fired power station in Illinois.[14] Plans were advanced and contracts signed, however, construction of the coal-fired plant was deferred in 1982 due to a lesser demand for electricity, impacting

directly Soyland's plans to construct the CAES plant.[A42] CAES in URC's was considered by various other countries/utilities at this time, including in Yugoslavia and in Luxembourg, the latter not constructed, but for which a small test cavern was excavated at Bremm, near Mosel.[A43] At the Roda Stern Rock Laboratory (RSRL) near Gothenburg, Sweden, built during the late 1980s to assist development of natural gas storage in URC's, a number of caverns were constructed and a series of tests in one cavern during 1990-1992 were pertinent to the development of CAES.[A44]

Japan and Korea considered CAES in both URC and LRC's from the late-1980s (Supplementary Appendix 1, Tables A5&A6). A series of trial boreholes were drilled into granitic rocks of Cretaceous age, and tests on an unlined cavern, sealed by concrete plugs at a depth of ~530 m at the Kamioka mine in west central Japan were conducted during the late 1980s.[A45] Nothing was developed.

URC storage is once again under consideration in various countries (Supplementary Appendix 1, Table A5), including a 300 MW CAES facility reportedly planned, using a cavern excavated in sandstone at a depth of ~500 m near Datang, Inner Mongolia, China,[A46] and in former LPG chalk storage caverns at Petit-Couronne, northern France.[A47] The ALACAES project, re-purposing part of a disused, unlined tunnel ~450 m deep near Biasca in the Swiss Alps, is a 0.5 MW ACAES demonstration plant incorporating a TES within the storage chamber.[30,A48] Construction commenced in June 2014, with commissioning and first testing having begun in 2015, during which the main sealing plugs suffered significant leakage. The problem was rectified and extended tests of the storage and TES were ongoing.

Conventionally mined, lined rock caverns

Over the years, assessments and tests of CAES LRC potential in a number of countries lacking other suitable rock types have been undertaken, most notably in Japan and Korea (Supplementary Appendix 1, Table A6). A programme known as 'Urban CAES' in the mid-late 1980s assessed both hard and soft rock LRCs in Japan.[A49,A50] The concept was not progressed. In the early-late 1990s, during planning of a 500 MW gas turbine plant supported by a 100,000 m^3 cavern, several in situ LRC tests and a 2 MW, 4-hour storage pilot CAES gas turbine (CAES-G/T) plant was constructed in worked-out areas of a coal mine at Kamisunagawa-cho, Hokkaido, northern Japan.[A51,A52,A53] The pilot plant cavern, lined by reinforced concrete segments with concrete back-fill and a butyl-rubber lining, was completed in 2000 and the facility commissioned in June 2001. Test operations were successful and although there were plans to develop a 35-MW, 8-hour CAES plant and research on rubber linings continued,[A53] nothing was developed. During studies developing an LRC natural gas storage, the ANGAS project successfully tested a small LRC using compressed air at the Kamioka Mine in Japan.[A54]

In the early 2010s, investigations into LRC storage commenced at Jongson in Korea, with tests of two concrete-lined, pilot caverns, constructed in a working limestone mine[A55] A 100 MW CAES plant using a concrete and rubber sheet lined LRC in granite is planned in the Inner Mongolian region (China).[A56] In Austria, the EU-funded RICAS2020 project is investigating AACAES potential, using an LRC constructed in an area of a worked

limestone-hosted iron ore mine at Eisenerz in Austria, with the TES independent of the geology.[A57] A small-scale 5 MW pilot LRC facility is being constructed and tested, with for a full-scale, 100 MW test power plant facility planned.

Renewables (wind & solar) CAES

Although discussed as early as the mid-1970s and early-1980s,[13,A58] the application of CAES to compensate for fluctuating renewable energies was not a major consideration at that time. However, increasing penetration of intermittent renewable energies such as wind and photovoltaics into electricity supply systems, linked to national commitments to reduce CO_2 emissions, and the need for the balancing of supply to the grid, has driven renewed interest in CAES since the 1990s and into the 21st Century. Many countries see CAES as a key enabling technology for the integration of such intermittent renewable resources with many proposed projects across all storage types, notably in the US, involving CAES linked to renewable electricity generation, storage and grid support (Supplementary Appendix 1, Tables A1-A6).[A59,A60]

Between 2000 and 2018 many projects around the world have been considered, including in the US, Canada, UK, Austria, Denmark, Netherlands, Italy, Egypt, China and South Korea. Considerable research into CAES of all types has recently been funded by the US government and EPRI through e.g. the American Recovery and Reinvestment Act of 2009 (ARRA), and in Europe through Horizon 2020 and the EU Trans-European Networks for Energy (TEN-E) Infrastructure Regulation (347/2013 EU).[e.g.8] The EU-funded Framework Programmes and the French SEARCH and SACRE projects have funded investigations into aspects of CAES, ACAES and grid modelling across differing storage types. In the US some ARRA and EPRI funded assessments have reached advanced design and permitting stages (e.g. Seneca Lakes and PG&E's King island project). The European-funded TEN-E scheme aims to promote 'Projects of Common Interest' that support future energy supply and security. In none of these countries has construction of commercial plants commenced.

As alluded to, a small-scale, near-isothermal 2 MW CAES demonstration plant, supporting wind generation, operated between 2012-2016 at Gaines in Texas[26,27] Elsewhere, in addition to PG&E's depleted field investigations,[27] such storage in support of wind generation has been assessed recently at e.g. Portland, Victoria, Australia.[A22] Aquifer storage has been assessed in the North Sea and Sweden, whilst economic and feasibility studies were undertaken into the potential for an abandoned gold and silver mine beneath a wind site and supporting a 50MW CAES plant in Colorado.[A16] The project has not been progressed. More recently, Hydrostor Australia Pty Ltd, part-funded by the Australian Renewable Energy Agency (ARENA), announced a clean energy hub at Strathalbyn, 60 kilometres southeast of Adelaide, Australia, including construction of a 5 MW/10 MWh commercial demonstration ACAES facility using a decommissioned Angas Zinc Mine.[A61] It is due for commissioning in 2020/21. Projects in China supporting renewable generation are progressing in most storage types, with some facilities under construction, although to date nothing has been put into service.[A62,A63]

S1, Table S1. Summary of main compressed air or CAES projects and/or assessments in former brine and new solution-mined salt caverns. Cell highlighting: grey = tests, or operational, green = associated with storage from renewable generation.

Facility/project/ assessment name	Type/ rocksalt type	Date	Location	Power capacity (MW)	Storage depth, top (m)	Description/status
McIntosh conceptual study	Diabatic/ domal	Early 1970s	Alabama, USA	800	~460	Concept design. Informed 110MW McIntosh plant built later (1991)
Denmark assessment	Diabatic/ domal	Early 1970s	Denmark			Interest, but no further detail
Bay of Fundy +tidal power	Diabatic/ domal?	1970s	Nova Scotia, Canada			Early studies. Not progressed
Northern Ireland Electric Service CAES study	Diabatic/ bedded	Mid-1970s	Larne, Northern Ireland			Feasibility of CAES cavities in Larne area. Not progressed
Huntorf (NKW, now EON Kraftwerk)	Diabatic/ domal	1978	N. Germany	290 upgraded to 321	650	Operational. 2 CAES caverns, 1 natural gas cavern
Carmichael Dome study (Middle South Services, DoE/EPRI)	Diabatic +recuperator / domal	Late-1970s	Mississippi, USA	220	≤1060	Joint Doe/EPRI funded techno-economic feasibility assessments of 3 storage types. Salt cavern (2) led by MSS. 47 sites Hazlehurst/Prothro/Carmichael domes
Mississippi Power & Light Co., Petal salt dome	Diabatic/ domal	Late-1970s-early-1980s	Hattiesburg, MS, USA	~100		Evaluation of 2 propane storage caverns. Not progressed
CEGB feasibility	Diabatic/ bedded	1980s	England, UK		~450	Feasibility study for isobaric & isochoric mode. Not progressed
UE&C & BBC hybrid CAES concept	Diabatic/ adiabatic/ domal	Early 1980s	Carmichael, MS, USA	220		Engineering design & economic study. Not progressed
Hybrid CAES concept	Adiabatic/ domal	Early 1980s	Mississippi USA	220		Engineering design & economic study. Not progressed
Houston Lighting & Power Co., Big Creek salt dome	Diabatic/ domal	1980s	Fort Bend County, TX, USA	~100		Evaluation of virgin site. Not progressed

McIntosh (PowerSouth)	Diabatic +recuperator / domal	1991	Alabama, USA	110	457	Operational (1991-present day). 1 CAES cavern
SE Mississippi study	Diabatic/ domal	Early 1990s	Mississippi USA	280		Technical, economic assessment only
Central North Dakota wind energy system	Diabatic/ bedded	Early 1990s	North Dakota, USA	1500, 20-250 hours storage		Wind energy baseload system potential and Great Plains of America supplying Minneapolis 800 km to SE. Not progressed
'Great Plains' Kansas wind/CAES	Diabatic/ bedded	Early 1990s	Western KS, USA	1500, 50 hours		Assessing wind-generated electricity & supply to southern California
Nuclear Electric assessment	Diabatic/ bedded	1990s	England, UK	~300	~450-500	Feasibility study for isobaric & isochoric mode. Not progressed
Donbass	Diabatic/ bedded?	1989-1991	Russia-Ukraine border	1050		Construction began. Abandoned (collapse Soviet Union)
Shiqma (Israel Electric Corp.)	Diabatic/ Bedded	Mid-1990s	Israel	300-400	1,200	Assessment for up to 6 CAES caverns. Not progressed
Mt Sdom (Israel Electric Corp.)	Diabatic/ bedded	Mid-1990s	Israel	300-507	500	Assessment for 2 CAES caverns. Not progressed
EPRI & NYSERDA New York State feasibility study	Diabatic/ bedded (Silurian)	Early-mid 1990s	New York State, USA	100-350	180-915	Assessment of LPG, brine & new caverns. Not progressed
Texas Panhandle study (SECO/Ridge Energy)	Diabatic/ bedded	Early-2000s	Texas, USA	~135		Wind-CAES assessment. Up to 6 CAES caverns. Not progressed
Alton CAES (Alton Nat. Gas/Landis Energy)	Diabatic/ bedded	2005	Truro, Nova Scotia, Canada	220		Salt caverns for natural gas storage & CAES supporting renewables. Dropped?
Offshore storage & renewable energy study	Diabatic/ domal	Late 2000s-mid 2010s	Southern North Sea, UK sector			Number of technical/ economic feasibility studies. Not started
Finger Lakes & Silver Springs regions (Energy East Corporation, NYSEG & EPRI). ARRA funds	Diabatic/ bedded	2007-2009	Seneca Lakes, New York State, USA	~180 (150-360)	~610	Brine cavern at 1st site 'shovel ready'. FEED. Dropped (2010)
		2010-2012 (ARRA)		130-210	~730	2nd site, up to 3 new cavern. FEED studies. Cancelled 2012 (cost)
North Dakota (Sirius Exploration & EPRI)	Diabatic/	2008-2011	North Dakota, USA	390, 30 hours	~1950	Feasibility study for CAES tied to ND wind energy. Shelved?

	bedded potash					
Gaines (General Compression) +wind	Isothermal/ bedded	2012-2016	Texas, USA	2	745	Pilot plant, 1 cavern, operational from 2012, but shut down 2016
APEX Bethel Energy Centre (Tennessee Colony)	Diabatic/ domal	Early mid-2010s	Texas, USA	317 (270-540)	~1140	Fully permitted and construction-ready for 1 cavern, supporting ERCOT renewable electricity. Stalled?
APEX Matagorda Energy Centre (Ridge Energy SS)	Diabatic/ domal	Mid-2010s	Texas, USA	317-540	~1140	Advanced planning, 2 caverns permitted, supporting ERCOT renewable electricity. Dropped (post-2012)
Chamisa 'Tulia CAES plant' project	Diabatic/ bedded	Mid-2010s	Texas, USA	270	~710	Advanced planning for 5-7 caverns, supporting ERCOT renewable electricity. Some permits obtained. Dropped?
Pierce Junction (Ridge Energy SS)	Diabatic/ domal	Mid-2010s	Texas, USA	270 (2x135)		Assessment. Dropped?
'Pathfinder Wind and Energy Storage Project' (Haddington Ventures [Magnum Gas Storage LLC], Duke Energy)	Diabatic/ bedded?	Mid-2010s	Delta, Millard County, Central Utah, USA	~300 (2x150) - ~1268		Up to 4 CAES caverns assessed Central UT, linked to 2100 MW wind farm in SE WY supplying electricity to CA. Phase I 317MW, Phase II 1200MW. Progressing?
Brayton Energy hybrid CAES system	Hybrid adiabatic?/ bedded	2010-present?	Phoenix, AZ, USA	~100 (~1 GWh)	>300	Assessing 1 cavern system using solar energy to heat compressed air
Alberta Saskatchewan Intertie Storage Project (ASISt) +wind (Rocky Mountain Power)	Diabatic/ bedded	Mid-2010s	Alberta/ Saskatchewan, Canada	160		60 hour (9600 MWh), 2 cavern wind-CAES project. Planning
Advanced 2nd Generation CAES and ACAES Plants (US DoE funds)	Adiabatic/ bedded/domal	Early 2010s	USA	180, 310 & 450		US DoE stimulus funds for 2nd gen$^{n.}$ CAES to support Ren. Energy & Smart Grid
'ADELE' (RWE Power led consortium)	Adiabatic/ domal	2007-mid 2010s	Staßfurt, Germany	~360	~400	Assessment, not progressed (late 2015)
Endesa assessment (Endesa S.A. & EPRI)	Diabatic/ adiabatic/ bedded	Mid-2010s	Spain	150		Feasibility study on plant design and storage options - 2-3 suitable salt formations identified. Progressing?

