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IMAGES
4th Annual Progress Meeting
21st Nov 2016

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Faculty of Engineering
University of Nottingham

WindTP
GREEN ▪ AFFORDABLE ▪ DISPATCHABLE

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TRD contribution.

Study on the Cold Store for a Pumped Thermal Energy Storage System

&

New Liquid Piston Compressor Rig

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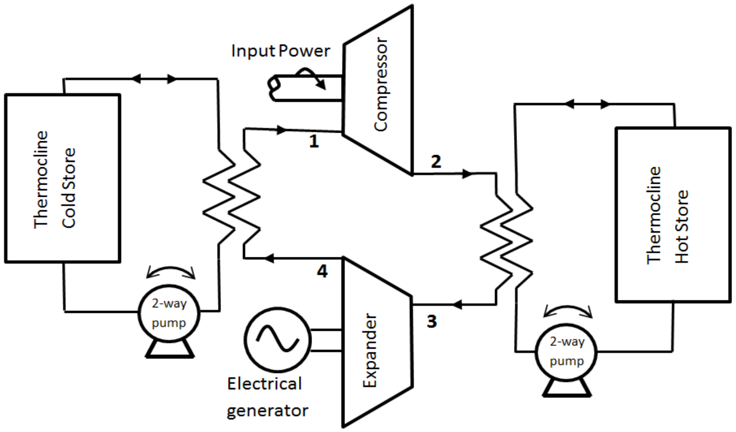
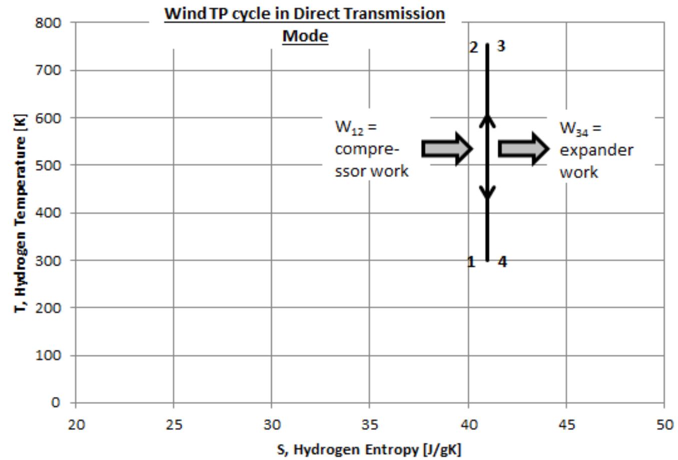
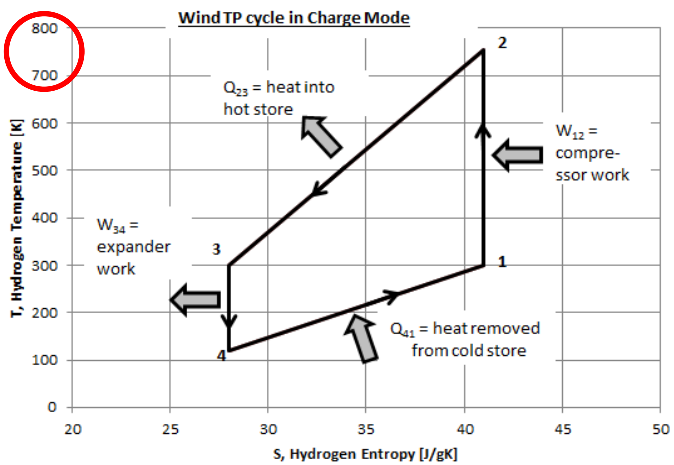
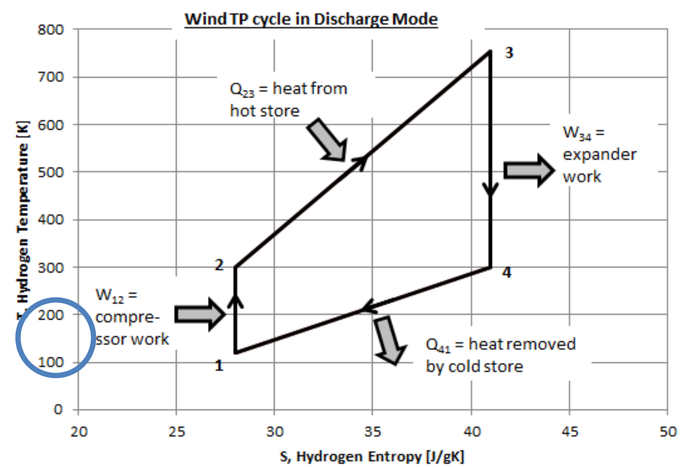
Background - Pumped Thermal Energy Storage

principal components and example T-S diagrams





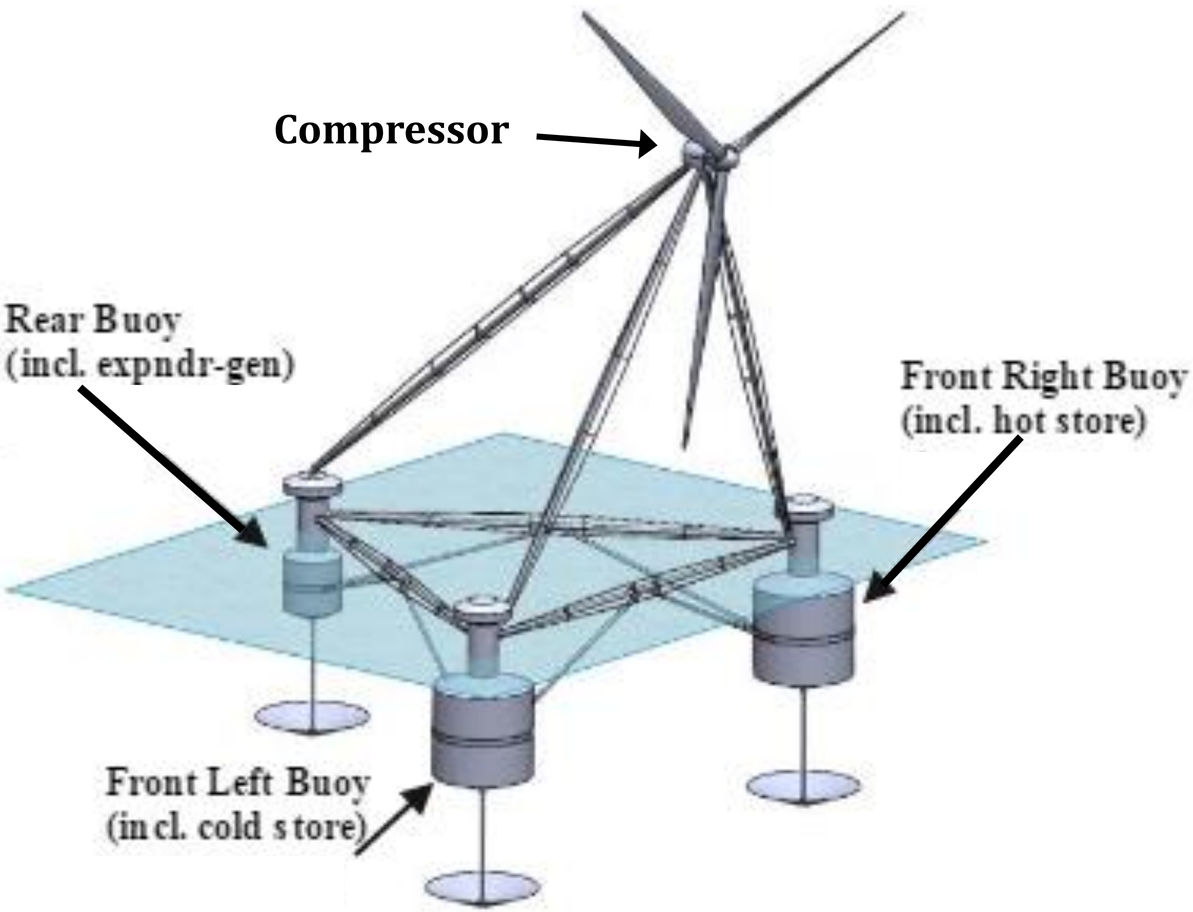




Need high isentropic efficiency compressors and expanders and **effective thermal stores**

