Compressed Air Energy Storage:

Underground Technologies

Professor Seamus D. Garvey, University of Nottingham

European Workshop on Underground Energy Storage, Nov 7-8, 2019

Contents

- **Compressed Air Energy Storage (CAES) – what it IS**
- **Compressed Air Energy Storage (CAES) – what it IS NOT!**
- **CAES: UK underground potential E.S. capacity**
- **CAES: Integrates extremely well with loads & generators**
- **CAES: Next steps**

Much of this presentation was delivered previously at a meeting of Geological Society of London on Jan 21, 2019. A recording of that presentation is at … https://www.geolsoc.org.uk/Lovell19

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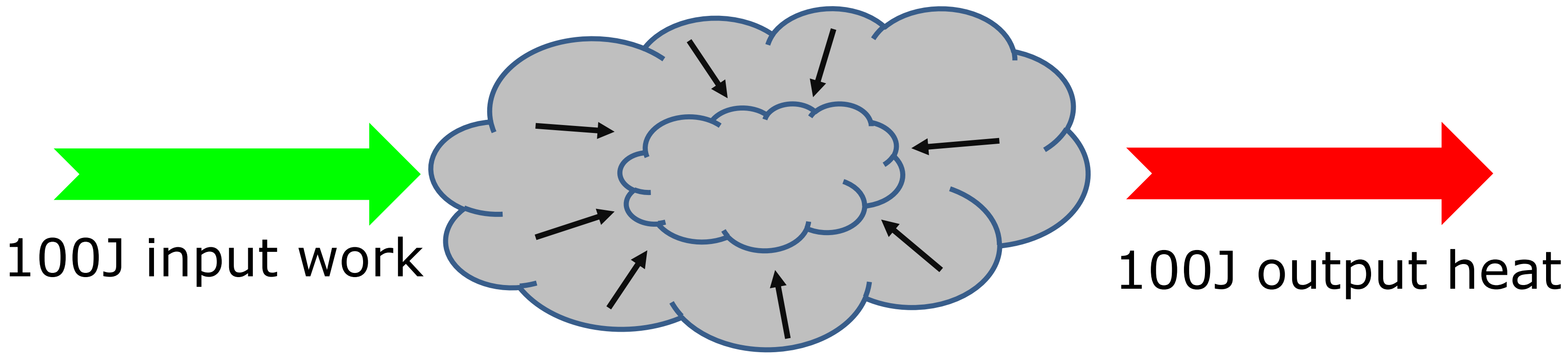
What C.A.E.S. IS

<u>CAES is a broad set of EXERGY-Storage technologies</u> which involves compressing air to store exergy and expanding air to release exergy.



CAES systems store zero net energy in the form of pressurised air!

What C.A.E.S. IS

The exergy stored in compressed air is given by …

$$B_{HP-air} = \left(p_0 \times V_{store}\right) \times \left(r \log r - (r - 1)\right)$$

… where …

r **represents the pressure ratio,**

p_0 **represents ambient pressure**

V_{store} **represents the volume of high pressure (HP) air stored**

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What C.A.E.S. IS

Example: 41.3m³ of storage at r = 200 stores 1MWh.

Example: 98.3m³ of storage at r = 100 stores 1MWh.

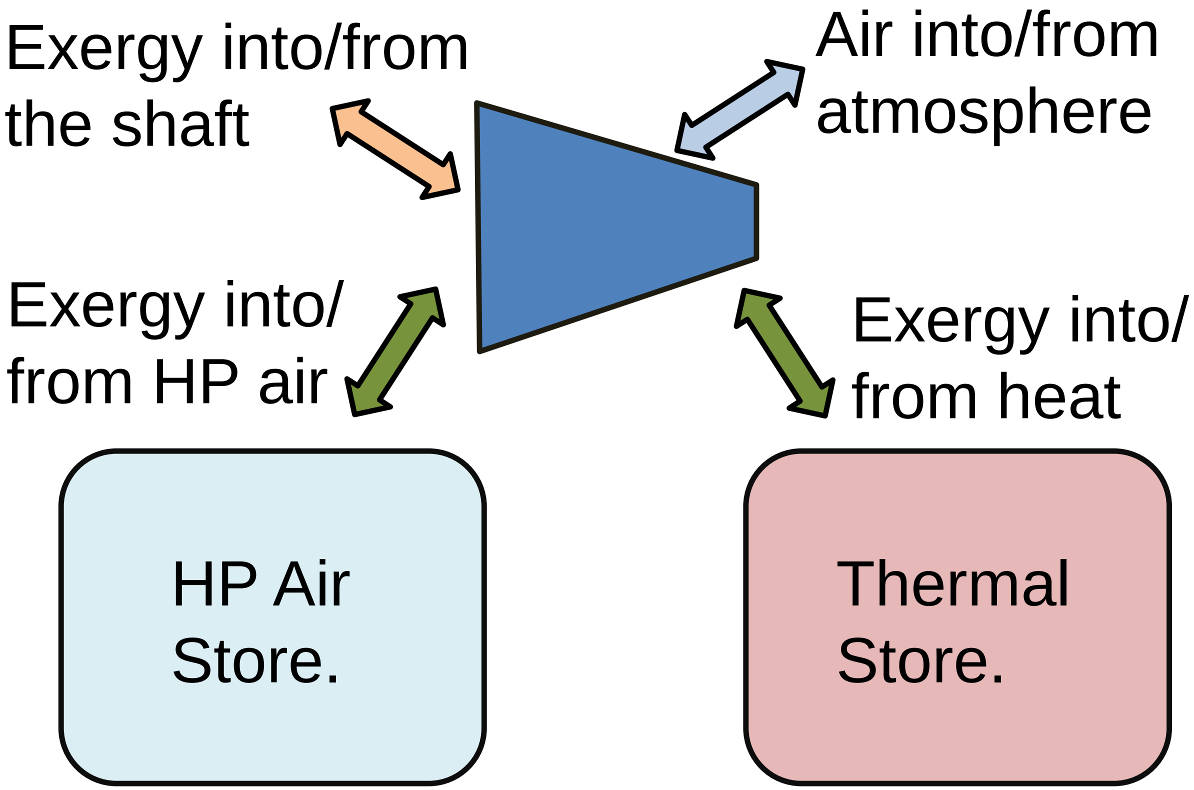
Example: 242.4m³ of storage at r = 50 stores 1MWh.

Example: To store 10TWh using HP air at ~100bar (r = 100), we would need ~983 million m³ of storage.

In most cases of CAES systems, the cost of the HP air store dominates the cost of the system.

What C.A.E.S. IS

CAES always involves managing heat as well as HP air.



Relatively expensive in tanks (~$50/kWh - $100/kWh)

Relatively inexpensive if done using sensible heat.