EU 'Project 1010' Islandmagee (Gaelectric)	Diabatic/ bedded	Mid-2010s	N Ireland, UK	~330	~1500	Advanced planning, 2 CAES caverns supporting renewable energy. Applications & EA report. Ceased?
EU 'Project 1005' (Gaelectric)	Diabatic/ bedded	Mid-2010s	Cheshire, UK	268	~500	Feasibility & planning. Ceased?
EU 'Project 1013' (Corre Energy Storage BV)	Diabatic/ Domal?	Mid-2010s	Zuidwending, Netherlands	330		Feasibility & planning for CAES & offshore wind. Delayed
EU 'Project 1022 – CARES' (Storelectric) +renewables	Adiabatic/ bedded	Mid-2010s	Cheshire, UK	540 (total)	~500	Test (40 MW) and full plant (540 MW). Planning
EU 'Project 1023 - Cheshire Gas CAES' (Storelectric)	Diabatic/ bedded	Mid-2010s	Cheshire, UK	300	~500	Advanced planning retrofittable CCGT CAES plant technology storing locally generated renewable electricity. Stalled?
Energy Storage Niederrhein project	Diabatic/ domal	Mid-2010s	Wesel, NW Germany		~930	Advanced design & planning stage for up to 3 CAES caverns. Stalled?
'ALP-CAES' conceptual PHS/ CAES hybrid study +renewables	Diabatic/ domal/bedded?	Mid-2010s	Denmark			Air compressed by brine pumped into cavern. Concept
Hybrid CAES fuel system	Diabatic/ bedded	2012-2014	China	~410		System performance & economic study
Huai'an City project (Sci. Foundation of China [973] Program)	Diabatic/ bedded	2014	Jiangsu Province, China	60	~1330-1470	Geotechnical feasibility study for CAES and renewables/grid support.
Feicheng A-CAES (Chinese Acad. Sciences, Energy Storage Alliance, Gezhouba Utd Alliance) +wind/solar	Adiabatic/ Bedded	2019-present day	Feicheng, Shandong, China	10 initial (1250 final)		Ground breaking ceremony Nov. 23 2019 for initial 10MW advanced CAES system. Construction 2-5 years, ultimately 1250MW & 7500MWh
'Salt Cave Compressed Air Energy Storage National Test and Demonstration Project' (Chinese Academy Sciences) +wind/solar	Adiabatic/ bedded	Mid-late 2010s-early 2020s	Jintan, Jiangsu Province, China	60 initial (300MWh)		Initial geotechnical feasibility study non-supplementary fuel (NSF-CAES). 1st phase of construction started Sept. 2020
CAES assessment N Spain	Diabatic?/ domal	Mid-late 2010s	Cantabrian Mts, N Spain	10-100	400-800	Small-scale CAES assessment for renewable energy storage in salt domes.

University of Waterloo & industrial partners study	Diabatic/ adiabatic/? domal/bedded	2016	Nova Scotia, Ontario & Alberta, Canada			Study of CAES in salt caverns & renewables, optimising economic value to microgrids.
Austria study (Austrian Research Promotion Agency)	Adiabatic/ domal/bedded	2017	Upper Austria	10-50		Feasibility study of potential for brine & new caverns +renewables. Sand in TES.
NAM70 Challenge (Storelectric)	Diabatic?/ domal?	2018	Netherlands & S. North Sea			Study re-purposing oil & gas infrastructure +offshore wind
Goderich Mine (NRStor-led consortium, incl. Hydrostor)	Adiabatic/ bedded	2019-present day	Ontario, Canada	1.75 (10+ MWh)	~550	Commissioned Nov. 2019 & world's 1st commercial ACAES plant. 1 cavern

S1, Table S2. Summary of main compressed air or CAES projects and/or assessments in depleted fields. Cell highlighting as in S1, Table S1.

Facility/project/ assessment name	Type/ rock type	Date	Location	Power capacity (MW)	Storage depth (m)	Status
CEC feasibility study (Calif. Energy Commission & U.S. DoE)	Diabatic/ sandstone	Early-mid 1970s	California, USA	200-250x3 (600-750 total)	670-750	Early Acres American Inc. site feasibility &, design study. 10 sites identified, one selected for study.
			Princeton, Glen County, CA			Feasibility & conceptual design of preferred location. Not progressed.
TVA (Tennessee Valley Authority)	Diabatic/ sandstone	Early 1990s	Tennessee, USA	600-1200		Geotechnical assessment of potential. Not progressed
EPRI & NYSERDA New York State feasibility study	Diabatic/ various	Early 1990s	New York State, USA	≥100	457-1525	Part of general CAES feasibility studies for state. Not progressed
Big Springs fields (NPPD)	Diabatic/ Dakota Sandstone	Early-2010s	Nebraska, USA	100-300		Feasibility studies & modelling. Stalled?
Huntley field (Gaelectric)	Diabatic/ sandstone	Early-2010s	Montana, USA	270		Feasibility studies & modelling. Stalled?
East Keith field (Gaelectric)	Diabatic/ sandstone	Mid 2010s	Montana, USA	270		Feasibility studies, modelling & geochemical analyses. Stalled?
Dunnigan Hills (PG&E & EPRI)	Diabatic/ Cretaceous sandstone	2009-2010	Yolo County, California, USA	110	~750	Geotechnical assessment of potential. Rejected
King Island field PG&E (EPRI, ARRA 2009 & CEC funding)	Diabatic/ sandstone	Mid-2010s onwards	San Joaquin County, California, USA	300	~1450	Feasibility studies, EA & technical reports completed 2018. Preferred site with wells, reservoir model & air injection/pressure tests. ?Stalled - costs alt. energy storage technologies?

East Island field		Diabatic/ sandstone	Mid-2010s onwards	San Joaquin County, California, USA	300	~1450	Alternative site investigated, cores retrieved. Not progressed
Thornton field	PG&E/EPRI/ Univ Calgary	Diabatic/ sandstone	Mid-2010s onwards	San Joaquin County, California, USA	300 (aiding studies)	~1000	Studies into gas/air mixes for oxidation & combustion/fire risk
'SMUD' CAES studies +wind integration (Sacramento Municipal Utility District)		Diabatic/ sandstone	Early-2010s	California, USA	135	~1890	North Sherman field evaluated. Rejected
					~268		Assessment of potential & feasibility in State. One field identified. Stalled?
Tri-State (G&T – EPRI)		Diabatic/ various	Mid-2010s	E. Colorado, USA			Feasibility study
Southern California (Edison/ Hydrodynamics)		Diabatic/ sandstone	2010s	California, USA			CAES siting study & evaluation of potential structures
Pecos Valley project (Montoya), Austin Energy		Diabatic/ various	2010s	West Texas, USA			Evaluation by Hydrodynamics of 726 oil & gas-bearing structures
Alberta (Hydrodynamics for Altalink)		Diabatic/ sandstone	2010s	Alberta, Canada			Evaluation of structures, potential sites identified
Pittsfield region (Hydro-dynamics, Nicor Ventures)		Diabatic/ sandstone	2010s	Pittsfield, Illinois			Part of regional study
Portland Wind Farm support (Monash Univ.)		Diabatic/ sandstone?	2011	Onshore Victoria, Australia	80-240 (2x20-80MW)		Assessment of potential & feasibility for CAES &/or PHS to support onshore wind generation.
"Three North Region" CAES +wind & solar (National Key R&D		Diabatic/ sandstone	Late-2010s	North & NE China		Up to 1000	Early-stage assessment

Program of China, Chongqing University)						

S1, Table S3. Summary of main compressed air or CAES projects and/or assessments in aquifers. Cell highlighting as in S1, Table S1.

Facility/project/ assessment name	Type/rock type	Date	Location	Power capacity (MW)	Storage depth (m)	Status
Pays de Bray (EDF)	Diabatic/ various	Early-mid 1970s	France			Feasibility studies. Not progressed
Brookville Dome (National Academy of Science study)	Diabatic/ sandstone	Early 1970s	Illinois, USA	150 units	~205	Brookville Dome considered for a conceptual CAES design
CEC feasibility study (Calif. Energy Commission & U.S.DoE)	Diabatic +recuperator / sandstones	Early-mid 1970s	California, USA	200-250x3 (600-750 total)	~670	Acres American Inc. aquifer studies, 3 identified. Not progressed
Brookville storage site (General Electric, US Energy R&D Admⁿ)	Diabatic +recuperator / sandstones	Mid-1970s	Illinois, USA	600 (10-hour cycle)	~205	Conceptual design, techno-economic requirements study. Not progressed
Calcutta-Carbon field (Strata Power of Indiana)	Diabatic/ vuggy reef dolomites	Early-mid-1970s	Indiana, USA	150	~380	Detailed feasibility studies & 'gas testing'. Not progressed
Aquifer CAES development programme (Public Service Company of Indiana, DoE/EPRI)	Diabatic +recuperator / sandstones	Mid-late 1970s	IL, IN, KY & TN, USA	Up to 1120		Joint Doe/EPRI funded techno-economic feasibility assessments of 3 storage types. Aquifer led by PSCI.
Kansas Utility System study	Diabatic/ sandstone/ carbonate	Mid 970s	Kansas, USA	150-200	230-915	Regional assessment. Not progressed
Hume (URS Corporation/ Hydrodynamics)	Diabatic/ M Devonian carbonate	Late 1970s	Illinois, USA	200-250	~200	Assessment & conceptual designs & economic analyses. Not progressed

Brocton (URS Corporation/ Hydrodynamics)	Diabatic/ M Devonian sandstones	Late 1970s	Illinois, USA	200-250	~200	Assessment & conceptual designs & economic analyses. Not progressed
Pittsfield aquifer test (DoE/EPRI)	Diabatic/ St Peter Sst.	Late 70s-1984	Illinois, USA	25 (test)	~200	Extensive tests, injection of air bubble early 1980s, PNL led. Not progressed
Sesta injection test (ENEL)	Diabatic/ 'fractured porous rock'	1987-1991	Sesta, Italy	25		Demonstration plant. Closed due to reservoir anomaly.
Israel Electric Corporation (IEC) study	Diabatic/ 'fractured aquifer'	Mid-1980s-Early 1990s	Israel	200-400 (?3x ~100 units)		Detailed analysis & feasibility assessments. Not progressed
Gippsland Basin assessment (for State Elec Comm^{n} Victoria)	Diabatic +recuperator / sandstones	Early 1990s	New South Wales, Aust.	100-300	~600	Assessment & modelling of aquifer. Not progressed
EPRI & NYSERDA New York State feasibility study	Diabatic/ various	Early 1990s	New York State, USA		457- 1525	Part of general CAES feasibility studies for state. Not progressed
Iowa Stored Energy Park (IESP), Dallas Centre +wind	Diabatic/ Mt Simon Sst	Early 2000s-2011	Iowa, USA	270	~880	Linked to wind. Extensive tests over 8 years. 3 wells +lab studies. Dropped
Vincent-Eagle Grove Structure (Hydrodynamics/Prairie Wind)	Diabatic/ sandstone	Early 2000s	Iowa, USA	100-200		Feasibility studies to support wind generation. Not progressed
NYSERDA & NYSEG CAES assessment	Diabatic/ various	Late 2000s	New York State, USA			NYSERDA commissioned feasibility study in State
Bakersfield (PG&E with EPRI, ARRA 2009 & CEC funding) +wind	Diabatic/ sandstone	Early 2010s	Kern County, CA, USA	300		Feasibility studies & modelling. Stopped, interest switching to north California. Stalled?