Background - Wind Driven - Thermal Pumping (Wind-TP)

Off shore platform



Sources of exergy loss from a thermal store

1. Heat transfer from the surface of the store to outside

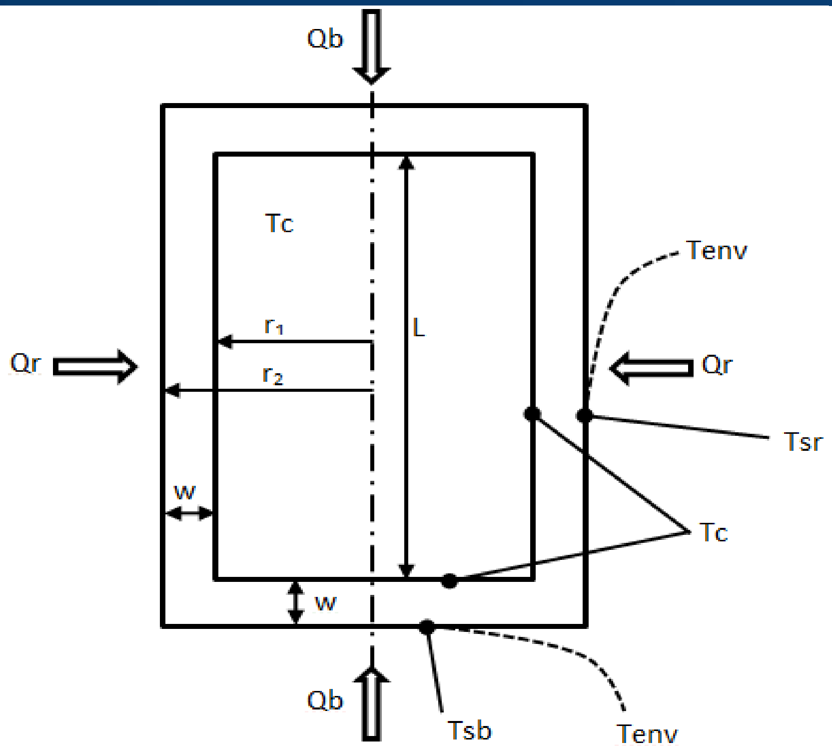
2. Heat transfer and pressure drop within thermal store during charging and discharging

3. Heat transfer when store remains idle, self discharge

Consider a 10m long 7m radius coolth store with peak heat flow of 2MW

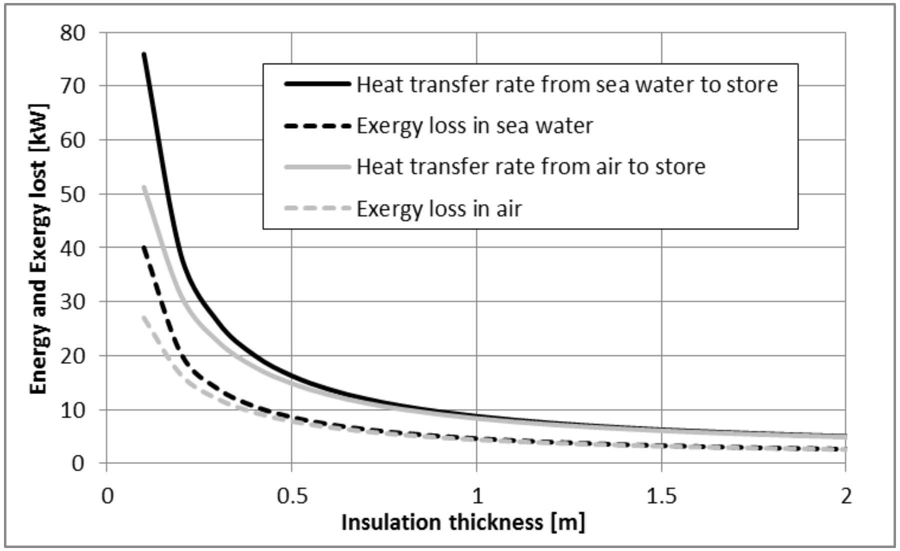
Cold store thermal mass = (2MW x 72hrs)/(180K)=2.88x10^9J/K.
(store size = 0.15GWh)

1. Exergy loss from cold store surface



Difference between heat transfer coefficient expected when anchored in sea water compared to air has little effect

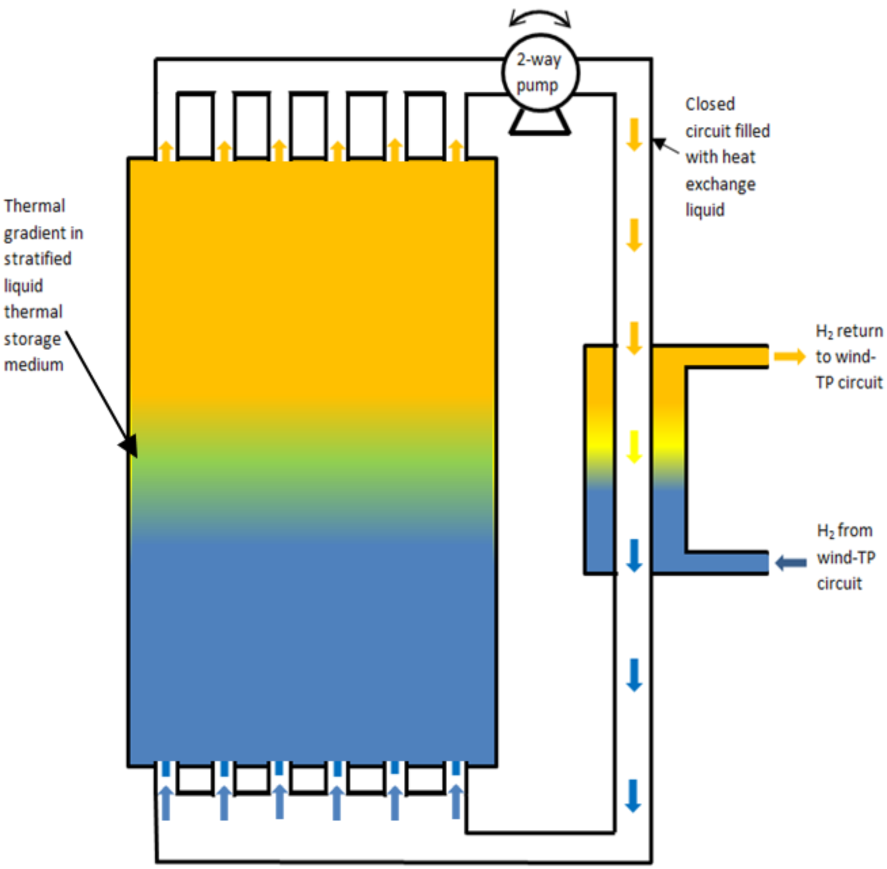
Heat loss from surface of cold store reduces to 10kW with 1m thick insulation.