What C.A.E.S. IS

Steel tanks are potentially viable HP air stores for CAES



$$V_{steel} = V_{air} \times k \times \left(\frac{p_{gauge}}{\sigma_{max}} \right)$$

$$1.5 \le k \le 2$$

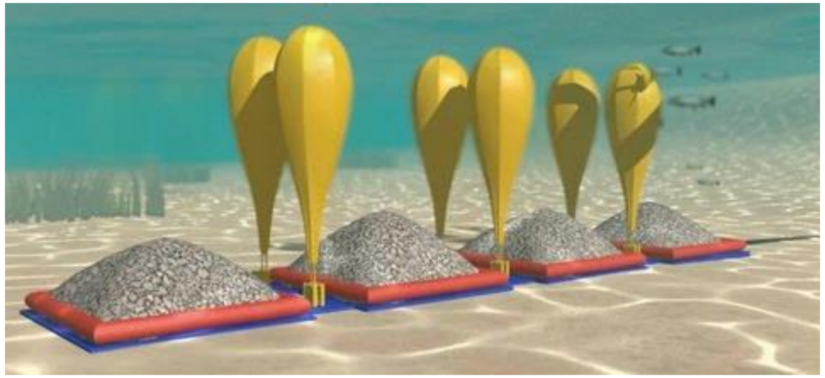
Higher pressures … lower $/kWh of exergy

$$\text{cost} \propto \frac{(r-1)}{(r \log r - (r-1))}$$

Recent quotes (from China!) indicate <$80/kWh possible at 250bar.

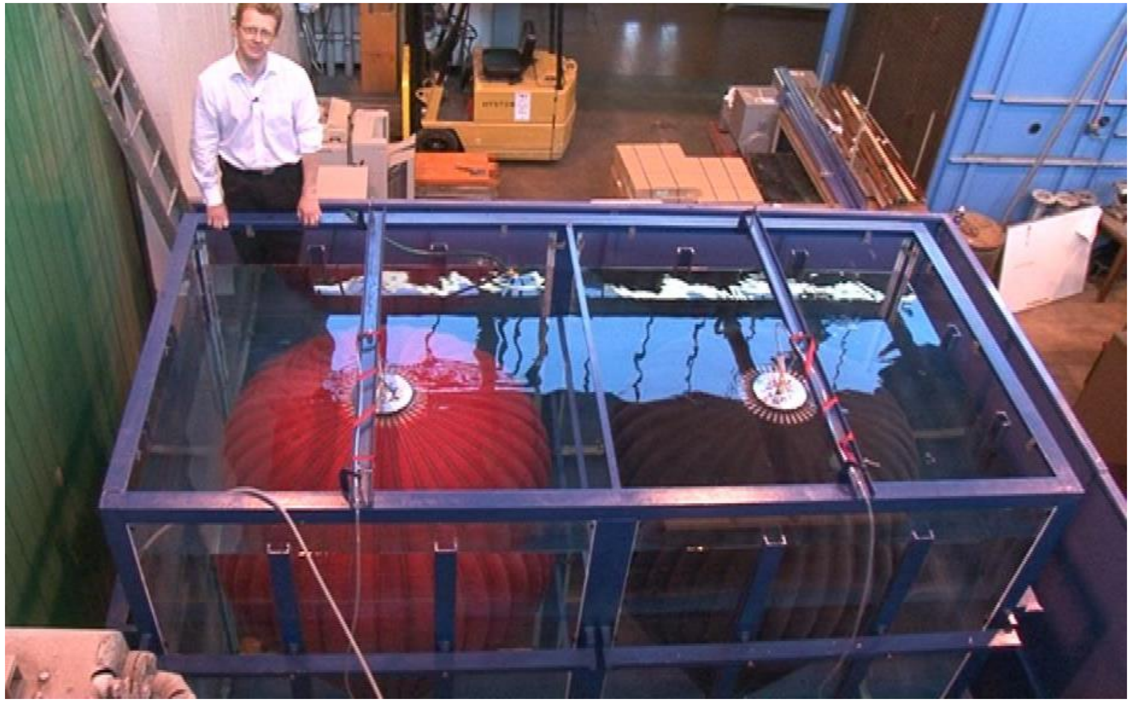
What C.A.E.S. IS

CAES can be done with underwater storage of HP air!



What C.A.E.S. IS

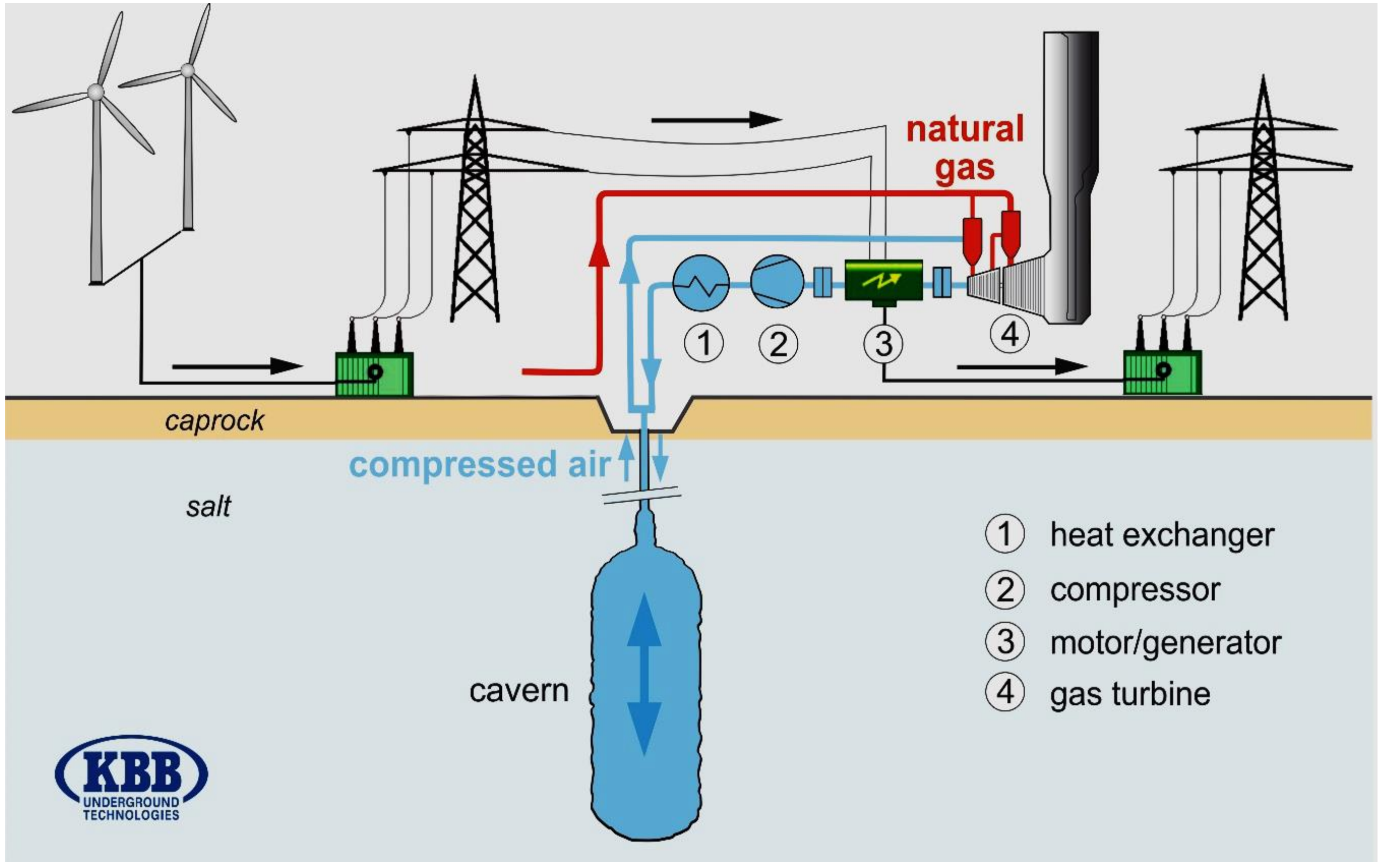
UWCAES is very attractive because of constant-pressure characteristic