'SMUD' CAES (Sacramento Municipal Utility District)	Diabatic/ sandstone	Mid 2010s	California, USA	~268		Assessment of potential & feasibility in the State. Site identified. Stalled?
Columbia Hills (BPA & PNNL)	Diabatic/ fractured basalts	Early 2010s	Washington State, USA	207	>3000	Advanced assessment & planning
Yakima Canyon, Selah (BPA & PNNL)	Adiabatic/ fractured basalts	Early 2010s	Washington State, USA	83	~4250	TES & geothermal energy. Advanced assessment & planning
UK offshore saline aquifer potential (PhD research)	Diabatic & adiabatic/ sandstones	2018	UK North Sea	4-12 (per well)	260-4000	PhD research into offshore aquifer potential.
Faludden reservoir for CAES on Gotland (onshore) Uppsala/ Lund Univ. & Swedish Survey	Diabatic?/ sandstones	2018/2019	Onshore Sweden	~70	~270-410	Regional aquifer assessment on island to support wind generation Est. capacity 130-1300 MWh

S1, Table S4. Summary of main compressed air or CAES projects and/or assessments in abandoned mines, or worked areas. Cell highlighting as in S1, Table S1.

Facility/project/ assessment name	Type/ rock type/ mine	Date	Location	Power capacity (MW)	Storage depth (m)	Description/status
CEC feasibility study (Calif. Energy Commission & U.S.DoE)	Diabatic/ hard rock	Early-mid 1970s	California, USA	200-250x3 (600-750 total)	~700	Acres American Inc. hard rock cavern appraisal. 12 sites identified, none found suitable.
Mt Hope mine (Jersey Central Power & Light Co)	Diabatic/ iron ore	Early-mid-1970s	New Jersey, USA	190-1000	~825	Initial test plant with planned 1000 MW. Isobaric or isochoric. Existing & new caverns. Not progressed
Kamioka CAES test	Diabatic zinc mine	Late 1980s-early 1990s	Kamioka mine, Japan		~520	Underground 'air receiver' for operations (water-compensated). 'Cavern' leakage testing for CAES
Norton Mine, Ohio (Ohio Edison Co.)	Diabatic/ limestone	1980s	Norton, Cleveland, Ohio, USA	~100	~686	Assessment, for 10 hr charging, 10 hr discharging cycle. Not progressed
Pyhäsalmi mine (Technical Research Centre of Finland)	Diabatic zinc mine	Early 1990s	Finland	34 (150-210 MWh)	400-800	Pre-feasibility, techno-economic studies. Isobaric or isochoric. Not progressed
Old Grace Mine (CAES Corp.)	Diabatic	Early 1990s	Philadelphia, USA	110	~270	EPRI grant applied for. Water-compensated. Not progressed
New York State assessment (Seneca Lakes Mine)	Diabatic/ salt	1990s	New York State, USA	150-300	~625	Part of general CAES feasibility studies for state. Not progressed
MSc CAES research study	Diabatic/ various	Mid-1990s	South Africa	200-1000		Old mine potential - gold mines most favourable. Not progressed

Norton Mine (Haddington Ventures FirstEnergy Generation Corp)	Diabatic/ hard rock	2001-2013	Norton, Cleveland, Ohio, USA	Up to 2700 (units of 300)	~722	Permits, advanced design & testing. Air leakage. Project cancelled (2013)
ESKOM	Diabatic/ adiabatic/ various	1990s-2000s	South Africa			Considered economic benefits of CAES for integrated energy plans
'Shen Lang' studies	Diabatic/ coal mines	Early-2000s	China			Method(s) developed. Patents obtained (2004). Planned?
Energy Storage and Power +wind (PSEG Holdings)	Diabatic/ salt & coal	Mid-2000s	New Jersey & New York states, USA			Theoretical concept of old mine potential plus wind. Planned?
NYSERDA & NYSEG CAES assessment	Diabatic/ various	Late 2000s	New York State, USA	>100	700-1150	NYSERDA commissioned feasibility study
Clear Creek Power wind & CAES (Clear Creek Power)	Diabatic/ gold, silver	2007	Georgetown, Colorado, USA	50-1000 (525-10,000 MWh)		One or 5 windfarms linked to one 50MW or 1000MW storage. Not progressed
Lyons Salt Mine (Empire, BSC Holding Inc., Sega Inc.)	Diabatic/ salt	2009	Kansas, USA		~305	Feasibility of storing wind energy, small pressure test. Not progressed
Minnesota mine study, +wind (Uni. Minnesota)	Diabatic/ iron ore	Early 2010s	Minnesota, USA	100		Feasibility study/assessment mine CAES & wind energy. Pending?
"Three North Region" CAES +wind & solar (National Key R&D Program of China, Chongqing University)	Diabatic/ coal mine	Late-2010s	North & NE China	~10?	Up to 1000	Feasibility study of clean CAES system using old coalmine voids
Angas ACAES Project (Hydrostor & ARENA [Australian Renewable Energy Agency])	Adiabatic/ zinc mine	2019-2021	Adelaide, S. Australia	5 (10 MWh)	~240	Commercial demonstration facility, funded from renewable energy agency. Water-compensated & due 2020/21

S1, Table S5. Summary of main compressed air or CAES projects and/or assessments in conventionally mined, unlined rock caverns/voids. Cell highlighting as in S1, Table S1.

Facility/project/ assessment name	Type/ rock type	Date	Location	Power capacity (MW)	Storage depth (m)	Status
Battelle assessment	Diabatic/ various	Early 1970s	USA	174	~183	Preliminary study for cavities created by nuclear explosives. Not progressed
Glan (Vattenfall/Stal Laval)	Diabatic/ Metamorphic (gneiss)	Early 1970s	Eastern Sweden	220-230	~435	Advanced plans, including trial borings (1972-1973), water-compensated. Not progressed
Växjö (Sydsvenska Kraftgrupp A.B./Stal Laval	Diabatic/ Metamorphic (gneiss)	Early 1970s	Southern Sweden	240	250	Advanced plans, water-compensated storage. Not progressed
'Airstore' (Vattenfall/Stal Laval)	Diabatic/ Metamorphic (gneiss)	Early-mid 1970s	Sweden	232	250	Advanced plans, series linked tunnels, water-compensated. Not progressed
'SITRA' subsurface power plants study	Diabatic/ various hard rock (granite/gneiss)	Early 1970s	Finland	~200	100-600	Feasibility study of water-compensated scheme to replace pumped hydro capacity
Ffestiniog test (CEGB)	Metamorphic hard rock	Early-1970s	North Wales, UK			Preliminary pressurisation tests, small unlined gallery
National Science Foundation (NSF) study	Diabatic/ Trenton-Black River carbonate	Early-mid 1970s	IL, IN, OH & southern MI, USA	280	~490	Regional assessments. Not progressed
	Diabatic/ hard rock (granite/ gneiss)		Between Boston & Washington, USA	280	~490	Regional assessments. Not progressed
CEC feasibility study (California	Diabatic/ hard rock (Lst/igneous)	Early-mid 1970s	California, USA	252.5(x3)	690	Early hard rock site identification (13) feasibility studies, conceptual, water compensated designs. Not progressed.

Energy Commission [CEC] & U.S. DoE)			Shultz Mountain, CA	250x3 (750 total)	~700	Feasibility & conceptual water compensated design of preferred location. Not progressed.
Kansas Utility System study	Diabatic/ hard rock (carbonate/ granite/gneiss)	Mid-1970s	Kansas, USA	150-200	259-915	Regional assessment. Not progressed
Vianden (Société Electrique de L'Our & RWE)	Diabatic/ Devonian slates	Early-mid 1970s	Luxembourg	285	500	Advanced design & planning, water compensated, pumped storage scheme. Not progressed
Bremm test	'Clay slate'	Early-mid 1970s	Mosel, Germany			Test cavern for planned pumped storage scheme
Yugoslavia	Diabatic+ recuperator/ hard rock	1970s	Former Yugoslavia	260		Preliminary water-compensated design concepts with heat recuperation. Not progressed
Meadowbank Mine test	Salt mine - bedded	Late-1970s	Cheshire, UK		140	Compressed air test of cavity for gas storage development
EDF CAES plant	Diabatic/ granite	1970s-early 1980s	Bretagne, France	250-300		Advanced planning & site characterisation with test boreholes. Water compensated. Not progressed
Mt Hope mine (Jersey Central Power & Light Co)	Diabatic/ iron ore	Mid-1970s	New Jersey, USA	190-1000	~825	Initial 190MW test plant, with planned 1000 MW. Existing & new workings. Not progressed
Potomac Electric Power Co. feasibility study (DoE/EPRI fund)	Diabatic +recuperator/ Sykesville Gneiss	Early-mid 1970s	Maryland, USA	924	Up to 1500	Joint DoE/EPRI funded techno-economic feasibility assessments of 3 storage types. URC led by PEPCO.
Sykesville storage site (General Electric, US Energy R&D Admⁿ)	Diabatic +recuperator/ Sykesville Gneiss	Early-mid 1970s-	Maryland, USA	600 (units of 150)	~220 (overburden)	Conceptual techno-economic requirements water compensated design study. Not progressed.

Jefferson Island salt mine (LSU & US DoE)	Diabatic/ salt mine	Late 1970s-early 1980s	Louisiana, USA		~400	Instrumented holes drilled in mine for CAES tests on Gulf Coast salt domes
Soyland CAES study (Soyland Power Cooperative, Inc.)	Diabatic+ recuperator/ Cambrian dolomite	Early 1980s	Illinois, USA	220	~700	To support coal-fired plant. Water compensated. Permits & contracts signed, but not progressed - power station deferred in 1982
San Diego hard rock (San Diego Gas & Electric Co.)	Diabatic/ granite	1980s	California, USA	~100		Assessment, for 10 hr charging, 10 hr discharging cycle. Not progressed
EPRI & NYSERDA New York State feasibility study	Diabatic/ dolomites/ igneous	Early 1990s	New York State, USA	150	305-1525	Part of general CAES, water compensated feasibility studies for state. Not progressed
Upper Midwest studies	Diabatic/ granite	1990s	U. Midwest, USA	220-880	450-540	Northern States Power regional water compensated design assessment. Not progressed
		Early 2010s		Up to 1080	607	U.S. DoE Wind Energy Program. Planned?
Central Research Institute of Electric Power Industry (CRIEPI)	Diabatic/ granite	Late 1980s-early 1990s	Kongo, Japan	~500		Feasibility & site investigations – borehole pressure tests for two rock types
			Kyushu, Japan			
Suez +large-scale wind (University Nottingham)	Adiabatic/ hard rock	Mid-2010s	Suez, Egypt	Up to 580 (various plants)		Assessment of 3 large-scale energy storage system supporting wind & TES. Also LRC? Planned
Datang CAES	Diabatic/ sandstone	Mid-2010s	Datang, Inner Mongolia,China	300	500	Few details. Planned
Pollegio-Loderio tunnel	Adiabatic/ Levantine Gneiss	2015-present	Biasca, South Switzerland	0.5	>450 (overburden)	Small demonstration project. Operational

DEMETAIR small-scale CAES	Adiabatic/ unspecified	2016	Europe & US			Feasibility analysis & assessment of small-scale CAES using drilled shaft, possibly lined
Petit-Couronne	Adiabatic/ chalk	2017	Northern France		~150	Assessment to convert LPG storage caverns to CAES. Planning?