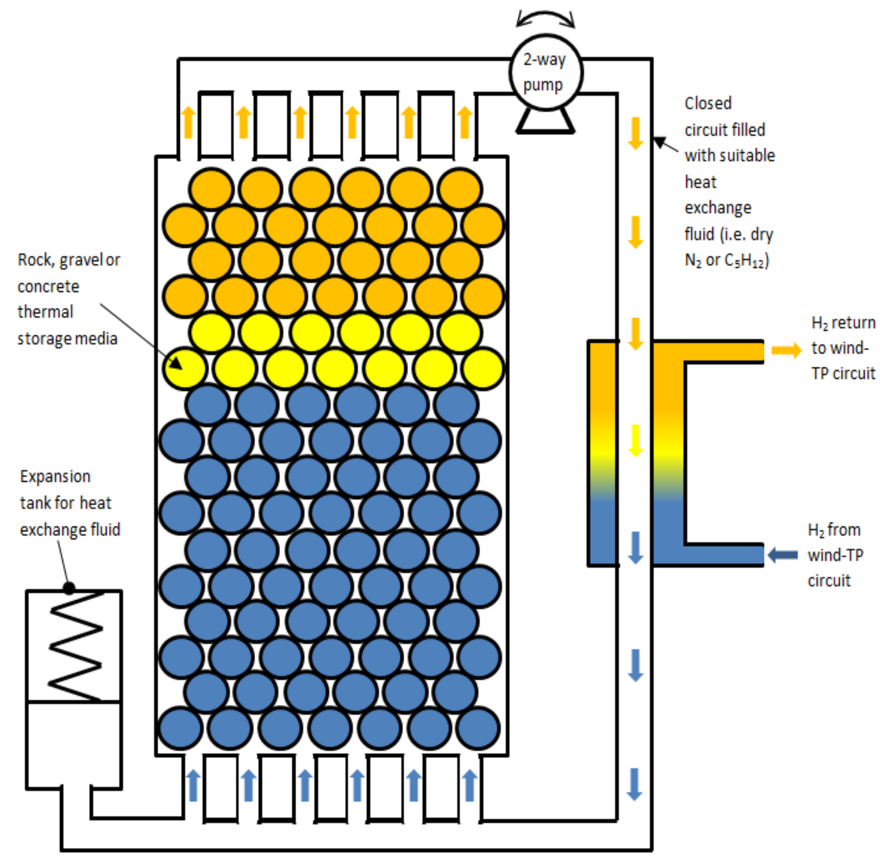


2. Exergy loss due to heat transfer during charging and discharging

Depends on design of thermal store

Consider a liquid thermocline and a packed bed thermocline





Ideal thermal store
(abrupt thermal front)

Liquid Thermocline Model

Calculate change in shape of thermal front from diffusion equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

IC $T(z, t = 0) = f(z)$

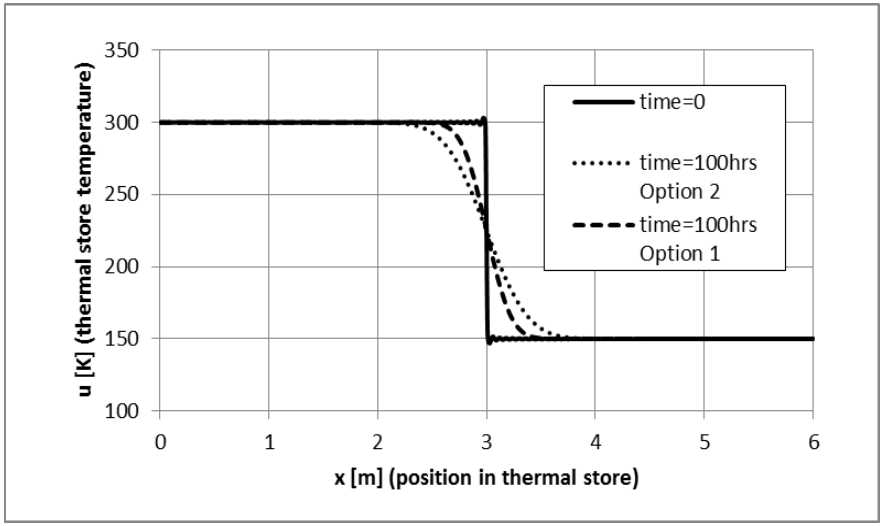
$$for\ 0 < z < {}^{L}\!/_{2} \quad f(z) = T_c$$
$$for\ {}^{L}\!/_{2} < z < L \quad f(z) = 0$$

$$T(z,t) = T_c + \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n cos\left(\frac{n\pi}{L}x\right) e^{\frac{-n^2\pi^2}{L^2}\alpha t}$$

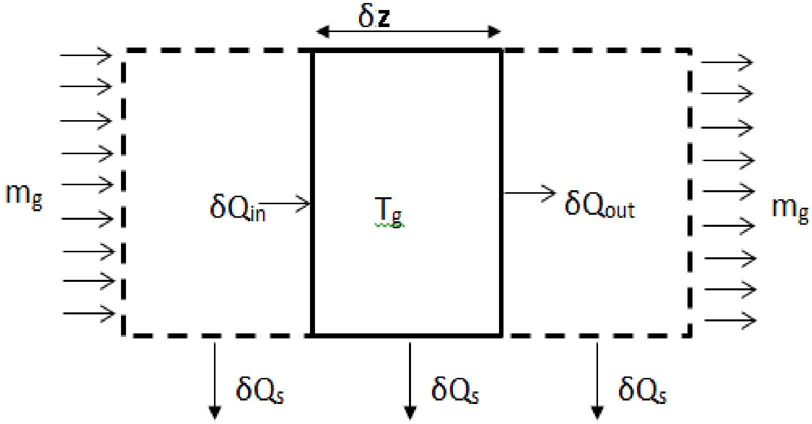
$$a_0 = \frac{T_c}{2}\ and\ a_n = \frac{2T_c}{n\pi} sin\left(\frac{n\pi}{2}\right)$$

α is the thermal diffusivity of the liquid, depending on liquid properties only, i.e. assuming no turbulence

Turbulent diffusivity ~10 times higher



Packed Bed Model



Consider energy balance for element of 1D model

$$\rho_g C_{pg} A \delta z \frac{\delta T_g}{\delta t} = \delta Q_{in} - \delta Q_{out} + \delta Q_s$$

Some assumptions and algebra leads us to the following equation (Schumann model)

$$\frac{\partial T_s}{\partial t} + \frac{l}{\tau}\frac{\partial T_s}{\partial z} = \frac{l^2}{\tau}\frac{\partial^2 T_g}{\partial z^2} \qquad l = \frac{m_g C_{pg} R}{3hA(1-\varepsilon)} \qquad \tau = \frac{\rho_s C_{ps} R}{3h}$$

where $\frac{l}{\tau}$ is the nominal speed of the thermal front and $\frac{l^2}{\tau}$ is an effective diffusivity term. The effective diffusivity of the packed bed can then be written as a function of all the packed bed parameters as follows.

$$D_{eff} = \frac{{m_g}^2 {Cp_g}^2 R}{3hA^2(1-\varepsilon)^2 \rho_s Cp_s} \quad \left[{}^{m^2}/{}_{s}\right]$$