Trials of *Energy Bags* in 2009.
(E.ON funded)

For economical storage, you need ~500m water depths (50bar)

What C.A.E.S. IS



http://ees-magazine.com/wp-content/uploads/2014/07/Fig.2_diabatic-compressed-air-energy-storage-power-plant.jpg

Underground storage of HP air is especially attractive at large scales.

Some view that <$5/kWh marginal cost is possible for energy storage capacity.

What C.A.E.S. IS

Intrinsically, CAES has separate components of cost for the *power* and the *energy storage*.

Compression machinery is very well-established in the range 1-12bar.

The low-pressure machines are the most expensive (per kW).

Modern aero gas turbines are operating with pressure ratios of >50:1

The power conversion machinery and the HP air stores are characterised by very long natural lifetimes.

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What C.A.E.S. is NOT!

#1. CAES is NOT easily understood by anyone whose engineering qualifications do not run beyond "A-level physics"!

The strong interplay between heat and air compression/expansion leads to subtleties that are easily underestimated.

Moreover, whilst anyone with reasonable mechanics knowledge can indeed devise a CAES system, it does take engineering training to understand what will be affordable and what not.

What C.A.E.S. is NOT!

#2. CAES is NOT “a mature technology”.

Two grid-scale plant have been in operation for decades but both of these were quite adventurous prototypes in their day and they were not designed for the E.S. requirements of 2020 or 2030 etc..

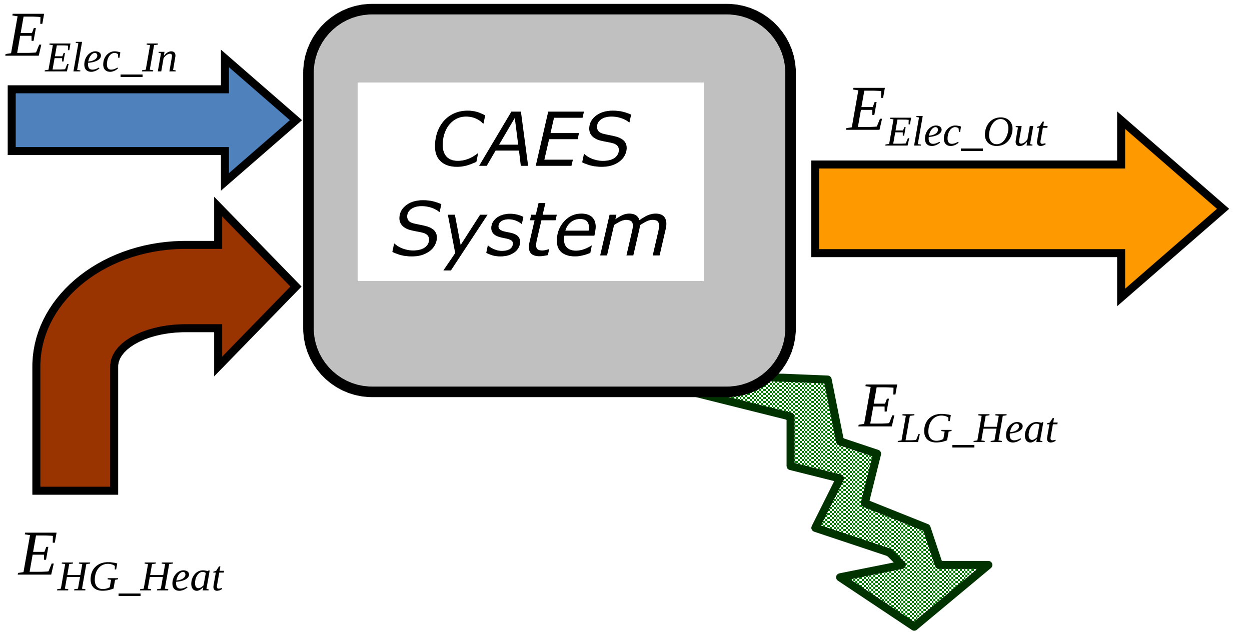
Also, CAES is not “a single technology”.

There is huge scope for further learning and further cost-reduction.

What C.A.E.S. is NOT!

#3. CAES is NOT inefficient.

The two existing grid-scale plant are *diabatic* (they use fuel to heat the air prior to expansion of the stored air).



$$\eta_{turnaround} = \frac{E_{Elec\_Out}}{E_{Elec\_In} \quad E_{HG\_Heat}}$$

Properly assessed, the McIntosh CAES plant is ~79% efficient and this could be raised to 84% without major difficulty.

What C.A.E.S. is NOT!

#3. CAES is NOT inefficient ../cntd.