S1, Table S6. Summary of main compressed air or CAES projects and/or assessments in conventionally mined, lined rock caverns/voids. Cell highlighting as in S1, Table S1.

Facility/project/ assessment name	Type/host rock type	Date	Location	Power capacity (MW)	Storage depth (m)	Status
Sodegaura test	Diabatic/ soft sediment	Late 1980s-early 1990s	Tokyo Bay, Sodegaura, Japan		600-640	Rock mechanical, geo-mechanical & economic assessments. Water compensated. Not progressed
Roda Stern laboratories	Hard rock (gneiss)	Late 1980s-1990s	Göteburg, Sweden		60	Compressed air tests in gas storage LRC test facility.
'Urban CAES tank'	Diabatic/ NA	Late 1990s	Japan			Small scale test. Closed
CAES-G/T Pilot Plant	Diabatic/ coal mine	Mid 1990s-early 2000s	Kamisunagawa-cho, Hokkaido, Japan		450	Initial in situ tests
CAES-G/T Pilot Plant	Diabatic/ coal mine	Mid 1990s-early 2000s	Kamisunagawa-cho, Hokkaido, Japan	2	450	Small pilot facility after initial in situ tests. Closed
CAES-G/T Pilot Plant	Diabatic/ coal mine	Early 2000s	Kamisunagawa-cho, Hokkaido, Japan	35	450	Planned pilot facility. Never started
LRC feasibility study	Diabatic/ hard rock	Early 2000s	Israel		>100	Feasibility & energy loss study of concrete-lined single/multiple tunnels
Kamioka (ANGAS project)	Zinc mine	Mid 2000s	Kamioka mine, Japan		400	Small LRC test for larger natural gas storage. Tested hydraulically & with air
SEARCH (CAES)	Adiabatic/ granite	2009-2013	France			National Research Agency (ANR) study of ACAES heat storage media in an LRC
Jongson pilot test	Diabatic/ limestone mine	Early 2010s	Jongson, Sth. Korea		100	Caverns excavated & numerous tests commenced
CAES plant study	Diabatic/ Granite	Mid-2010s	Inner Mongolia, China	100		Feasibility & modelling studies. Planned

DEMETAIR small-scale CAES	Adiabatic/ unspecified	2016	Europe & US			Feasibility analysis & assessment of small-scale CAES using drilled shaft, possibly lines
RICAS2020 Mine Project - Horizon 2020 funded study)	Adiabatic/ Iron ore/Lst mine	2017	Eisenerz, Austria	5 100	~220	EU Horizon 2020 funded feasibility & small test (operational) leading to full-scale test plant (planned)

S2: Additional data relating to exergy storage estimates

S2, Table S1. Summary of the main dimensions and pressure ranges of salt caverns constructed or proposed for underground gas storage in the UK (from Evans, 2016). Does not include: i) the proposed facility in Triassic halites of the Carnduff, Larne region in Northern Ireland as this was dropped early in the investigations, ii) various former brine caverns in the Teesside brine fields used for gas, hydrogen and liquid storage, and iii) the Zechstein halite beds of the Southern North Sea.

Facility – status/age of salt/name (operator)			**Number of caverns**	**Cavern dimensions – height/diam. (m)**	**Cavern depths – top/base (m, bgl)**	**Average cavern volume – physical (m^3)**	**Total cavern volume – physical (mcm)**	**Pressure range – min/max (MPa/psi/bar)**
Operational	*Permian*	Hornsea (Scottish and Southern Energy), E Yorks	9	100/80-100	~1780-1830 – 1880-1930	~220,000	~1.98	Max = 27/3916/270 Min = 12/1741/120
		Aldbrough I (Statoil and Scottish & Southern Energy), E Yorks	9	100/80-100	~1780-1830 – 1880-1930	~270,000	~2.43	Max = 27/3916/270 Min = 12/1741/120
	Triassic	Holford H165 (Ineos Enterprises), Cheshire	1	70/70	350/420	175,000	0.175	Max = ~8.5/1233/85 Min = ~7/1015/70
		Hole House (EDF Trading), Cheshire	4	100/90	300/400	Not available	Not available	Not available
		Hilltop Farm/Hole House ext. (EDF Trading), Cheshire	10	~120/100	~240-380	600,000-650,000	~6.25	Max = 4.5/653/45 Min = 2.9/421/29
		Holford (Uniper UK, formerly EON Gas Storage UK), Cheshire	8	100/84-100	570-610/670-700	~370,000	~2.96	Max = 10.5/1523/105 Min = 4/580/40
		Stublach (Storengy), Cheshire	20	100-115	~500/600	~330,000	~6.60	Max = 10.1/1465/101 Min = 3/435/30
Under	*Permian*	Islandmagee (Islandmagee Storage Limited), N Ireland	7	160/80	~1500	480,000	~3.36	Max = 25/3626/250

								Min = 12/1741/120
		Whitehill (EON Gas Storage UK), E Yorks	10	100/80	~ 1730-1830	250,000	~2.50	Max = 34.5/5004/345 Min = 10/1450/100
	Triassic	Gateway (Gateway Gas Storage Ltd), East Irish Sea	20 (24 max.)	229-315/85-120	~624	~1,000,000	~20	Max = 12/1741/120 Min = 3.6/522/36
		King Street Energy (King Street Energy Ltd), Cheshire	11 (+7?)	170/110	~320-420	500,000-850,000	~5.50	Max = 6.6/957/66 Min = not known
		Preesall (Halite Energy Ltd), NW England	19	Smallest: 55 & 60 Largest: 191 & 100	340-456/413-618	58,000-860,000	6.8	Max = 9.2/1336/92 Min = 3.3/483/33
		Keuper Gas Storage (Keuper Gas Storage Ltd), Cheshire	19	100/100	~650-750	314,000	~5.97	Max. = 12.34/1790/123 Min. = 4.38/635/43.8
		Portland (Portland Gas), Dorset	14	100/90	~ 2400/2500	~250,000	3.50	Max = 44/6382/440 Min = brine hydrostatic (halmostatic) pressure

S2, Table S2. General halite properties and input parameters for the online exergy calculation tool operational parameters relevant to the current CAES exergy storage calculations for UK halite-bearing basins.

Property		**Value**
Temperature of air at cavern inlet, K / °C		323 / 50[A64]
Temperature of cavern wall, K / °C	*Huntorf*	323 / 50[33,A65]
	This study	Based on average geothermal gradient for individual basins (see below)
Geothermal gradients for mid-cavern wall temperatures (°C/km)		
UK in general (average)		26[A66]
Cheshire Basin (average)		27[A66]
East Yorkshire (average)		31.9[A66]
Wessex (average)		34.5[A66]
East Irish Sea (average)		28[A67]
Rock density, ρ: (kg/m^3 / g/cm³*)*		2200 / 2.2[A68]
Rock thermal conductivity, k: (W.m-1.K-1, W/mK)	*general range/mean*	2.6-7 / 4[A68,A69]
	UK Triassic basins	5.2[A70,A71]
	UK Permian basin	5.19-5.52[A72]
Rock/specific heat capacity, C_p: (J/KgK / J.g^{-1}K^{-1})		800-920 / 0.80-0.92[A69]
Mass flow in, Kg/s		108[9,A73]

S2, Table S3. Summary of the combined exergy storage estimates for the three cavern models in the main UK onshore halite-bearing basins and the East Irish Sea over the two main depth ranges analysed for CAES purposes. Represents the theoretical, total storage capacity of the halite beds if all cavern locations identified were available. Also shown are the estimates taking just 1% of the potential caverns available and also the storage for a percentage based upon operational and permitted underground gas storage cavern numbers (148) relative to the number of potential caverns. Estimate of stored exergy to work (TWh) for the preferred CHT model also included based on 92% conversion rate after[41].

Cavern depth range (m) & category	**Cavern numbers**	**Isothermal Exergy**		**CHT Exergy**			**Adiabatic Exergy**	
		(MWh)	**(TWh)**	**(MWh)**	**(TWh)**	**Work from stored exergy (92%; TWh)**	**(MWh)**	**(TWh)**
500-1300, all	32,185	393,586,369	393.6	297,822,744	297.8	274.0	287,114,794	287.1
500-1300, 1%	322	3,935,864	3.94	2,978,227	2.98	2.7	2,871,148	2.87
500-1300, *as %age (0.46%) from possible cavern nos.*	148	1,809,874	1.81	1,369,513	1.37	1.3	1,320,273	1.32

rel UGS cavern numbers (148)								
500-1500, all	44,849	617,246,694	617.3	464,806,877	465.0	427.8	449,993,508	450.0
500-1500, 1%	449	6,172,470	6.17	4,648,069	4.65	4.3	4,499,935	4.50
500-1500, as %age (0.33%) from possible cavern nos. rel UGS cavern numbers (148)	148	2,036,891	2.04	1,533,845	1.53	1.4	1,484,962	1.49

S2, Table S4. Summary exergy data calculated for the massively bedded halites in the main UK halite bearing basins assessed in this study. Also shown are the estimates for caverns with heights of 100 m and over, and 100-150 m, together with estimates based upon both 1% of caverns and based upon the number of operating or planned/permitted gas storage cavern numbers in each basin (bracketed numbers in 'Category' column). Also shown the stored exergy to work in TWh for the preferred CHT model. Mbr: Member, Fm: Formation

Basin	Cavern depths (m)	Category	Cavern numbers	Isothermal Exergy		CHT Exergy			Adiabatic Exergy	
				(MWh)	(TWh)	(MWh)	(TWh)	Stored exergy to work (TWh)	(MWh)	(TWh)
Cheshire Basin (Northwich Halite Mbr)	*500-1300*	***All***	1,936	10,532,363	10.5	7,990,574	7.99	7.4	7,691,342	7.7
		100 m+	1,452	9,455,997	9.5	7,172,645	7.2	6.6	6,904,414	6.9
		100 m+, 1%	15	94,560	0.1	71,727	0.07	0.06	69,044	0.07
		100 m+, rel. UGS cavern nos. (5%)	73	475,405	0.48	360,608	0.36	0.33	347,123	0.35
		100-150 m	651	3,758,531	3.8	2,840,021	2.8	2.6	2,743,307	2.7
		100-150 m, 1%	7	37,585	0.04	28,400	0.03	0.028	27,433	0.03
		100-150 m, rel. UGS cavern nos. (11.2%)	73	421,464	0.42	318,466	0.32	0.3	307,621	0.31
	500-1500	***All***	2,098	12,251,933	12.3	9,278,415	9.3	8.6	8,943,610	8.9
		100 m+	1,607	11,117,024	11.1	8,417,389	8.4	7.7	8,114,054	8.1
		100 m+, 1%	16	111,170	0.11	84,174	0.08	0.074	81,141	0.08
		100 m+, rel. UGS cavern nos. (4.5%)	73	505,005	0.51	382,371	0.38	0.35	368,591	0.37
		100-150 m	804	5,396,008	5.4	4,064,163	4.1	3.8	3,935,792	3.9
		100-150 m, 1%	8	53,960	0.05	40,642	0.04	0.037	39,358	0.04
		100-150 m, rel. UGS cavern nos. (9.1%)	73	489,936	0.49	369,010	0.37	0.34	357,354	0.36
East Irish Sea (Preesall Halite Mbr)	*500-1300*	***All***	11,331	63,080,839	63.1	48,496,879	48.5	44.6	46,104,301	46.1
		100 m+	7,771	58,192,370	58.2	44,756,733	44.8	41.2	42,526,328	42.5
		100 m+, 1%	78	581,924	0.58	447,567	0.45	0.41	425,263	0.43
		100 m+, rel. UGS cavern nos. (0.3%)	24	179,722	0.18	138,227	0.14	0.13	131,339	0.13
		100-150 m	4,484	18,831,553	18.8	14,478,111	14.5	13.3	13,776,735	13.8
		100-150 m, 1%	45	188,316	0.19	144,781	0.15	0.14	137,767	0.14
		100-150 m, rel. UGS cavern nos. (0.5%)	24	100,793	0.1	77,492	0.08	0.074	73,738	0.07
Wessex Basin (Dorset Halite Mbr)	*500-1300*	***All***	18,020	316,545,097	316.5	238,767,229	238.8	219.7	230,820,244	230.8
		100 m+	14,983	301,946,526	302.0	227,823,334	227.8	209.6	220,171,954	220.2
		100 m+, 1%	150	3,019,465	3.0	2,278,233	2.3	2.1	2,201,720	2.2
		100 m+, rel. UGS cavern nos. (0.1%)	14	282,137	0.28	212,876	0.21	0.19	205,727	0.21
		100-150 m	2,278	24,426,196	24.4	18,253,951	18.3	16.8	17,801,585	17.8
		100-150 m, 1%	23	244,262	0.24	182,540	0.18	0.17	178,016	0.18
		100-150 m, rel. UGS cavern nos. (0.6%)	14	150,117	0.15	112,184	0.11	0.10	109,404	0.11
	500-1500	***All***	26,718	488,676,960	488.7	367,314,696	367.3	337.9	356,175,517	356.2
		100 m+	22,149	463,368,075	463.4	348,408,519	348	320.2	337,727,745	337.7
		100 m+, 1%	222	4,633,681	4.6	3,484,085	3.5	3.2	3,377,277	3.4
		100 m+, rel. UGS cavern nos. (0.06%)	14	292,887	0.29	220,223	0.22	0.20	213,472	0.21
		100-150 m	4,915	61,088,188	61.1	45,541,438	45.5	41.9	44,500,931	44.5
		100-150 m, 1%	49	610,882	0.61	455,414	0.46	0.42	445,009	0.45
		100-150 m, rel. UGS cavern nos. (0.3%)	14	174,005	0.17	129,722	0.13	0.13	126,758	0.13
Eastern England (Fordon Evaporite	*500-1300*	***All***	898	3,428,070	3.4	2,568,061	2.6	2.4	2,498,908	2.5
		100 m+	115	1,518,327	1.5	1,139,006	1.1	1.0	1,106,571	1.1
		100 m+, 1%	1	15,183	0.02	11,390	0.01	0.009	11,066	0.01
		100 m+, rel. UGS cavern nos. (32.2%)	37	488,505	0.49	366,463	0.37	0.34	356,027	0.36
		100-150 m	93	905,467	0.91	678,808	0.69	0.64	660,072	0.66
		100-150 m, 1%	<1	9,055	0.01	6,788	0.01	0.009	6,601	0.01