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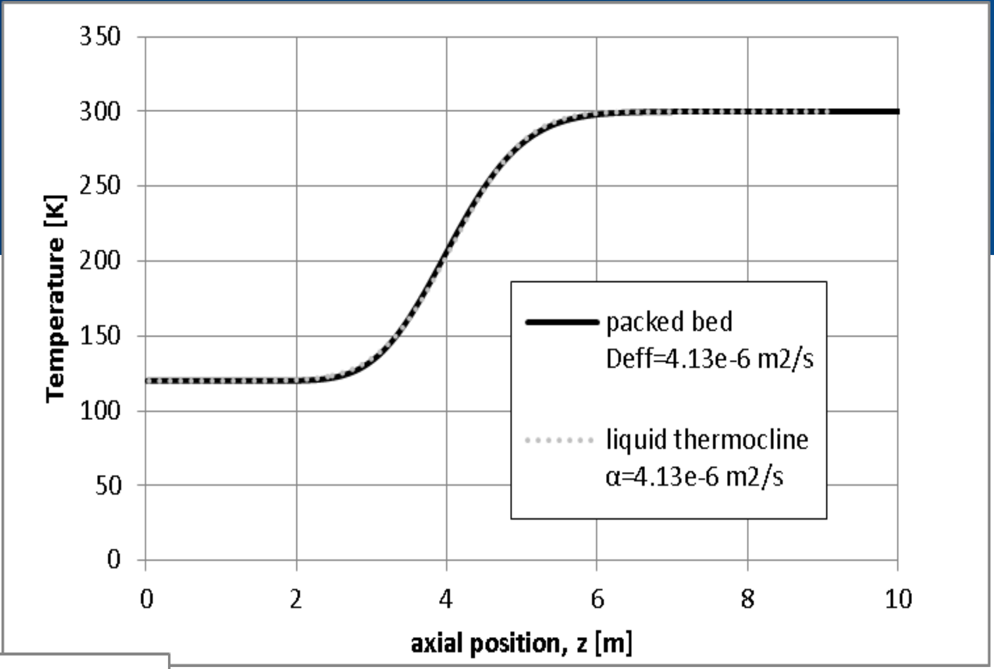
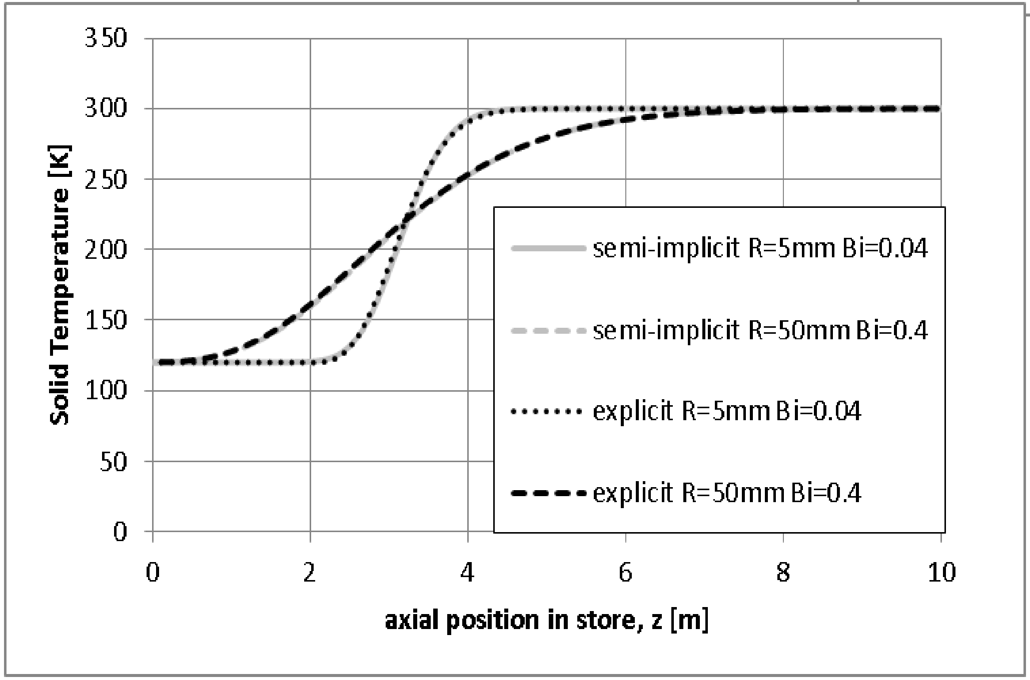
Packed bed behaviour analogous to liquid thermocline

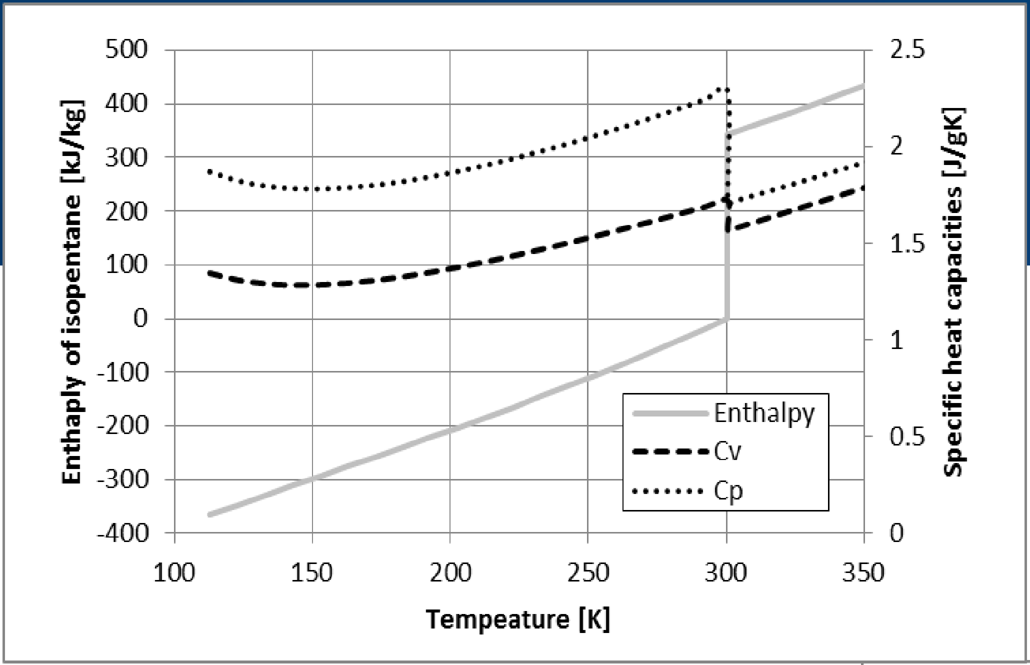




Achieved perfect agreement with two packed bed numerical models –

simple explicit method

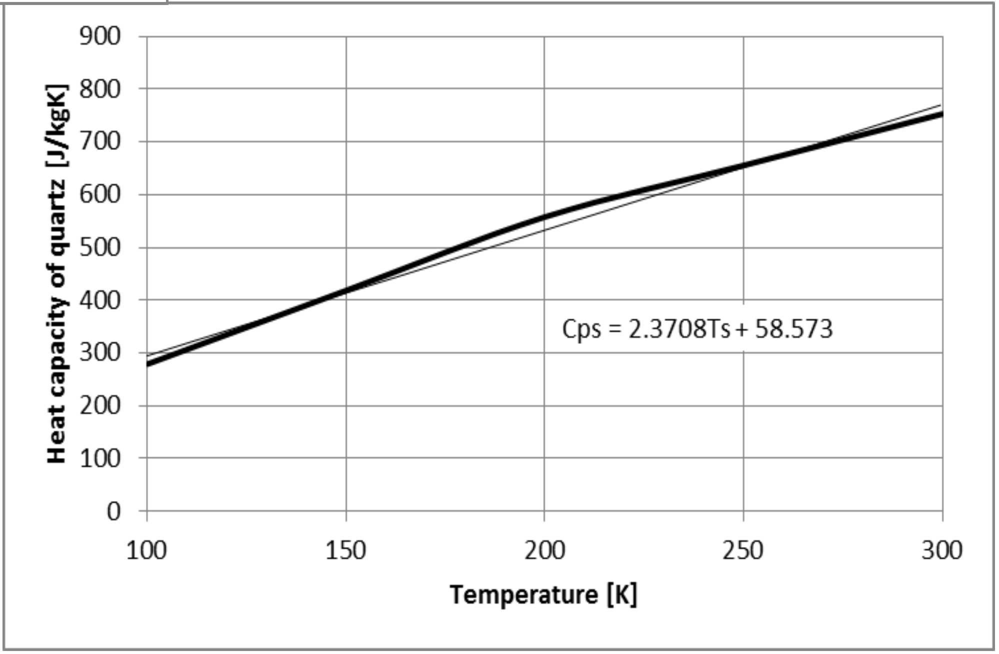
semi-implicit approach as used by White et al.



Heat capacity of isopentane C_5H_{12} remains high at low temperature

Heat capacity of gravel expected to fall significantly at low temperature

This means will need larger volume to store the same amount of exergy



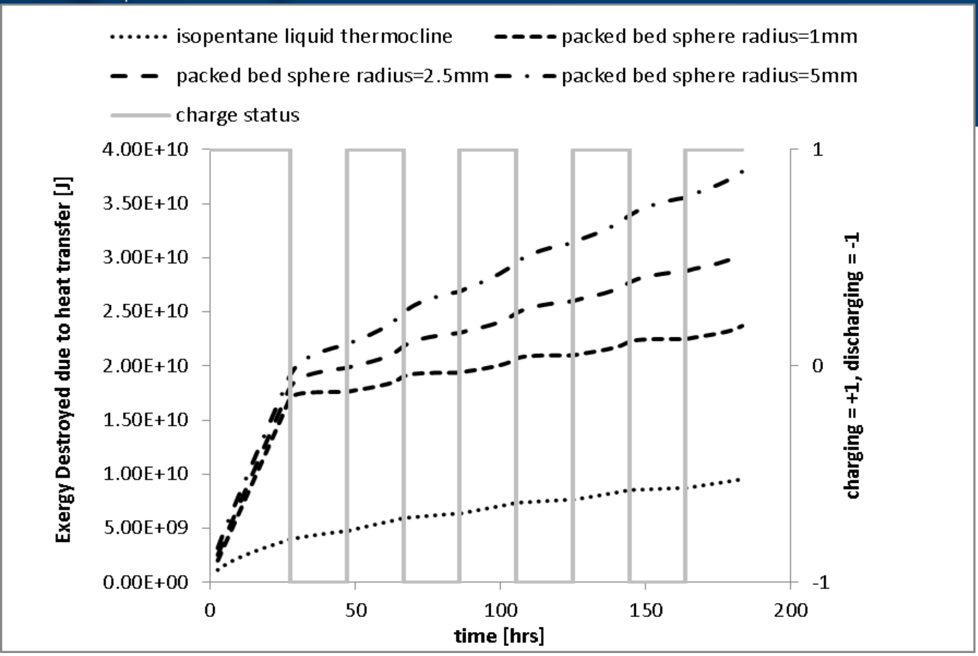
Thermocline smearing
liquid isopentane vs packed bed of concrete