ALL thermo-mechanical energy storage systems are characterised by a *work-conversion ratio*.

$$\textit{Work-conversion ratio} = \frac{\textit{Total amount of work converted.}}{\textit{Energy passed into and back out of the system}}$$

For CAES, the *Work-conversion ratio* = 2 (as low as it can be)

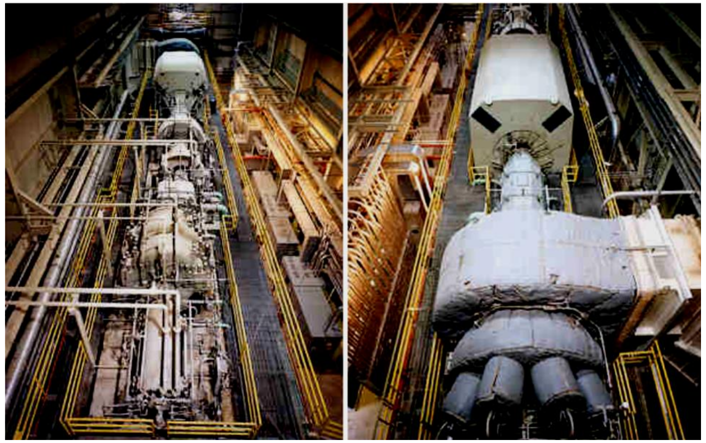
For typical pumped thermal ES, the *Work-conversion ratio* = 5.

What C.A.E.S. is NOT!

#4. *Diabatic* CAES is not really CAES at all!

~50% of the exergy in existing grid-scale *CAES* systems is stored in the fuel!

Huntorf: for each 1000J of electricity output, 800J of electricity input and 1600J of heat input

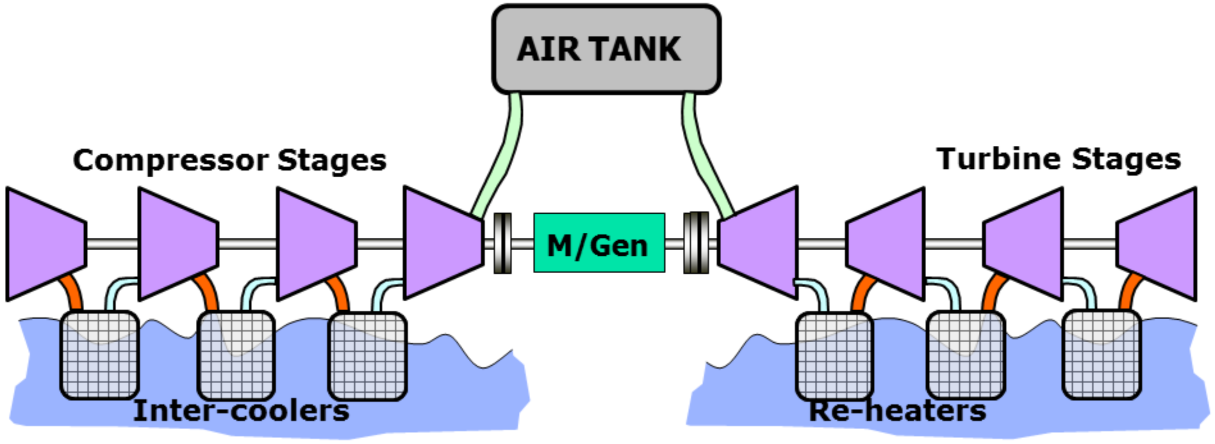


McIntosh: for each 1000J of electricity output, 690J of electricity input and 1170J of heat input

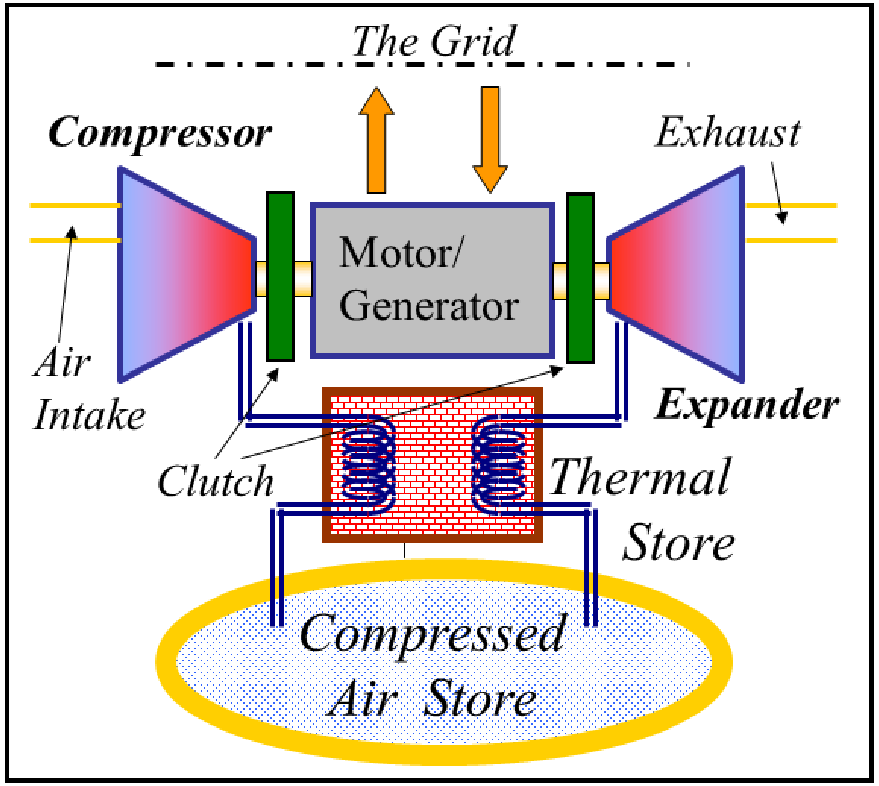
What C.A.E.S. is NOT!

#5. *Adiabatic* CAES (vs *isothermal* CAES) is not motivated by "efficiency"

Either adiabatic or isothermal compression / expansion processes can be arbitrarily efficient.



ARCUS
EVANS Biannual Energy Storage
Conference, Dec. 1-3, 2010.



What C.A.E.S. is NOT!

#5. *Adiabatic* CAES (vs *isothermal* CAES) is not motivated by "efficiency"

Choosing one route or the other has to do with:

(a) controlling the costs of the power-conversion equipment

(b) adjusting what fraction of the total exergy stored is in heat

(c) enabling more rapid power-swings.

What C.A.E.S. is NOT!

#6. CAES is <u>NOT</u> best done with *Isochoric* (constant volume) air stores.

For best usage of a given capacity of HP storage, use *Isobaric* (constant pressure) and not *Isochoric* (constant volume).

Inject/remove liquid as air is removed/injected to maintain pressure.

Advantages:

(1) Power-conversion machinery always works with same pressures

(2) No thermal-swing issues on the walls of the containment.

What C.A.E.S. is NOT!

#6. CAES is <u>NOT</u> best done with *Isochoric* (constant volume) stores ../cntd.