		100-150 m, rel. UGS cavern nos. (39.8)	37	360,240	0.36	270,064	0.27	0.25	262,609	0.26
	500-1500	***All***	4,702	53,236,963	53.2	39,716,887	39.7	36.5	38,770,080	38.8
		100 m+	1,589	37,506,364	37.5	28,016,245	28.0	25.8	27,313,371	27.3
		100 m+, 1%	16	375,064	0.38	280,163	0.28	0.26	273,134	0.27
		100 m+, rel. UGS cavern nos. (2.3%)	37	873,339	0.87	652,361	0.65	0.6	635,994	0.64
		100-150 m	413	5,223,359	5.2	3,892,304	3.9	3.6	3,804,344	3.8
		100-150 m, 1%	4	52,234	0.05	38,923	0.04	0.037	38,043	0.04
		100-150 m, rel. UGS cavern nos. (9%)	37	467,952	0.47	348,705	0.35	0.32	340,825	0.34

S2, Table S5. Flow rates calculated for differing cavern ranges based upon data output from the online tool calculations to derive CHT exergy figures. Data used are the average maximum storage pressures and air masses from which cavern fill times are estimated for withdrawal rates of 108 and 417 kg/s, and 1.5 MPa/hr. Also shown is the equivalent air mass withdrawal rate (kg/s) based upon a pressure reduction rate of 1.5 MPa/hr.

Area/ basin	**Cavern depth range (m)**	**Cavern heights (m)**	**Av CHT pressure (Pa)**	**Av CHT pressure (MPa)**	**Av CHT mass (kg)**	**Cavern fill time @ 108 kg/s (days)**	**Cavern empty time @ 417 kg/s (days)**	**Cavern empty time @ 1.5 MPa/hr pressure reduction rate (days)**	**Approximate equivalent air mass withdrawal in kg/s @ a pressure reduction rate of 1.5 MPa/hr**
Cheshire Basin	500-1300	100+	15,293,954	15.29	81,103,110	8.69	2.25	0.425	2,210
		100-150	15,865,042	15.87	70,677,438	7.57	1.96	0.441	1,856
	500-1500	100+	16,423,016	16.42	84,756,946	9.08	2.35	0.456	2,150
		100-150	17,987,315	17.99	79,800,651	8.55	2.21	0.500	1,849
East Irish Sea	500-1300	100+	11,220,296	11.22	99,073,111	10.62	2.75	0.312	3,679
		100-150	10,141,718	10.14	57,829,005	6.20	1.61	0.282	2,376
Wessex Basin	500-1300	100+	20,246,773	20.25	236,838,988	25.38	6.57	0.562	4,874
		100-150	22,281,225	22.28	122,616,642	13.14	3.40	0.619	2,293
	500-1500	100+	22,440,128	22.44	240,921,128	25.82	6.69	0.623	4,473
		100-150	24,795,961	24.80	139,259,714	14.92	3.87	0.689	2,340
East Yorkshire	500-1300	100+	22,274,794	22.27	151,499,106	16.24	4.20	0.619	2,834
		100-150	21,714,732	21.71	112,827,744	12.09	3.13	0.603	2,165
	500-1500	100+	26,517,591	26.52	120,416,950	12.90	3.34	0.737	1,892
		100-150	26,214,340	26.21	140,530,782	15.06	3.90	0.728	2,234

S2, Table S6. Table of dynamic storage estimates for each basin, based upon a fill rate of 108 kg/s and withdrawal rate of 108 kg/s.

Basin	Cavern depth range (m)	Cavern heights (m)	Category	Number of caverns	Av. working exergy (CHT static: MWh)	Av. CHT fill time (injection rate of 108 kg/s) - days	Av. empty (production) time (production rate of 108 kg/s) - days	Fill-empty cycle (based on fill rate & production rates, no standby time) - days	Cycles per year, based on calculated fill-empty cycle (approx.)	Dynamic (yearly) exergy storage from av. calculated exergy & number cycles/yr (MWh)	Dynamic (yearly) exergy storage from av. calculated exergy & cycles/yr (TWh)	Exergy to work (TWh), based upon 92% conversion of dynamic (yearly) exergy	%age of UK electricity requirement (300 TWh/yr)	%age of UK electricity requirement (300 TWh/yr) for 92% conversion of exergy to work
Cheshire	500-1300m	100m+	100m+ cavern heights	1,452	4,939.8	8.69	8.69	17.38	21	150,605,977	150.6	138.6	50.2	46.2
			1% caverns available	15						1,506,060	1.5	1.4	0.5	0.5
			Caverns as %age relative UGS cavern numbers (5%)	73						7,571,788	7.6	7.0	2.5	2.3
		100-150m	100-150m cavern heights	651	4,362.6	7.57	7.57	15.15	24	68,429,153	68.4	63.0	22.8	21.0
			1% caverns available	7						684,292	0.7	0.6	0.2	0.2
			Caverns as %age relative UGS cavern numbers (11.2%)	73						7,673,315	7.7	7.1	2.6	2.4
	500-1500m	100m+	100m+ cavern heights	1,607	5,238.0	9.08	9.08	18.17	20	169,122,909	169.1	155.6	56.4	51.9
			1% caverns available	16						1,691,229	1.7	1.6	0.6	0.5
			Caverns as %age relative UGS cavern numbers (4.5%)	73						7,682,621	7.7	7.1	2.6	2.4
		100-150m	100-150m cavern heights	804	5,054.9	8.55	8.55	17.10	21	86,729,131	86.7	79.8	28.9	26.6
			1% caverns available	8						867,291	0.9	0.8	0.3	0.3
			Caverns as %age relative UGS cavern numbers (9.1%)	73						7,874,660	7.9	7.2	2.6	2.4
ESB	500-1300m	100m+	100m+ cavern heights	7,771	5,759.5	10.62	10.62	21.23	17	769,312,770	769.3	707.8	256.4	235.9
			1% caverns available	78						7,693,128	7.7	7.1	2.6	2.4
			Caverns as %age relative UGS cavern numbers (0.31%)	24						2,375,950	2.4	2.2	0.8	0.7
		100-150m	100-150m cavern heights	4,484	3,228.8	6.20	6.20	12.39	29	426,350,261	426.4	392.2	142.1	130.7
			1% caverns available	45						4,263,503	4.3	3.9	1.4	1.3
			Caverns as %age relative UGS cavern numbers (0.54%)	24						2,281,982	2.3	2.1	0.8	0.7
Wessex Basin	500-1300m	100m+	100m+ cavern heights	14,983	15,205.5	25.38	25.38	50.76	7	1,638,118,718	1,638.1	1,507.1	546.0	502.4
			1% caverns available	150						16,381,187	16.4	15.1	5.5	5.0
			Caverns as %age relative UGS cavern numbers (0.09)	14						1,530,646	1.5	1.4	0.5	0.5
		100-150m	100-150m cavern heights	2,278	8,013.1	13.14	13.14	26.28	14	253,517,428	253.5	233.2	84.5	77.7
			1% caverns available	23						2,535,174	2.5	2.3	0.8	0.8
			Caverns as %age relative UGS cavern numbers (0.61)	14						1,558,053	1.6	1.4	0.5	0.5
	500-1500m	100m+	100m+ cavern heights	22,149	15,730.2	25.82	25.82	51.64	7	2,462,715,504	2,462.7	2,265.7	820.9	755.2
			1% caverns available	221						24,627,155	24.6	22.7	8.2	7.6
			Caverns as %age relative UGS cavern numbers (0.06)	14						1,556,640	1.6	1.4	0.5	0.5
		100-150m	100-150m cavern heights	4,915	9,265.8	14.92	14.92	29.85	12	556,905,630	556.9	512.4	185.6	170.8
			1% caverns available	49						5,569,056	5.6	5.1	1.9	1.7
			Caverns as %age relative UGS cavern numbers (0.28)	14						1,586,303	1.6	1.5	0.5	0.5
East Yorkshire (Permian)	500-1300m	100m+	100m+ cavern heights	115	9,904.4	16.24	16.24	32.47	11	12,803,130	12.8	11.8	4.3	3.9
			1% caverns available	1						128,031	0.1	0.1	0.04	0.0
			Caverns as %age relative UGS cavern numbers (32.17)	37						4,119,268	4.1	3.8	1.4	1.3
		100-150m	100-150m cavern heights	93	7,299.0	12.09	12.09	24.18	15	10,245,463	10.2	9.4	3.4	3.1
			1% caverns available	1						102,455	0.1	0.1	0.03	0.0
			Caverns as %age relative UGS cavern numbers (39.78)	37						4,076,152	4.1	3.8	1.4	1.3
	500-1500m	100m+	100m+ cavern heights	1,589	17,631.4	12.90	12.90	25.81	14	396,207,478	396.2	364.5	132.1	121.5
			1% caverns available	16						3,962,075	4.0	3.6	1.3	1.2
			Caverns as %age relative UGS cavern numbers (2.33)	37						9,225,725	9.2	8.5	3.1	2.8
		100-150m	100-150m cavern heights	413	9,424.5	15.06	15.06	30.12	12	47,166,719	47.2	43.4	15.7	14.5
			1% caverns available	4						471,667	0.5	0.4	0.2	0.1
			Caverns as %age relative UGS cavern numbers (9.0)	37						4,225,590	4.2	3.9	1.4	1.3
Total exergy storage for various categories														
Total for 500-1300m, 100m+ cavern heights										2,570,840,595	2,570.8	2,365.2	856.9	788.4
Total for 500-1500m, 100m+ cavern heights										3,797,358,661	3,797.4	3,493.6	1,265.8	1,164.5
Total for 500-1300m, 100-150m cavern heights										758,542,305	758.5	697.9	252.8	232.6
Total for 500-1500m, 100-150m cavern heights										1,117,151,740	1,117.2	1,027.8	372.4	342.6
Total for 1% 500-1300m, 100m+ cavern heights										25,708,406	25.7	23.7	8.6	7.9
Total for 1% 500-1500m, 100m+ cavern heights										37,973,587	38.0	34.9	12.7	11.6
Total for 1% 500-1300m, 100-150m cavern heights										7,585,423	7.6	7.0	2.5	2.3
Total for 1% 500-1500m, 100-150m cavern heights										11,171,517	11.2	10.3	3.7	3.4
Total for 500-1300m, 100m+ cavern heights, relative UGS cavern numbers										15,597,651	15.6	14.3	5.2	4.8
Total for 500-1500m, 100m+ cavern heights, relative UGS cavern numbers										20,746,968	20.7	19.1	6.9	6.4
Total for 500-1300m, 100-150m cavern heights, relative UGS cavern numbers										15,589,502	15.6	14.3	5.2	4.8
Total for 500-1500m, 100-150m cavern heights, relative UGS cavern numbers										15,968,534	16.0	14.7	5.3	4.9

S2, Table S7. Table of dynamic storage based on 108 kg/s fill rate & W/D rate of 417 kg/s.