Liquid thermocline (isopentane) store following example charge discharge cycle

Packed bed temperature following example charge discharge cycle

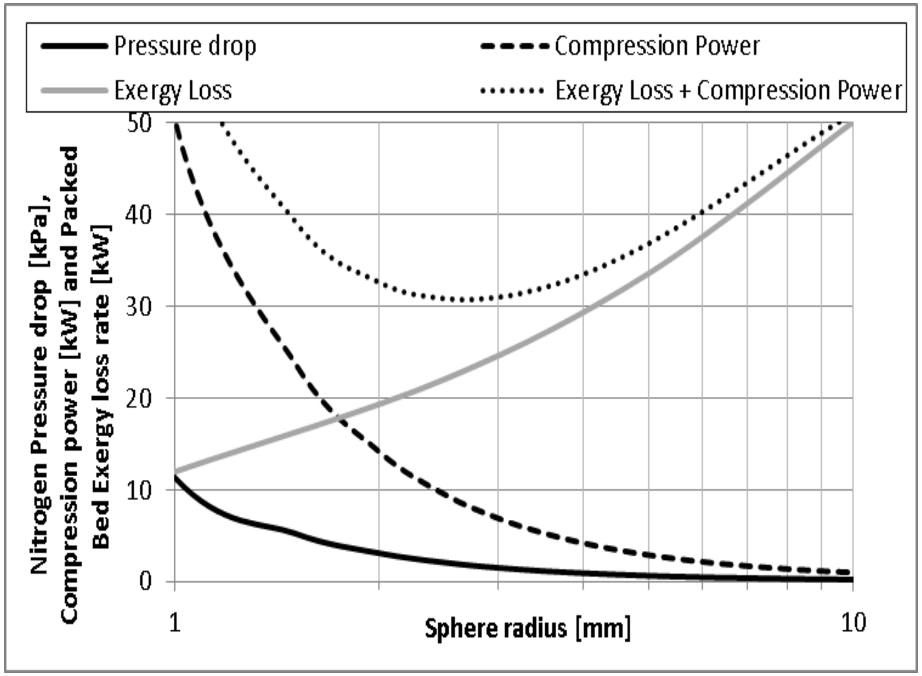
$1.5\times10^{-7} m^2/s$ for the isopentane vs. $2\times10^{-6} m^2/s$ for the packed bed filled with 5mm radius spheres

Exergy loss due to charging and discharging



packed bed exergy loss rate higher than the liquid thermocline

22kW for 2.5mm spheres compared to 9kW for liquid



Possible to find optimum packed bed sphere size

Optimum size 2.5mm packed bed requires 8kW of power to drive the nitrogen compressor

liquid thermocline would need less than 1kW to move the required mass flow of liquid

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3. Exergy loss due to self discharge

For laminar stratified liquid thermocline depends on thermal diffusivity α

For packed bed depends on effective thermal diffusivity

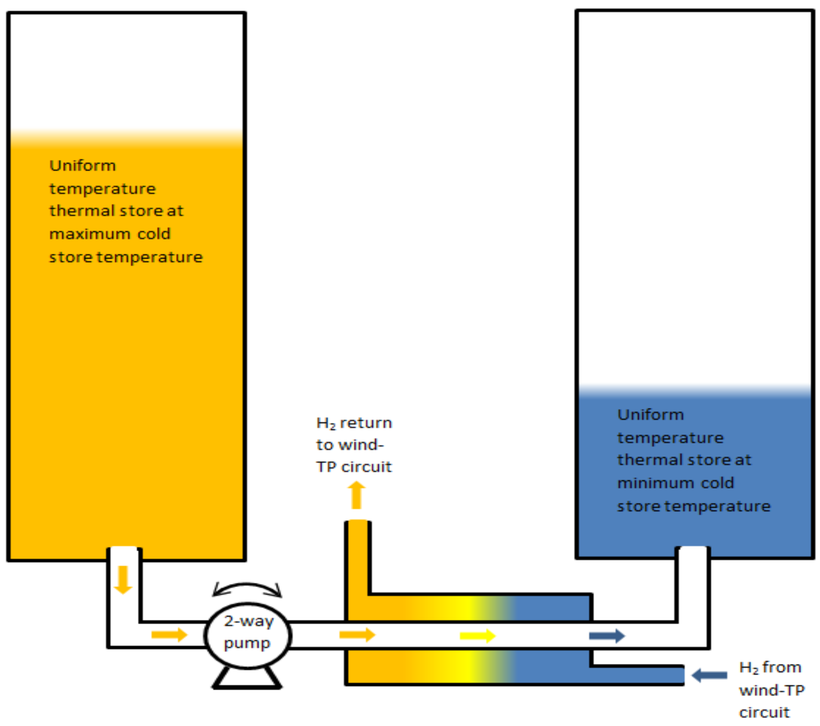
$$\alpha_{eff} = \frac{k_{eff}}{\rho C_p}$$

k_{eff} is typically a tenth of solid thermal conductivity (Dietz 1979) which leads to

$$\alpha \approx \alpha_{eff}$$

Self discharge exergy loss for packed bed similar to exergy loss rate for liquid thermocline (10kW for this geometry)

Two tank system



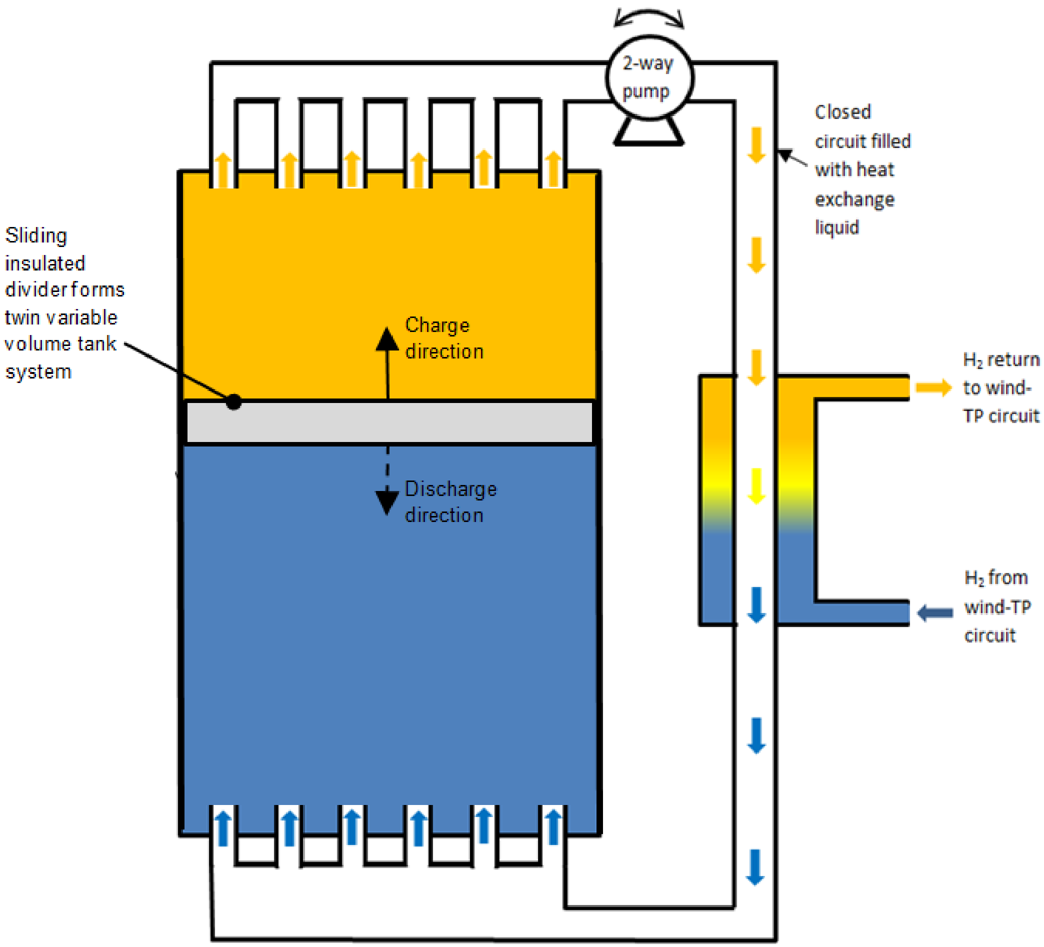
- No thermal spreading of thermocline and associated exergy loss
- Some exergy loss due to mixing with gas in tanks
- Need double the volume of storage tanks