Exergy in isochoric store:

$$\left(r\log r - r\right)\Big|_{r=(p_L/p_0)}^{r=(p_H/p_0)}$$

Exergy in isobaric store with press. ratio, r

$$\left(r\log r - (r-1)\right)$$

If HP air displaced naturally by hydrostatic head so that no power req'd to pump-in displacement fluid

$$\left(r\log r\right)$$

$p_H = 100p_0$	$p_L = 50p_0$	214.9
$p_H = 100p_0$	$p_L = 100p_0$	361.5
$p_H = 100p_0$	$p_L = 100p_0$	460.5

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UK Potential Resource

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UK Potential Resource

Applied Energy 208 (2017) 745–757

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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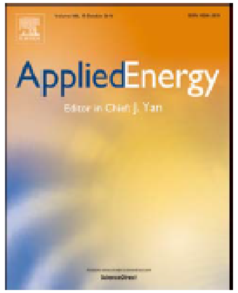

Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale compressed air energy storage system

Check for updates

Wei He[a], Xing Luo[a], David Evans[b], Jonathan Busby[b], Seamus Garvey[c], Daniel Parkes[b], Jihong Wang[a,*]

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[b] British Geological Survey, Keyworth, Nottingham NG12 5GG, United Kingdom
[c] Faculty of Mechanical Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom

The gas storage at Hornsea/Atwick cavern … 1.98 × 10^6 m^3, p_H = 270 bar.
~66 GWh of exergy storage in HP air. (Caverns average volume = 220 × 10^3 m^3)

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UK Potential Resource

Salt Basin (500-1500 m)	1% of buffered & >100 m cavern ht. – static (TWh)
Cheshire Basin	**0.12**
East Irish Sea (only 1300 m)	**0.66**
Wessex Basin	**3.9**
East Yorks - Boulby Halite	**0 (too thin)**
East Yorks - Fordon Evaporites	**0.32**
Totals (TWh)	**5**

For UK salt basins, 1% of available 100 m high caverns would provide static working exergy of 5 TWh, (D.J.Evans, BGS)

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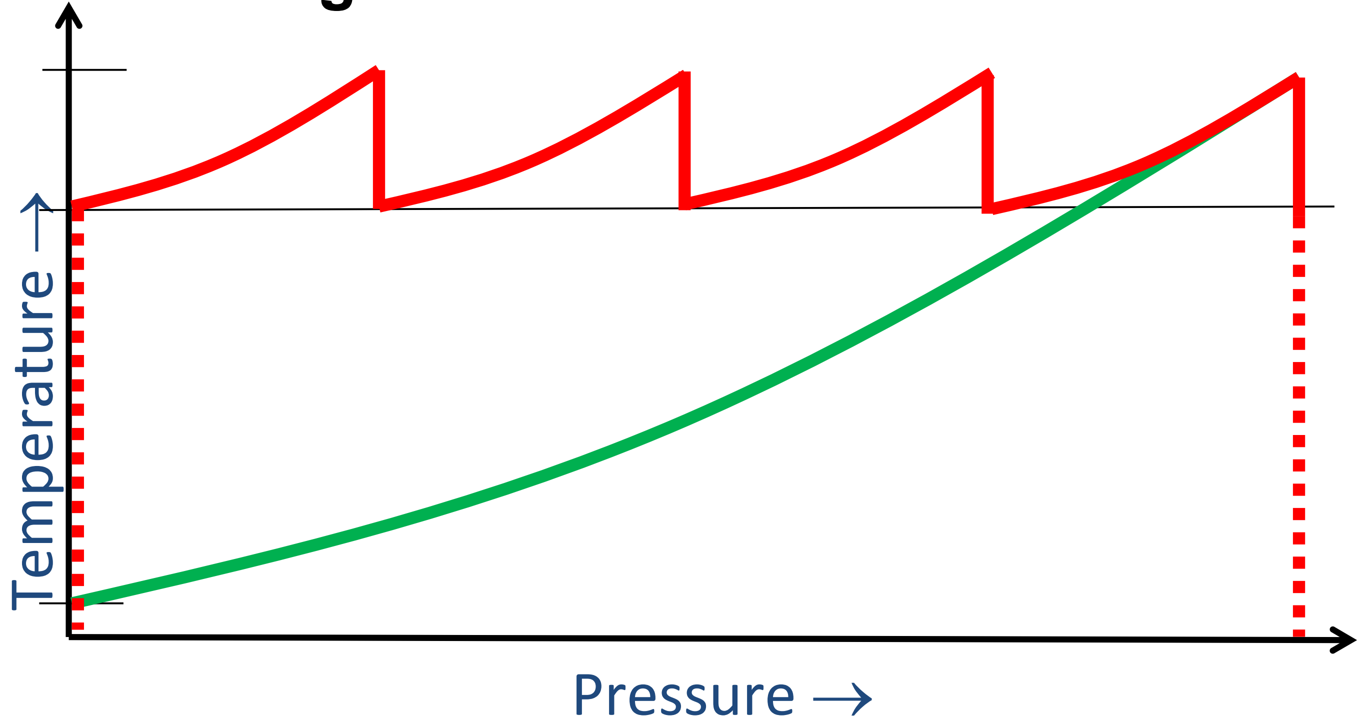
CAES Integrates well

The intrinsic connection between work and heat can be useful.

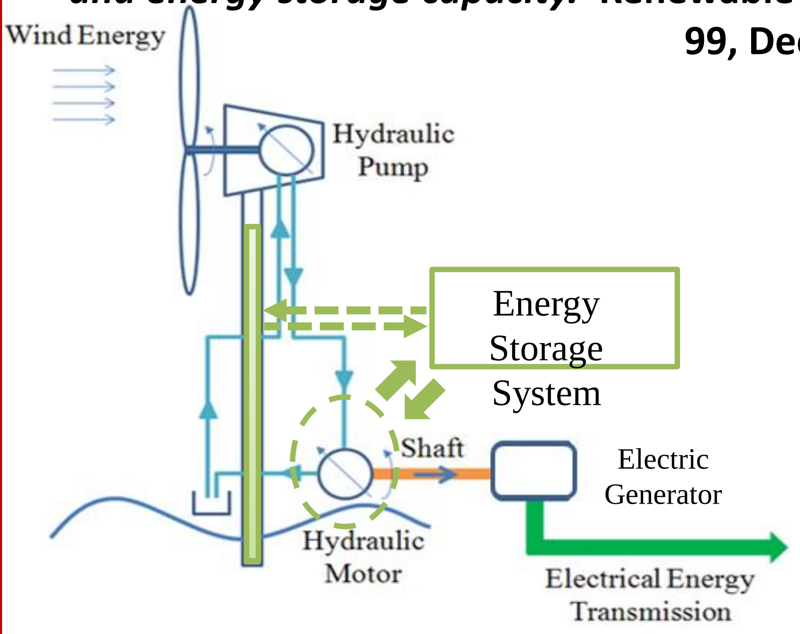
- **Data centres UPS (cooling + power <u>perfectly linked</u>)**
- **CAES plant have natural *inertia* (and that is good for an electricity grid)**
- **Exploitation of "low-grade" waste heat**