Basin	Cavern depth range (m)	Cavern heights (m)	Category	Number of caverns	Av. working exergy (CHT static: MWh)	Av. CHT fill time (injection rate of 108 kg/s) - days	Av. empty (production) time (production rate of 417 kg/s) - days	Fill-empty cycle (based on fill rate & production rates, no standby time) - days	Cycles per year, based on calculated fill-empty cycle (approx.)	Dynamic (yearly) exergy storage from av. calculated exergy & number cycles/yr (MWh)	Dynamic (yearly) exergy storage from av. calculated exergy and cycles/yr (TWh)	Exergy to work (TWh), based upon 92% conversion of dynamic (yearly) exergy	%age of UK electricity requirement (300 TWh/yr)	%age of UK electricity requirement (300 TWh/yr) for 92% conversion of exergy to work
Cheshire	500-1300m	100m+	100m+ cavern heights	1,452	4,939.8	8.69	2.25	10.94	33	239,248,352	239.2	220.1	79.7	73.4
			1% caverns available	15						2,392,484	2.4	2.2	0.8	0.7
			Caverns as %age relative UGS cavern numbers (5%)	73						12,028,326	12.0	11.1	4.0	3.7
		100-150m	100-150m cavern heights	651	4,362.6	7.57	1.96	9.54	38	108,704,598	108.7	100.0	36.2	33.3
			1% caverns available	7						1,087,046	1.1	1.0	0.4	0.3
			Caverns as %age relative UGS cavern numbers (11.2%)	73						12,189,609	12.2	11.2	4.1	3.7
	500-1500m	100m+	100m+ cavern heights	1,607	5,238.0	9.08	2.35	11.44	32	268,663,822	268.7	247.2	89.6	82.4
			1% caverns available	16						2,686,638	2.7	2.5	0.9	0.8
			Caverns as %age relative UGS cavern numbers (4.5%)	73						12,204,393	12.2	11.2	4.1	3.7
		100-150m	100-150m cavern heights	804	5,054.9	8.55	2.21	10.77	34	137,775,419	137.8	126.8	45.9	42.3
			1% caverns available	8						1,377,754	1.4	1.3	0.5	0.4
			Caverns as %age relative UGS cavern numbers (9.1%)	73						12,509,460	12.5	11.5	4.2	3.8
EISB	500-1300m	100m+	100m+ cavern heights	7,771	5,759.5	10.62	2.75	13.37	27	1,222,108,286	1,222.1	1,124.3	407.4	374.8
			1% caverns available	78						12,221,083	12.2	11.2	4.1	3.7
			Caverns as %age relative UGS cavern numbers (0.31%)	24						3,774,366	3.8	3.5	1.3	1.2
		100-150m	100-150m cavern heights	4,484	3,228.8	6.20	1.61	7.80	47	677,287,843	677.3	623.1	225.8	207.7
			1% caverns available	45						6,772,878	6.8	6.2	2.3	2.1
			Caverns as %age relative UGS cavern numbers (0.54%)	24						3,625,091	3.6	3.3	1.2	1.1
Wessex Basin	500-1300m	100m+	100m+ cavern heights	14,983	15,205.5	25.38	6.57	31.96	11	2,602,268,593	2,602.3	2,394.1	867.4	798.0
			1% caverns available	150						26,022,686	26.0	23.9	8.7	8.0
			Caverns as %age relative UGS cavern numbers (0.09)	14						2,431,540	2.4	2.2	0.8	0.7
		100-150m	100-150m cavern heights	2,278	8,013.1	13.14	3.40	16.54	22	402,730,542	402.7	370.5	134.2	123.5
			1% caverns available	23						4,027,305	4.0	3.7	1.3	1.2
			Caverns as %age relative UGS cavern numbers (0.61)	14						2,475,078	2.5	2.3	0.8	0.8
	500-1500m	100m+	100m+ cavern heights	22,149	15,730.2	25.82	6.69	32.51	11	3,912,199,486	3,912.2	3,599.2	1,304.1	1,199.7
			1% caverns available	221						39,121,995	39.1	36.0	13.0	12.0
			Caverns as %age relative UGS cavern numbers (0.06)	14						2,472,834	2.5	2.3	0.8	0.8
		100-150m	100-150m cavern heights	4,915	9,265.8	14.92	3.87	18.79	19	884,684,372	884.7	813.9	294.9	271.3
			1% caverns available	49						8,846,844	8.8	8.1	2.9	2.7
			Caverns as %age relative UGS cavern numbers (0.28)	14						2,519,955	2.5	2.3	0.8	0.8
East Yorkshire (Permian)	500-1300m	100m+	100m+ cavern heights	115	9,904.4	16.24	4.20	20.44	18	20,338,686	20.3	18.7	6.8	6.2
			1% caverns available	1						203,387	0.2	0.2	0.1	0.1
			Caverns as %age relative UGS cavern numbers (32.17)	37						6,543,751	6.5	6.0	2.2	2.0
		100-150m	100-150m cavern heights	93	7,299.0	12.09	3.13	15.22	24	16,275,650	16.3	15.0	5.4	5.0
			1% caverns available	1						162,757	0.2	0.1	0.1	0.0
			Caverns as %age relative UGS cavern numbers (39.78)	37						6,475,259	6.5	6.0	2.2	2.0
	500-1500m	100m+	100m+ cavern heights	1,589	17,631.4	12.90	3.34	16.25	22	629,403,880	629.4	579.1	209.8	193.0
			1% caverns available	16						6,294,039	6.3	5.8	2.1	1.9
			Caverns as %age relative UGS cavern numbers (2.33)	37						14,655,723	14.7	13.5	4.9	4.5
		100-150m	100-150m cavern heights	413	9,424.5	15.06	3.90	18.96	19	74,927,702	74.9	68.9	25.0	23.0
			1% caverns available	4						749,277	0.7	0.7	0.2	0.2
			Caverns as %age relative UGS cavern numbers (9.0)	37						6,712,651	6.7	6.2	2.2	2.1
Total exergy storage for various categories														
Total for 500-1300m, 100m+ cavern heights										4,083,963,916	4,084.0	3,757.2	1,361.3	1,252.4
Total for 500-1500m, 100m+ cavern heights										6,032,375,474	6,032.4	5,549.8	2,010.8	1,849.9
Total for 500-1300m, 100-150m cavern heights										1,204,998,633	1,205.0	1,108.6	401.7	369.5
Total for 500-1500m, 100-150m cavern heights										1,774,675,335	1,774.7	1,632.7	591.6	544.2
Total for 1% 500-1300m, 100m+ cavern heights										40,839,639	40.8	37.6	13.6	12.5
Total for 1% 500-1500m, 100m+ cavern heights										60,323,755	60.3	55.5	20.1	18.5
Total for 1% 500-1300m, 100-150m cavern heights										12,049,986	12.0	11.1	4.0	3.7
Total for 1% 500-1500m, 100-150m cavern heights										17,746,753	17.7	16.3	5.9	5.4
Total for 500-1300m, 100m+ cavern heights, relative UGS cavern numbers										24,777,983	24.8	22.8	8.3	7.6
Total for 500-1500m, 100m+ cavern heights, relative UGS cavern numbers										32,958,040	33.0	30.3	11.0	10.1
Total for 500-1300m, 100-150m cavern heights, relative UGS cavern numbers										24,765,037	24.8	22.8	8.3	7.6
Total for 500-1500m, 100-150m cavern heights, relative UGS cavern numbers										25,367,157	25.4	23.3	8.5	7.8

S2, Table S8. Table of dynamic storage based on 108 kg/s fill rate & maximum W/D rate of 1.5 MPa/hr.

Basin	Cavern depth range (m)	Cavern heights (m)	Category	Number of caverns	Av. working exergy (CHT static: MWh)	Av. CHT fill time (injection rate of 108 kg/s) - days	Av. empty (production) time (@max. production rate of 1.5 Mpa/hr) - days	Fill-empty cycle (based on fill rate & production rates, no standby time) - days	Cycles per year, based on calculated fill-empty cycle (approx.)	Dynamic (yearly) exergy storage from av. calculated exergy & number cycles/yr (MWh)	Dynamic (yearly) exergy storage from av. calculated exergy and cycles/yr (TWh)	Exergy to work (TWh), based upon 92% conversion of dynamic (yearly) exergy	%age of UK electricity requirement (300 TWh/yr)	%age of UK electricity requirement (300 TWh/yr) for 92% conversion of exergy to work
Cheshire	500-1300m	100m+	100m+ cavern heights	1,452	4,939.8	8.69	0.42	9.12	40	287,175,277	287.2	264.2	95.7	88.1
			1% caverns available	15						2,871,753	2.9	2.6	1.0	0.9
			Caverns as %age relative UGS cavern numbers (5%)	73						14,437,875	14.4	13.3	4.8	4.4
		100-150m	100-150m cavern heights	651	4,362.6	7.57	0.44	8.02	46	129,333,318	129.3	119.0	43.1	39.7
			1% caverns available	7						1,293,333	1.3	1.2	0.4	0.4
			Caverns as %age relative UGS cavern numbers (11.2%)	73						14,502,814	14.5	13.3	4.8	4.4
	500-1500m	100m+	100m+ cavern heights	1,607	5,238.0	9.08	0.46	9.54	38	322,070,119	322.1	296.3	107.4	98.8
			1% caverns available	16						3,220,701	3.2	3.0	1.1	1.0
			Caverns as %age relative UGS cavern numbers (4.5%)	73						14,630,441	14.6	13.5	4.9	4.5
		100-150m	100-150m cavern heights	804	5,054.9	8.55	0.50	9.05	40	163,883,455	163.9	150.8	54.6	50.3
			1% caverns available	8						1,638,835	1.6	1.5	0.5	0.5
			Caverns as %age relative UGS cavern numbers (9.1%)	73						14,879,965	14.9	13.7	5.0	4.6
ESB	500-1300m	100m+	100m+ cavern heights	7,771	5,759.5	10.62	0.31	10.93	33	1,494,747,095	1,494.7	1,375.2	498.2	458.4
			1% caverns available	78						14,947,471	14.9	13.8	5.0	4.6
			Caverns as %age relative UGS cavern numbers (0.31%)	24						4,616,385	4.6	4.2	1.5	1.4
		100-150m	100-150m cavern heights	4,484	3,228.8	6.20	0.28	6.48	56	815,624,667	815.6	750.4	271.9	250.1
			1% caverns available	45						8,156,247	8.2	7.5	2.7	2.5
			Caverns as %age relative UGS cavern numbers (0.54%)	24						4,365,520	4.4	4.0	1.5	1.3
Wessex Basin	500-1300m	100m+	100m+ cavern heights	14,983	15,205.5	25.38	0.56	25.94	14	3,205,215,126	3,205.2	2,948.8	1,068.4	982.9
			1% caverns available	150						32,052,151	32.1	29.5	10.7	9.8
			Caverns as %age relative UGS cavern numbers (0.09)	14						2,994,928	3.0	2.8	1.0	0.9
		100-150m	100-150m cavern heights	2,278	8,013.1	13.14	0.62	13.76	27	484,227,542	484.2	445.5	161.4	148.5
			1% caverns available	23						4,842,275	4.8	4.5	1.6	1.5
			Caverns as %age relative UGS cavern numbers (0.61)	14						2,975,937	3.0	2.7	1.0	0.9
	500-1500m	100m+	100m+ cavern heights	22,149	15,730.2	25.82	0.62	26.44	14	4,809,321,119	4,809.3	4,424.6	1,603.1	1,474.9
			1% caverns available	221						48,093,211	48.1	44.2	16.0	14.7
			Caverns as %age relative UGS cavern numbers (0.06)	14						3,039,889	3.0	2.8	1.0	0.9
		100-150m	100-150m cavern heights	4,915	9,265.8	14.92	0.69	15.61	23	1,064,674,415	1,064.7	979.5	354.9	326.5
			1% caverns available	49						10,646,744	10.6	9.8	3.5	3.3
			Caverns as %age relative UGS cavern numbers (0.28)	14						3,032,643	3.0	2.8	1.0	0.9
East Yorkshire (Permian)	500-1300m	100m+	100m+ cavern heights	115	9,904.4	16.24	0.62	16.85	22	24,666,230	24.7	22.7	8.2	7.6
			1% caverns available	1						246,662	0.2	0.2	0.1	0.1
			Caverns as %age relative UGS cavern numbers (32.17)	37						7,936,091	7.9	7.3	2.6	2.4
		100-150m	100-150m cavern heights	93	7,299.0	12.09	0.60	12.69	29	19,517,298	19.5	18.0	6.5	6.0
			1% caverns available	1						195,173	0.2	0.2	0.1	0.1
			Caverns as %age relative UGS cavern numbers (39.78)	37						7,764,947	7.8	7.1	2.6	2.4
	500-1500m	100m+	100m+ cavern heights	1,589	17,631.4	12.90	0.74	13.64	27	749,626,524	749.6	689.7	249.9	229.9
			1% caverns available	16						7,496,265	7.5	6.9	2.5	2.3
			Caverns as %age relative UGS cavern numbers (2.33)	37						17,455,117	17.5	16.1	5.8	5.4
		100-150m	100-150m cavern heights	413	9,424.5	15.06	0.73	15.79	23	89,982,713	90.0	82.8	30.0	27.6
			1% caverns available	4						899,827	0.9	0.8	0.3	0.3
			Caverns as %age relative UGS cavern numbers (9.0)	37						8,061,405	8.1	7.4	2.7	2.5
Total exergy storage for various categories														
Total for 500-1300m, 100m+ cavern heights										5,011,803,727	5,011.8	4,610.9	1,670.6	1,537.0
Total for 500-1500m, 100m+ cavern heights										7,375,764,857	7,375.8	6,785.7	2,458.6	2,261.9
Total for 500-1300m, 100-150m cavern heights										1,448,702,826	1,448.7	1,332.8	482.9	444.3
Total for 500-1500m, 100-150m cavern heights										2,134,165,251	2,134.2	1,963.4	711.4	654.5
Total for 1% 500-1300m, 100m+ cavern heights										50,118,037	50.1	46.1	16.7	15.4
Total for 1% 500-1500m, 100m+ cavern heights										73,757,649	73.8	67.9	24.6	22.6
Total for 1% 500-1300m, 100-150m cavern heights										14,487,028	14.5	13.3	4.8	4.4
Total for 1% 500-1500m, 100-150m cavern heights										21,341,653	21.3	19.6	7.1	6.5
Total for 500-1300m, 100m+ cavern heights, relative UGS cavern numbers										29,985,280	30.0	27.6	10.0	9.2
Total for 500-1500m, 100m+ cavern heights, relative UGS cavern numbers										39,490,967	39.5	36.3	13.2	12.1
Total for 500-1300m, 100-150m cavern heights, relative UGS cavern numbers										29,609,219	29.6	27.2	9.9	9.1
Total for 500-1500m, 100-150m cavern heights, relative UGS cavern numbers										30,339,534	30.3	27.9	10.1	9.3