Variable Volume Storage Tank

Avoids mixing between hot and cold storage media using a sliding divider

No exergy loss due to thermocline smearing as with two tank system

Half the volume required of a traditional two tank system



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Conclusions

- Exergy loss from heat transfer from the surface of example store is expected to be less than 10kW with 0.5m of typical insulation

- Simulations showed that a gas cooled packed bed thermocline incurred more exergy loss as a result of heat transfer during charging and discharging than an equivalently sized laminar stratified liquid thermocline.

- Self discharge loss similar for liquid and packed bed thermoclines.

- A cold store based on a split variable volume storage tank filled with isopentane appears to offer a compact solution with minimum exergy loss, exergy loss rate of the order 10 kW should be possible for a 0.15GWh store. An equivalent sized packed bed will incur an additional 20kW of loss which is still manageable considering size of thermal store.

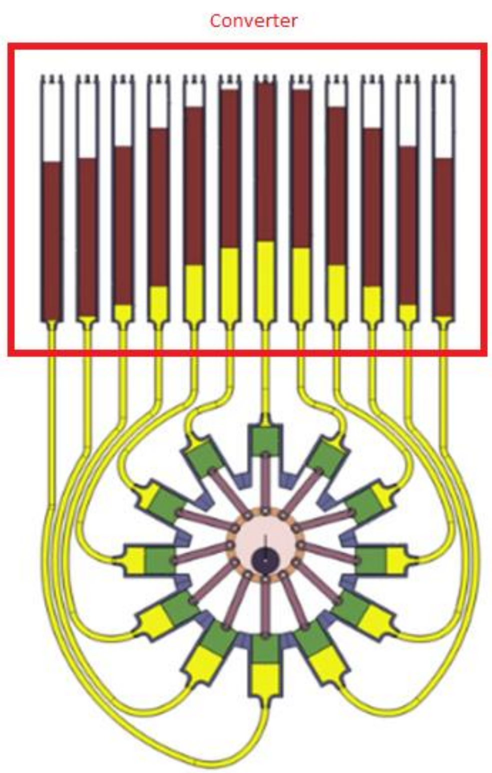
How do you compress gas adiabatically to 850K?

Conventional compressor mechanisms depend on oil, most lubricants limited to between 400 and 500K

Use a dry pump with no oil in mechanism, scroll, screw and roots claw are all versions off this. Oil in gearbox kept away from mechanism via thermal break. Clearances would have to be designed for high temp operation

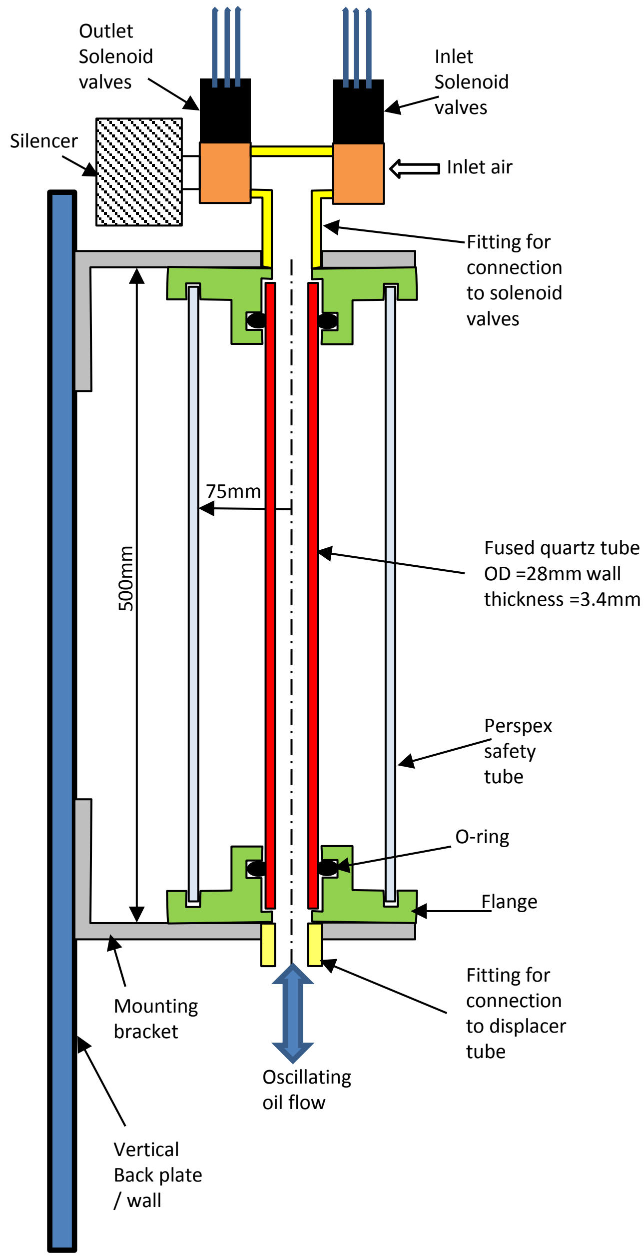
Liquid piston compressor design using oil displacer and convertor (patent filed by Professor Garvey 2014)

In convertor tube a spacer separates oil from the gas being compressed. Heat transfer between oil and gas to be studied in new rig.