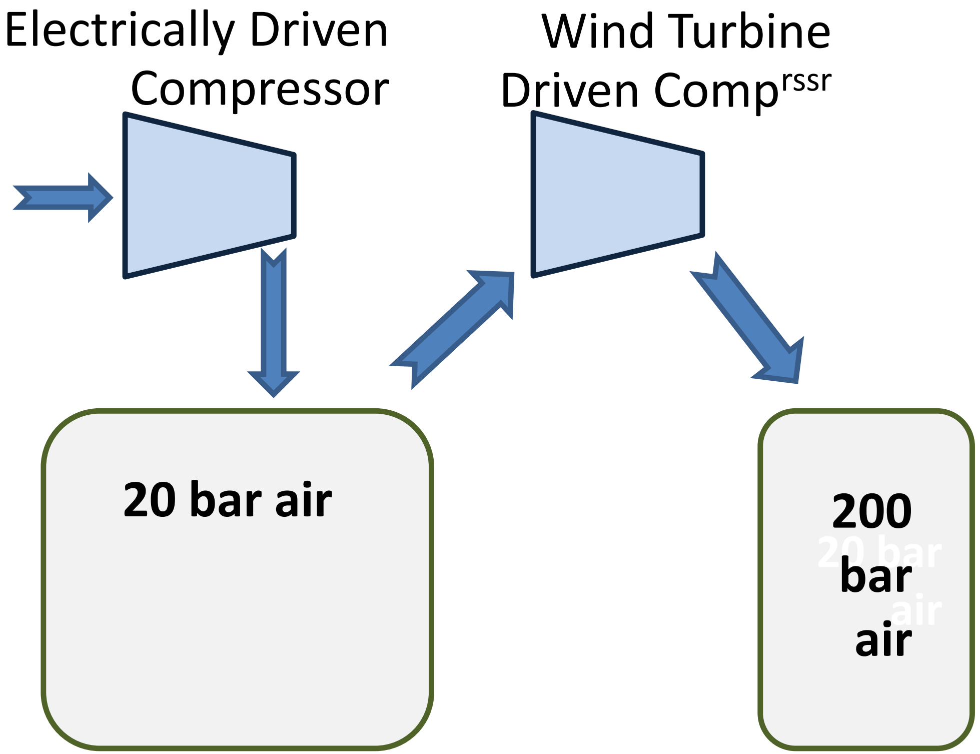


CAES Integrates well

Potentially, get wind turbines to compress air directly!

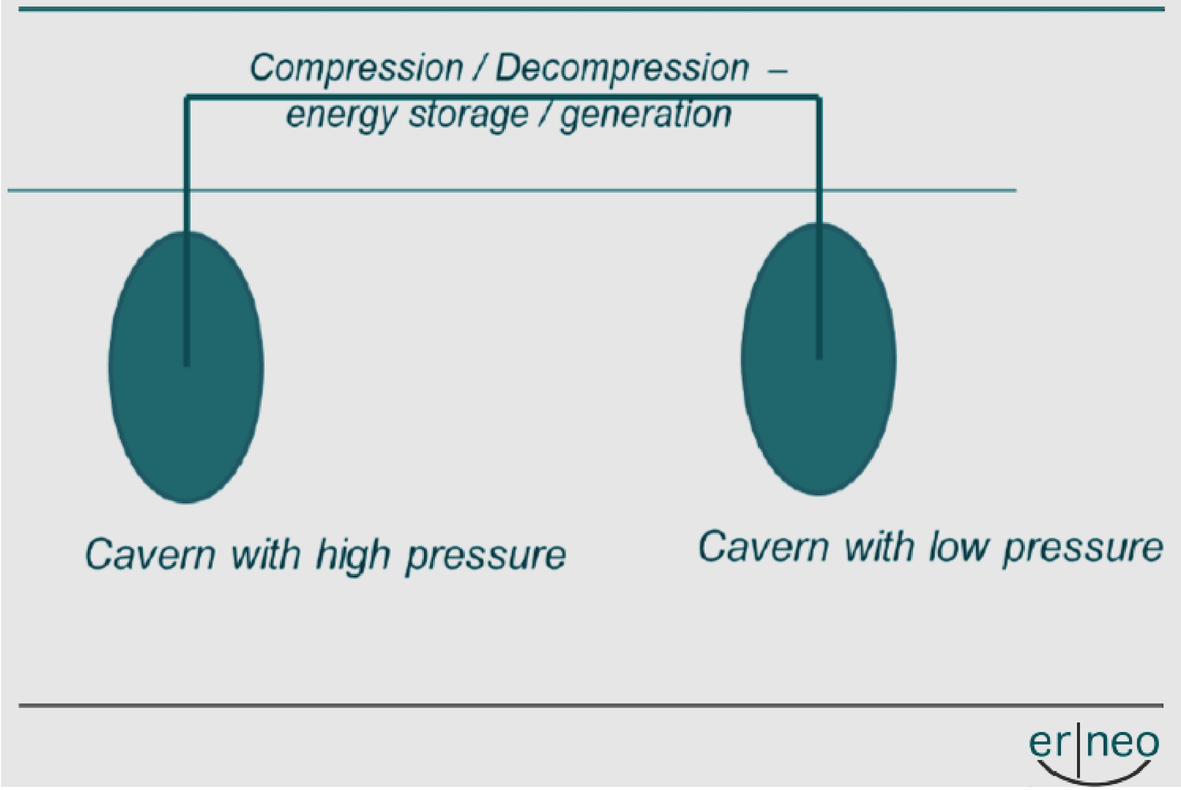
C Qin, E Innes-Wimsatt & E. Loth. *Hydraulic-electric hybrid wind turbines: tower mass savings and energy storage capacity.* Renewable Energy, 99, Dec. 2016,





CAES Integrates well

Note: the concept of 2-store CAES also proposed by ERNEO (Wolfgang Littmann)