S3: Methodology for estimating cavern volumes and exergy storage – summary of the revised Exergy Storage Tool

Selection of caverns - location, depths and sizes

The main halite formations identified were assessed for cavern locations, using ArcGIS, for thickness, depth, impurity content and cavern volumes, together with likely availability, set against various cultural and operational parameters.[42] The cavern design and operational parameters were based upon those design criteria applied to the construction and operation of gas storage caverns, with the halite beds evaluated over the depth ranges currently under consideration for CAES operations. The literature suggests that the operational window for CAES salt caverns lies between 500 and 1300 m, with the operating pressures being directly dependent on depth and power-plant components. Thus, casing shoe depths are set within these limits.[6,42] However, breakthroughs in compressor and turbine technology could allow CAES deployment to greater depths than previously possible, with 1500 m being considered at Larne in Northern Ireland.[43] Two depth ranges for casing shoe depths (and thus pressures) have thus been considered in this study: 500-1300 m and 500-1500 m.

Cavern data and volumes were then input to a modelling tool to derive the potential exergy storage for each of the caverns identified during a maximum fill cycle. Attempts to obtain realistic storage capacities were made by way of filtering the cavern data and by estimating dynamic storage capacity through multi-fill cycles, as outlined below.

Operational and exergy modelling input parameters

Prior to calculating the exergy, calculation of a number of halite (or rocksalt) properties and other input parameters for the tool are required, which are outlined in this section and summarised in Supplementary Appendix 2, Table A2. Data relating to potential storage caverns were derived from the halite surfaces and cavern locations for each halite-bearing basin. The cavern data (potential locations, heights, radii, basic volumes and depths) were derived as described in ref.[42] From these data and based upon the principles described for the calculation of working gas volumes for gas storage caverns in the Preesall Saltfield,[39] estimates of the working gas volumes for the cavern depths were calculated. Utilising general lithostatic and temperature gradients for the overburden in the regions, cavern volumes were adjusted for temperature and pressure variation at depths set for cavern casing shoes.

The calculation of cavern volumes is highly dependent upon the quality of the massively-bedded halite deposits, which depending upon their position within the basin, contain a variable insolubles (non-salt) content: those nearer to the basin centres generally having a lower percentage of insolubles and thinner mudstone interbeds. Attempts, based upon downhole geophysical log interpretation, were made to determine and map the insolubles content around the basins, from which cavern volumes were calculated.[42] For the purposes of this paper, uncertainties over the distribution of insolubles within each basin and brevity, the results presented here represent an average of 25% insolubles taken for the halite beds in all four basins. This is consistent with the average for the Triassic Northwich Halite Member

of the Cheshire Basin[e.g.A74] and is well within the range found in the Triassic halites of the EISB and Wessex Basin. In the Fordon Evaporites of East Yorkshire, insoluble content over cavern intervals is variable. Data from the development of the Aldbrough gas storage facility revealed for one cavern an average of 4.5% over the cavern interval, whilst in another cavern nearby, the insoluble content ranged between 15-38%.[A75] At this stage, the value of 25% taken for the other basins was thus thought to represent an objective and realistic first approximation of the insoluble content of the Zechstein halite beds in eastern England.

Data from the Huntorf facility has generally been used in assessments of the thermodynamic efficiency and storage capacity of CAES salt caverns.[e.g.83,A65] The cavern wall temperatures generally adopted are 50°C, which is somewhat high for the UK, given UK geothermal gradients in UK sedimentary basins and possible cavern depth ranges. The average UK onshore geothermal gradient is 26°C/km, but locally it can exceed 35°C/km in, for example, areas of granite intrusions.[A66] Geothermal gradients do, however, vary from one halite-bearing basin to another and average gradients for the basins in question are detailed in Supplementary Appendix 2, Table A2, based in most part on Busby.[A66] It is noted, however, that these are average gradients for the basins and often significant variations exist, with e.g. a temperature of 105°C reported in the halite beds at proposed storage depth for a gas storage facility in Wessex, equating to a geothermal gradient of ~40°C/km[A76] compared to the average of 34.5°C in Supplementary Appendix 2, Table A2. Temperatures at the cavern depths were therefore calculated based upon the UK geothermal gradients, which in all cases is lower than the 50°C temperatures assumed from Huntorf and adopted in other studies on exergy potential.

The thermal conductivity, k_W (W/(m · K)), of halite varies between 2.6 and 7 (Supplementary Appendix 2, Table 2), with an average of 4 usually adopted.[A69] However, values of 5 to 6 have been used in modelling of cavern performances during three cycling storage periods:[A77,A78] one day (CAES); one week; and one month (corresponding to an "aggressively" operated High Frequency Cycling Gas Storage Cavern [HFCGSC]).

In accordance with the safe design and operation of salt cavern rules developed in the gas storage industry, maximum and minimum operating pressures of 83%-30% of lithostatic pressure at casing shoe depth[A79] are assumed. In reality, given the more rapid cycle frequency of CAES, the minimum is likely to be slightly more than 30% and the maximum less than 83%.

Exergy storage modelling tool - development

The exergy storage tool developed previously[38] has been updated to implement the equations detailed below and thus permit a prediction of the exergy stored when charging an uncompensated isochoric (constant volume, variable pressure) system, with isothermal, CHT and adiabatic heat transfer from the cavern to the surrounding rock in the cavern walls. The assumptions, revised equations defining the exergy, rate of change of pressure and temperature in the cavern, and the heat transferred into the surrounding walls are described below.

The tool was tested using examples of natural gas storage caverns constructed and operational at both Hornsea and Aldbrough, and takes into account complexities associated with the thermodynamics of the internal air compression and expansion processes and the coupled heat transfer with surroundings.[38] It enables calculations for two modes of operation:

- assuming constant volume, variable pressure (isochoric) operation - i.e. the air cavern is operated in uncompensated isochoric condition
- assuming constant pressure, variable volume (isobaric) operation

Relative to the isochoric cavern scenario, few studies have considered the dynamic responses of an isobaric CAES cavern system. Indeed, most UGS and the operational CAES salt cavern storages operate in exclusively isochoric mode and isobaric cavern operation was not therefore considered in this study.

For capturing the unsteady heat transfer between the air and cavern wall, the tool considers three wall conditions which approximate the heat flux between air and surrounding rock. Two cavern wall conditions represent somewhat unrealistic, end-member models:

- adiabatic boundary conditions in which heat flux into the surrounding rock mass is zero
- isothermal boundary conditions in which heat flux is infinite with perfect conduction into and through the surrounding rock mass

In practice, realistic CAES cavern operation lies somewhere between the two end-member cases and the convective heat transfer (CHT) wall condition for a practical (diabatic) cavern operational scenario was developed.[38] For this model, during the cavern charging period, thermal energy of the air stored in the cavern is lost to the immediate surrounding rock mass whilst the air temperature still increases due to the internal compression. The two-end member scenarios produce slightly greater (isothermal) and smaller (adiabatic) exergy values, bracketing the CHT model.

We have further refined the modelling tool to implement their equations and predict the exergy stored when charging an uncompensated isochoric (constant volume, variable pressure) cavern or set of caverns. The CHT model is thought to more accurately represent actual storage conditions and it is the results of this scenario that are presented and discussed in detail here.

The surface area of the cavern and calculation of the heat transfer from the cavern void into the walls is necessary for CAES, estimates of which were derived relative to each cavern mid-point depth. They were calculated using the geothermal gradient for each specific basin, with an average annual surface temperature of 9.5˚C and pressure of 1 bar (14.5 psi). The tool imports the depths, volumes, temperatures and min/max storage pressures calculated for each cavern and models iteratively, the cavern-fill (exergy storage) from the starting point of the minimum to maximum permissible storage pressures. Results for the three differing cavern wall heat transfer models for each cavern over the two cavern depth ranges

are output to a spreadsheet as the 'working exergy' storage in megawatt hours (MWh), together with the maximum pressure (pascals) and stored air mass (kg).

The gas volumes in the salt cavern are referred to as 'working gas' (that between minimum and maximum operating pressures), 'cushion gas' (that below minimum operating pressure and providing the base pressure for cavern stability) and total gas volume (working gas plus cushion gas volumes). The working gas volume represents the 'static', one-fill gas capacity, not the larger total gas volume of the cavern and takes no account of multiple filling cycles. It is thus representative of a seasonal storage, similar to most aquifer and depleted field storages. We describe various attempts to derive realistic 'working exergy' storage estimates through a series of cavern-filling cycles.