Convertor Tube Experimental Rig almost ready for assembly

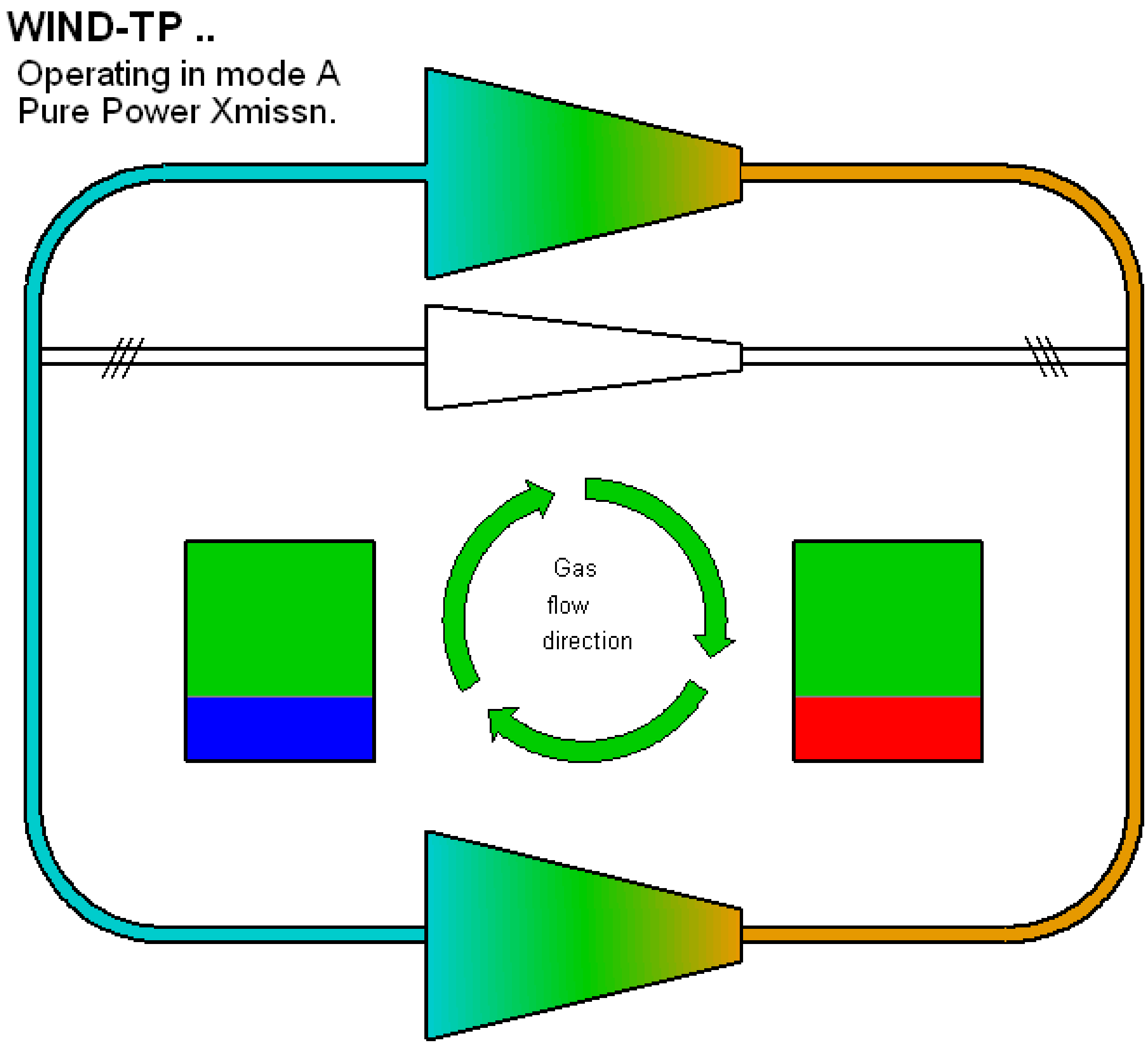
Design Parameters	Approximate values
Swept volume	100cc
Stroke	28cm
Dead volume	46cc
Pressure ratio	10:1
Max air temp	200°C
Inlet temp	Ambient
Max pressure	10 bar
Compression energy per cycle	30J



Part	Quantity	Supplier/Comment
Quartz tube OD=28mm wall 3.4mm length 500mm	2 (incase one breaks)	Robson Scientific £66 per tube+carriage & VAT
Solenoid valve rated for 10bar and 200°C	2	http://www.solenoid-valve.world/by-industry/food-industry/miniature-steam-solenoid-valve-SA610 £35
Fitting for connection to displacer feed tube	1	
Fitting for connection to solenoid valves	1	
Stainless steel pneumatic Silencer with 1/4inch fitting	1	RS £10
Mounting brackets	2	Specials to be made in workshop
Flanges	2	Specials to be made in workshop
Back Plate	1	Special to be made in workshop
Perspex tube 150mm diameter 0.5m length	1	

SDG contribution.

Advancing WindTP



Advancing WindTP

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U/G Student, Scott Wimhurst has done excellent further work on adiabatic compressor design & build.

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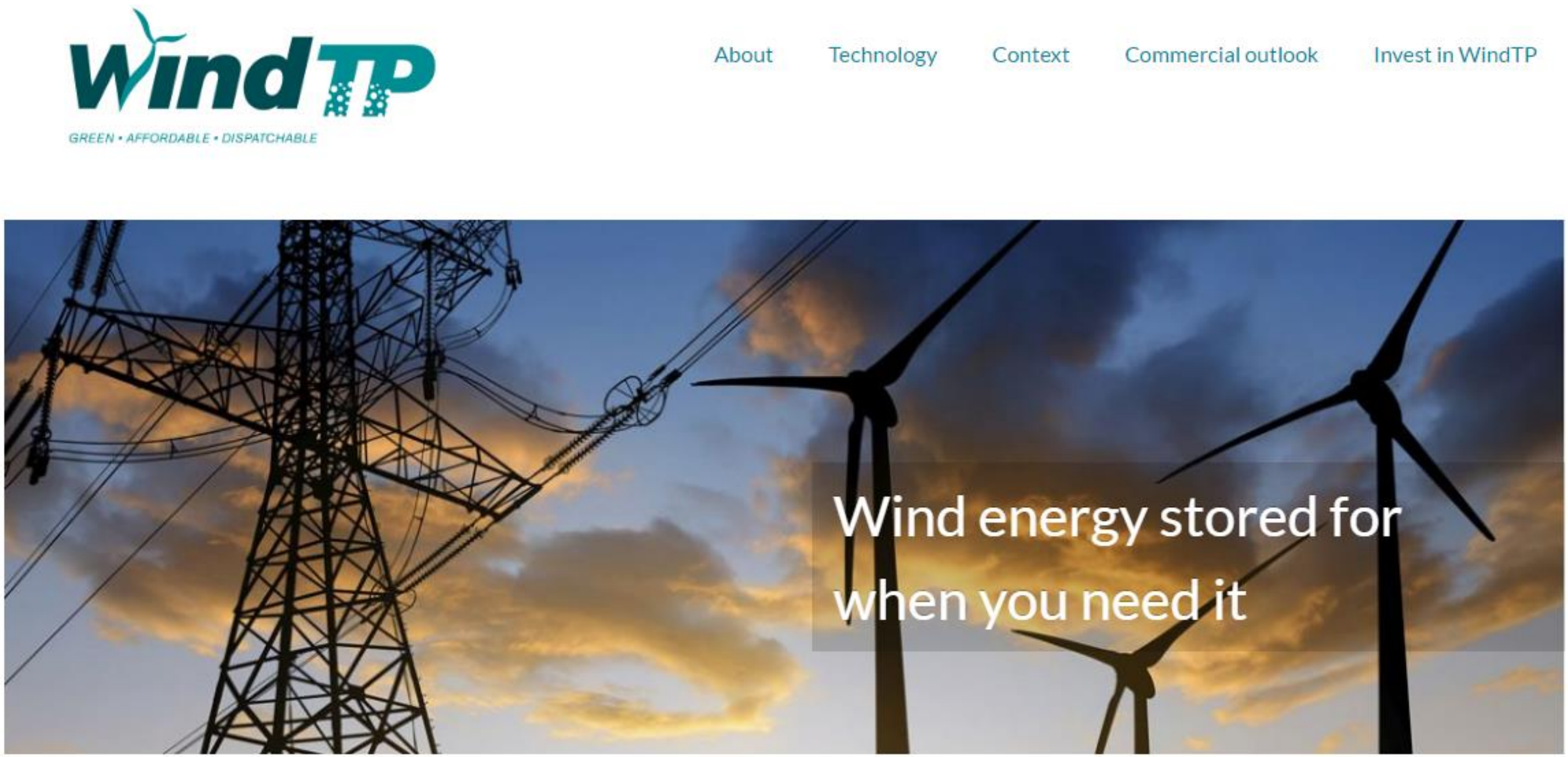
Advancing WindTP

www.Wind-TP.com (website created under a small EPSRC IAA award)