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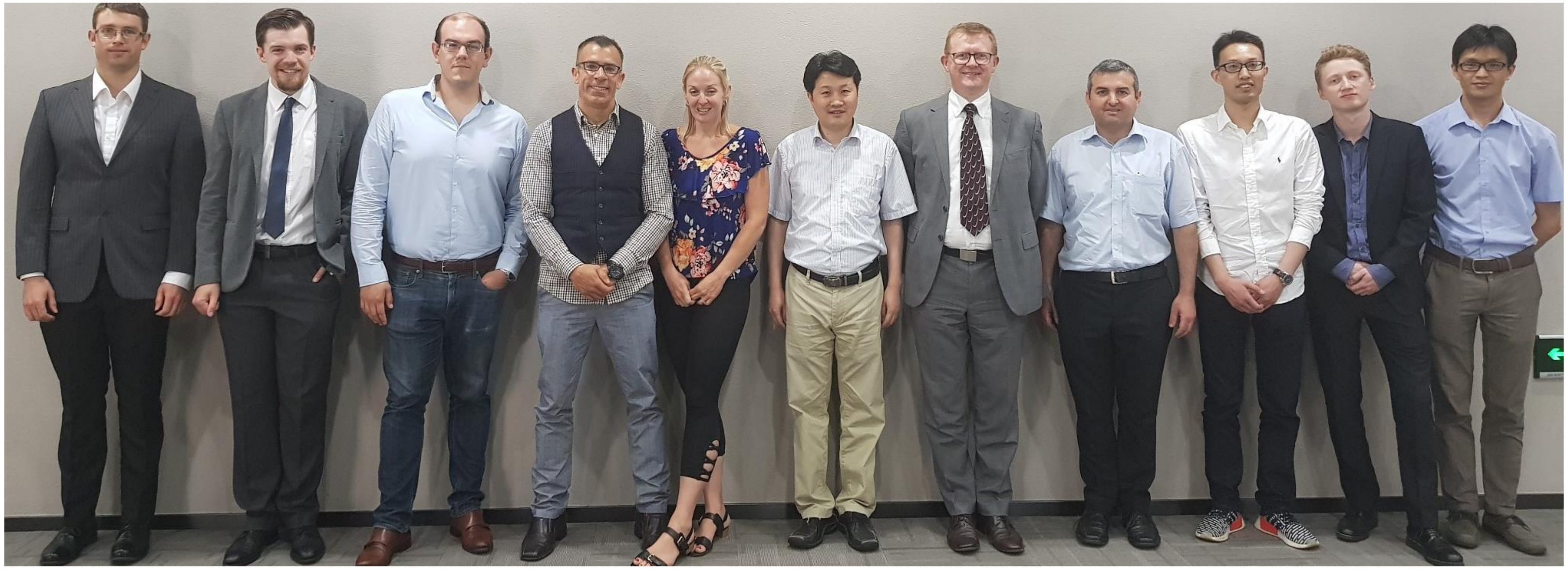
CAES Next Steps

International CAES Alliance formed (July 3, 2018).

- **Follow the (excellent) example of the UK CCUS task force?**
- **Identify ways to address some of the key remaining challenges.**



CAES Next Steps

Some important remaining technical challenges:

- **Cavern forming in halite … active shape control**
- **Cavern forming in halite … sealing at mud layers**
- **Hot compression/expansion machinery (~300°C inlet and ~600°C outlet)**
- **Reversible turbo-machines (halving the cost of power)**
- **Economic systems for capturing value of long-lifetime systems**
- **Conditioning of governments to “think big”**
- **Hydraulic compensation schemes for caverns (including Henry’s law)**
- **Integrated thermal storage with heat-exchangers**
- **High-pressure compressor/expander machines (variable ratio ?)**

CAES Next Steps

May 21st, 2019: Task force announced TO EXPLORE WAYS TO INTEGRATE MORE OFFSHORE WIND

No mention of CAES!

https://renews.biz/53299/uk-seeks-offshore-integration-solutions/

The group will publish a road map identifying pioneering techniques, such as using electricity from offshore wind to generate and store hydrogen as a power source. It will also examine how to introduce more flexibility into our energy system, for example by expanding battery storage and the use of demand side response (which enables consumers to take advantage of low electricity prices at certain times of day).

CAES Next Steps

May, 2019, the *Climate Change Committee* published its *Net Zero by 2050* report.

No mention of CAES!

https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

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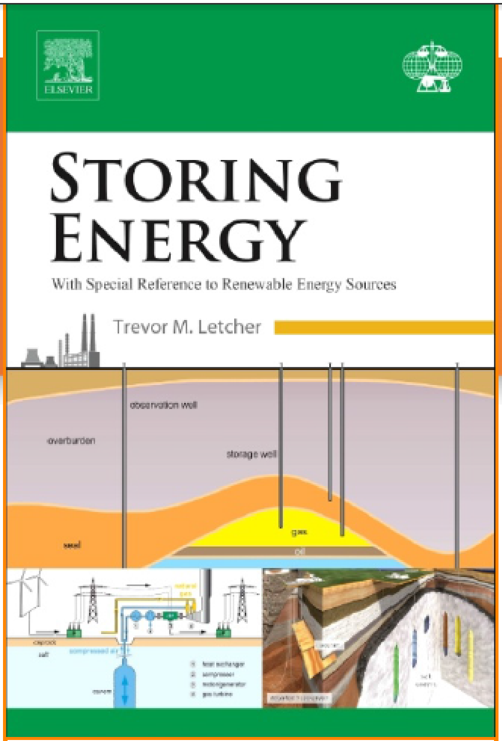
CAES Next Steps

April 2016. Contains 3 chapters on CAES.



Storing Energy

with Special Reference to Renewable Energy Sources

Trevor Letcher Emeritus Professor, School of Chemistry, University of KwaZulu-Natal, Durban, South Africa

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This comprehensive book discusses the needs of the world's future energy and climate change policies, covering the various types of renewable energy storage in one all-encompassing volume that allows readers to conveniently compare the different technologies and find the best process that suits their particular needs