The total exergy in a system consists of four elements: physical exergy, chemical exergy, kinetic exergy and potential exergy. Physical exergy is due to deviations of the system temperature (thermal exergy) and pressure (mechanical exergy) from the environment.[A80] In a CAES cavern, the exergy is due primarily to physical exergy, and thus this model only considers physical exergy. Exergy varies with the rate of air flow as expressed by

$$\dot{B} = \dot{m}\left[(h - h_0) - T_0(s - s_0)\right], \qquad (0.1)$$

where $\dot{B}$ is the exergy rate of change in J/s, h is specific enthalpy in J/kg, s is specific entropy in J/kgK, $\dot{m}$ is mass flow rate in kg/s and T is temperature in K. Properties with the subscript o refer to the property at the environmental reference. Assuming that the air behaves like an ideal gas, the following expressions for enthalpy and entropy difference can be used, respectively:

$$h - h_0 = c_p(T - T_0), \qquad (0.2)$$

$$s - s_0 = c_p \ln\left(\frac{T}{T_0}\right) - R\ln\left(\frac{P}{P_0}\right), \qquad (0.3)$$

where c_p is the specific heat capacity of air in J/kgK, R is the gas constant of air which equals $287.06\ J/kgK$, and P is pressure in Pa. The exergy stored in a CAES cavern is due to the changes in pressure and temperature inside the cavern as it charges, thus the stored exergy can be calculated using

$$B = \int_{\text{charging}} \dot{B}dt = \int_{\text{charging}} \dot{m}\left\{c_p(T - T_0) - T_0\left[c_p \ln\left(\frac{T}{T_0}\right) - R\ln\left(\frac{P}{P_0}\right)\right]\right\}dt. \qquad (0.4)$$

The change in mass inside the system, $\dot{m}$, is defined by the defence between the mass flow rate in and out of the system:

$$\dot{m} = \dot{m}_{in} - \dot{m}_{out}. \qquad (0.5)$$

Since only the charging process is considered, $\dot{m}_{out} = 0$. The change in the internal energy of the cavern can be described based on the first law of thermodynamics for an open system,

$$\frac{d(mu)}{dt} = \dot{Q} - \dot{W} + \dot{m}_{in} h_{in} \qquad (0.6)$$

where u is specific internal energy in J/kg, $\dot{Q}$ is the rate of heat input, $\dot{W}$ is the work done by the control volume ($\dot{W} = 0$ in this case) and h_{in} is the specify enthalpy in J/kg of the inflowing air. The kinetic and potential energy of the inflowing air are neglected. Defining specific internal energy as $u = h - pv$ where p is the pressure and v the specific volume of air, equation (0.6) can be expressed as

$$\frac{d(mh)}{dt} = \dot{Q} + \dot{m}_{in} h_{in} + V \frac{dp}{dt}. \quad (0.7)$$

If the heat capacity of air, c_p, is assumed to be constant, the rate of change of temperature and enthalpy can be related by

$$\frac{dh}{dt} = c_p \frac{dT}{dt}. \qquad (0.8)$$

Hence, equation (0.6) can be expressed as

$$\frac{dT}{dt} = \frac{\dot{Q} + \dot{m}_{in} c_p (T_{in} - T) + V \frac{dp}{dt}}{m c_p}, \qquad (0.9)$$

giving an expression for the rate of change of temperature, where T_{in} is the temperature of the inflowing air. The pressure variation inside the cavern can be determined by differentiating both sides of the ideal gas equation,

$$pV = mRT, \qquad (0.10)$$

with respect to time and using (0.9) for the temperature variations. Assuming a constant volume process and $\dot{m}_{out} = 0$, the following equation is found

$$\frac{dp}{dt} = \frac{1}{V}\left(kRT_{in}\dot{m}_{in} + (k-1)\dot{Q}\right) \qquad (0.11)$$

where k is the ratio of specific heats. The heat exchange through the cavern walls can be estimated by

$$\dot{Q} = \alpha_W A_W (T_W - T) \qquad (0.12)$$

where α_W is the average heat transfer coefficient in W/m^2K, A_W is the surface area of the cavern wall in m^2, and T_W is the wall temperature in K. The cavern wall is assumed to be an interface with negligible thickness between the compressed air region and the rock region. Heat transfer is assumed to be one dimensional in the radial direction and is described by[A81,A82,A83]

$$\rho_s c_{p,s} \frac{dT_s}{dt} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_s r \frac{\partial T_s}{\partial r}\right) \quad (0.13)$$

where the subscript s refers to the surrounding rock, ρ_s is in kg/m^3 is, $c_{p,s}$ is heat capacity in J/kgK, r is the radial distance from the cavern wall in m, k_s is heat conductivity in W/mK and T_s is the temperature in K. The boundary conditions of the system are

$$r = 0 \rightarrow -k_s \frac{\partial T_s}{\partial r} = \alpha_W (T - T_W), \qquad (0.14)$$
$$r = r_\infty \rightarrow T_s = T_{rock},$$

where T_{rock} is the ambient temperature of the surrounding rock and r_∞ represents a distance far enough away from the cavern such that T_{rock} is unaffected by the heat conduction from the cavern. The initial conditions of the temperature in the surrounding rock are modelled as a first order decaying system such that

$$T_{rock} + (T_{ini} - T_{rock}) \exp\left[-\frac{r}{b_{rock}}\right], \qquad (0.15)$$

where T_{ini} is the initial temperature of the cavern in K, and b_{rock} is the distance at which the temperature of the surrounding rock reaches $1/e \approx 36.8\%$ of $(T_{ini} - T_{rock})$. Equation (0.13) is solved using the Method of Lines.[A84]

Multicycle fills and 'dynamic working exergy' storage estimates

Gas storage caverns are cycled more than once a year, effectively increasing the one-fill 'static' working gas storage capacity generating a larger 'dynamic' working gas volume,[39] or 'dynamic exergy storage' as considered here. At this stage, it is impossible to determine precise cavern depths, sizes and temperatures and thus undertake detailed geo-mechanical and thermodynamic modelling for all potential cavern locations, volumes, storage pressures, operating scenarios and cycle times. In this section we outline the processes behind an attempt to calculate the general 'dynamic exergy storage' potential for both the 100 m and greater, and the 100-150 m cavern sets. This was undertaken by estimating the number of cycles per year, based upon cavern fill and withdrawal rates in UGS and CAES operations and taking from the exergy modelling tool the average values for the outputs of maximum cavern pressure, exergy stored and air mass in caverns (Supplementary Appendix 2, Table A5).

The cavern operation and actual amount of gas (or air) stored are dictated by the injection rates and operational pressure ranges permitted for the caverns. The storage pressure ranges between a minimum and maximum, being a function of the depth of the cavern and the proposed operating conditions, which are determined by the geomechanical properties of the halite and interbedded lithologies, and the type of storage: fast-cycle (daily or weekly), or more longer-term, seasonal storages. Maximum and minimum pressures respectively correspond to ~80-83% and 30% of the of the initial lithostatic pressure at the depth of the casing shoe, which is set in the salt beds some distance above the cavern roof.[A79] The maximum is to avoid over-pressuring and fracturing of the halite beds and the minimum is to support the cavern walls and roof, avoiding salt creep and closure of the cavern, or spalling and major salt falls (slabbing) during periods of low pressure during withdrawal

cycles. These pressures vary depending upon the nature and frequency of the storage operations: fast-cycle natural gas, hydrogen or CAES injection-withdrawal storage cycles, with large pressure rate changes dictate lower pressure ranges and maxima than for longer-term, more seasonal storages with fewer cycles and lower pressure rate changes.[A85] Pressure ranges for CAES will, in general, be much lower due to the much higher and more frequent cyclic pressure changes and the absolute pressure level will also be lower because the compressors, heat storages and turbines of current technology operate at pressures below 100 bar.[A85]

The maximum permissible rate changes for cavern filling and emptying are governed largely by the maximum flow rates in the boreholes and the maximum permissible pressure reduction rates in the caverns, which are determined by local rock geomechanical properties and operational requirements. For gas storage in general, this is ~1 MPa/d (10 bar/d), with maximum withdrawal rates corresponding to ~10% of the storage capacity per day and a maximum of perhaps 10 turnovers per year in terms of gas storage.[A79] More frequent cycling is expected in CAES operations, with daily or weekly pressure cycles not involving the injection and withdrawal of the entire working gas volume. Thus, the difference between maximum and minimum pressure generally is small: typically 2 MPa.[49,A86] Cycling entire cavern volumes once a week would likely be too frequent for the depths and operationally practical cavern volumes calculated in this study. It is noted, however, that a cavern with a volume of only 175,000 m^3 at a depth of ~370 m, is operated on a diurnal basis for gas storage in the Cheshire Basin.[A87] Designed to operate to a maximum pressure of the NTS system (up to 94 bar[A88]), it delivers ~2-4 mcm/d and suggests a similarly small CAES cavern of this size, operating daily, would be feasible.

Cavern emptying or withdrawal times were thus calculated for three scenarios based upon an injection phase (cavern charging), involving a conservative mass injection rate of 108 kg/s as reported from the Huntorf CAES facility[9] and three differing withdrawal rates (generation or cavern discharge phase): 108 kg/s (equivalent to injection rate), 417 kg/s (from Huntorf[9]) and a general maximum pressure rate reduction of 15 bar/h [1.5 MPa/h] for gas storage operations.[9,49,A86] For the latter, an approximate equivalent air mass withdrawal rate in kg/s was calculated to assess how realistic the rate might be for any particular scenario. For the higher flow rates, it may be that caverns would require more than one withdrawal well to achieve the air mass withdrawal rates. The calculated injection and withdrawal rates were then used to derive an estimate of the number of cycles per year and thus determine the 'dynamic' exergy capacity available for the different model categories and depth ranges (Supplementary Appendix 2, Tables A6-A8).

As can be seen, the working exergy storage increases with those based upon the Huntorf operational parameters (Supplementary Appendix 2, Table A6) being lower than those using faster withdrawal rates, which increases the number of storage cycles possible (Supplementary Appendix 2, Tables A7&A8). The results illustrate more markedly the potentially significant contribution of CAES in salt cavern to the UK's energy storage capacity and electricity supply. This is illustrated by taking the Cheshire Basin as an example. Here exergy storage estimates from the operational cycle based on 108 kg/s fill

rates and 108 kg/s withdrawal rates, suggest that caverns of 100 m and greater (1452-1607 caverns), or 100-150 m in height (651-804 caverns) over the two depth ranges have the potential to provide between ~151-170 TWh and 68-86 TWh storage respectively, or with the stored exergy converted to work, meeting between ~46-52% and 21-27% of the UK electricity demand respectively. For the operational cycle based on 108 kg/s fill rates and maximum withdrawal rates of 1.5 MPa/hr, the estimates range between ~287-296 TWh and 129-164 TWh storage respectively, or with the stored exergy converted to work, meeting between ~88-98% and 40-50% of the UK electricity demand respectively. Taking the estimates based on UGS cavern numbers for the two cavern sizes, stored exergy would, using the most cycled operational mode (Supplementary Appendix 2, Table A8), provide up to 14.9 TWh of exergy storage, converting to 13.7 TWh of work and meeting 4.5% of the UK electricity demand.

Combined, the halite basins studied provide important exergy storage and work output potential, with for example, just 1% of all 100 m plus height caverns in the 500-1500 m depth range in the basins providing between perhaps ~38-74 TWh (~13-25%) stored exergy in terms of UK electricity requirements, or ~35-68 TWh (~12-23%) of work depending on the mode of operation and cycle numbers (Supplementary Appendix 2, Tables A6-A8). Whilst caverns of 100-150 m height in the same depth range might provide ~11-21 TWh (~4-7%) stored exergy in terms of UK electricity requirements, or ~10-20 TWh (~3.7-6.5%) of work (Table A6Table A8). Relative to UGS cavern numbers in the basins, the figures for 100 m plus caverns in the depth range 500-1500 m are ~21-40 TWh (~7-13%) stored exergy in terms of UK electricity requirements, or ~19-36 TWh (~6-12%) of work, whilst 100-150 m height caverns might provide ~16-30 TWh (~5.5-10%) stored exergy in terms of UK electricity requirements, or ~15-28 TWh (~5-9%) of work (Supplementary Appendix 2, Tables A6-A8). These data illustrate the potential importance of CAES and salt cavern storage to meeting UK electricity demand and supply.

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