ISBN: 978-0-12-803440-8

PUB DATE: March 2016

LIST PRICE: $140.00

FORMAT: Hardback

KEY FEATURES

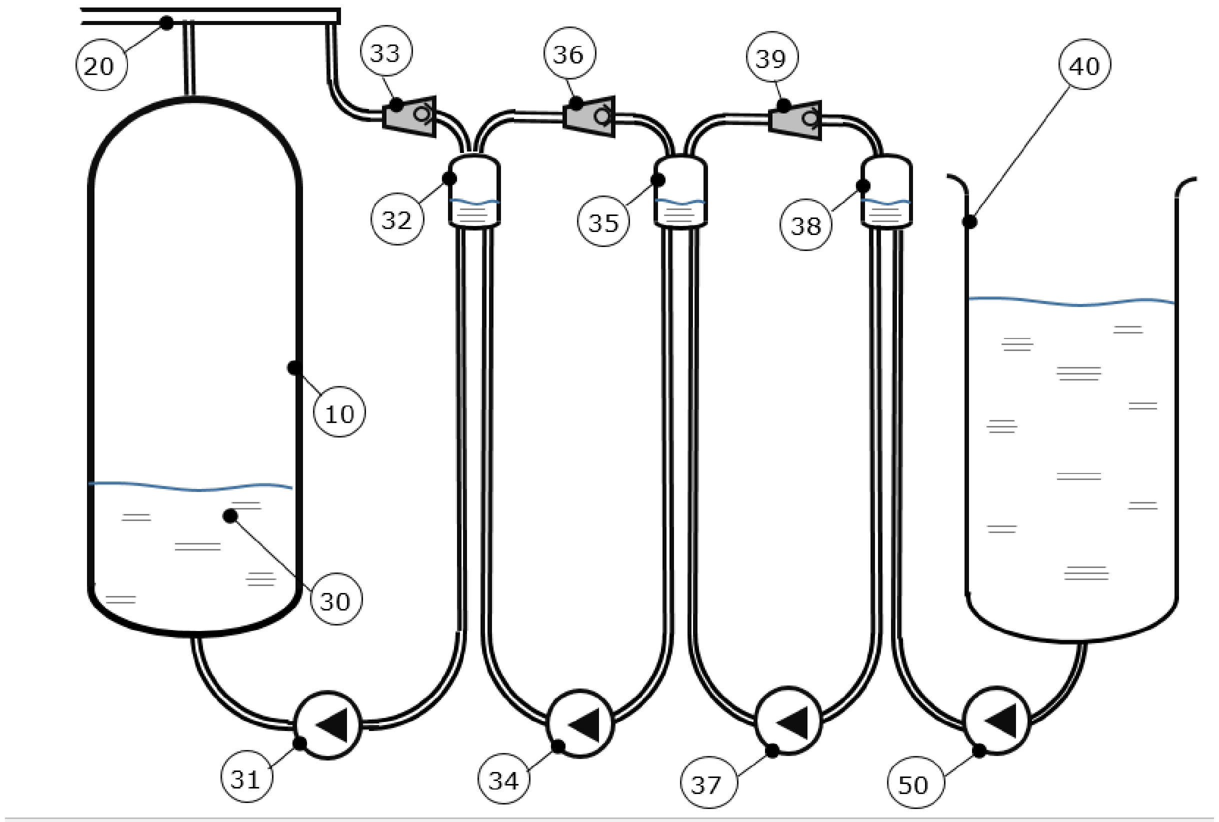
- Includes a chapter on policy of storage allowing readers to understand challenges facing implementing technologies in their research
- Each chapter is written by a world expert in the field providing the latest development in this fast moving and vital subject

CAES Next Steps

Keep on going with relevant work at Nottingham!


Thanks for listening.
Many thanks to EPSRC & Innovate-UK for support
Seamus.Garvey@Nottingham.ac.uk

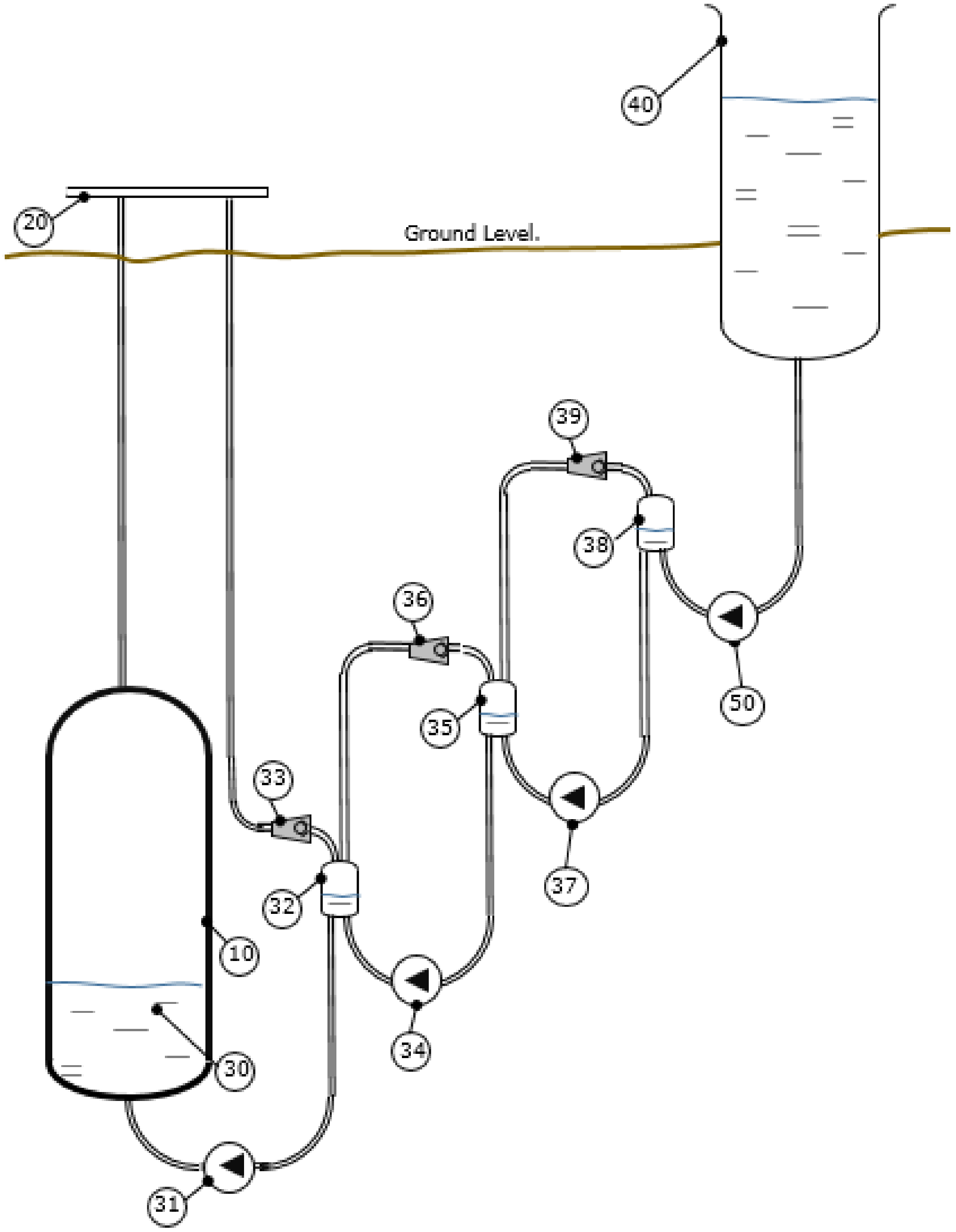
A concept to support isobaric storage.



Pressure rises / falls along a “staircase” with settling tanks at each step.

Cheesecake Energy Ltd.

A concept to support isobaric storage.



Pressure rises / falls along a "staircase" with settling tanks at each step.

Cheesecake Energy Ltd.