A new concept in Hybrid ES

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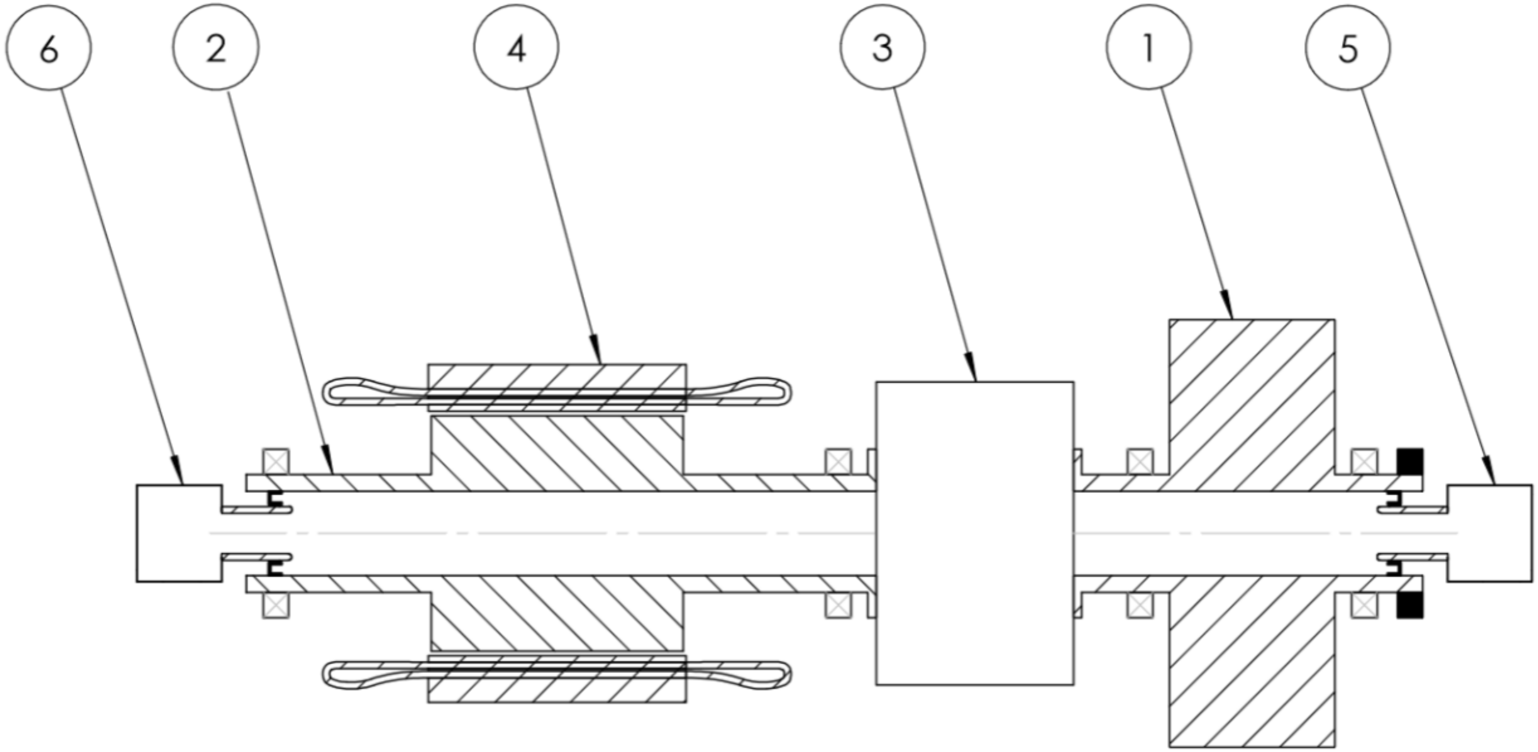
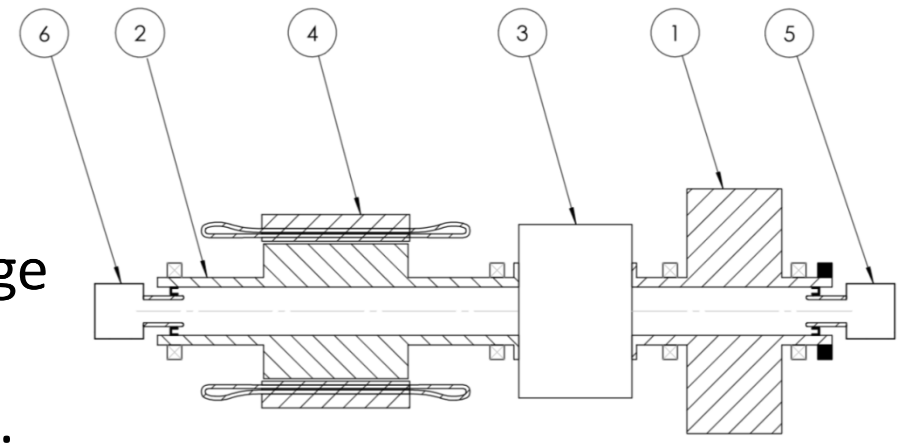
A new patent applied for jointly with *PowerContinuity*

Hybrid Energy Storage System Combines Flywheel Energy Storage with Fluid Power



A new concept in Hybrid ES

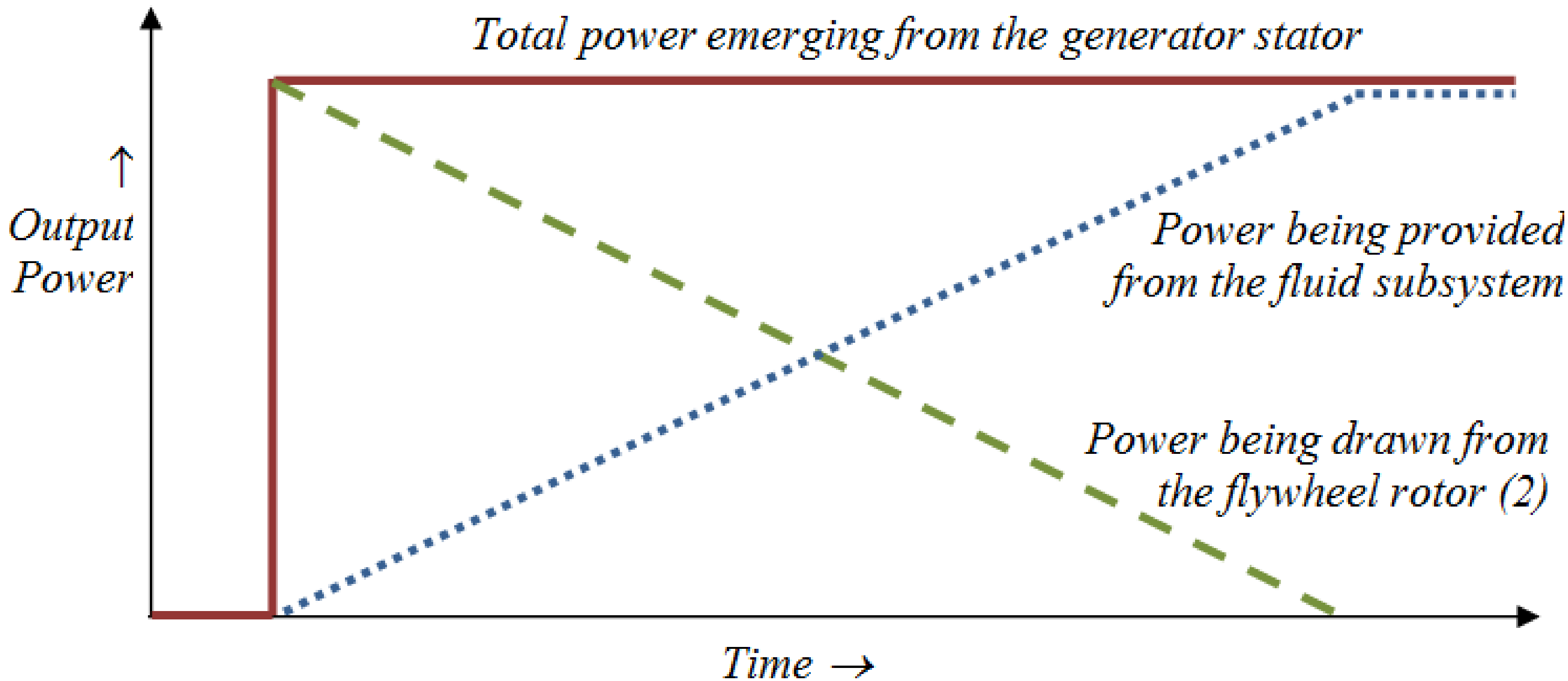
Core concepts:



- Real Inertia … requires that a large mass spins at *synchonous speed* (1500 rpm for a 4-pole machine).
- To use material well, we require high peripheral speeds (~3.2m radius for 1500 rpm with a 1500rpm rotor from EN24T)
- Fluid power (in the form of pressure x volume flow rate of a liquid) operates a *differential drive unit* (3) to move the *magnet rotor* (2) forward relative to the *flywheel rotor* (1)
- The fluid power is compatible with pumped thermal storage or compressed air energy storage.

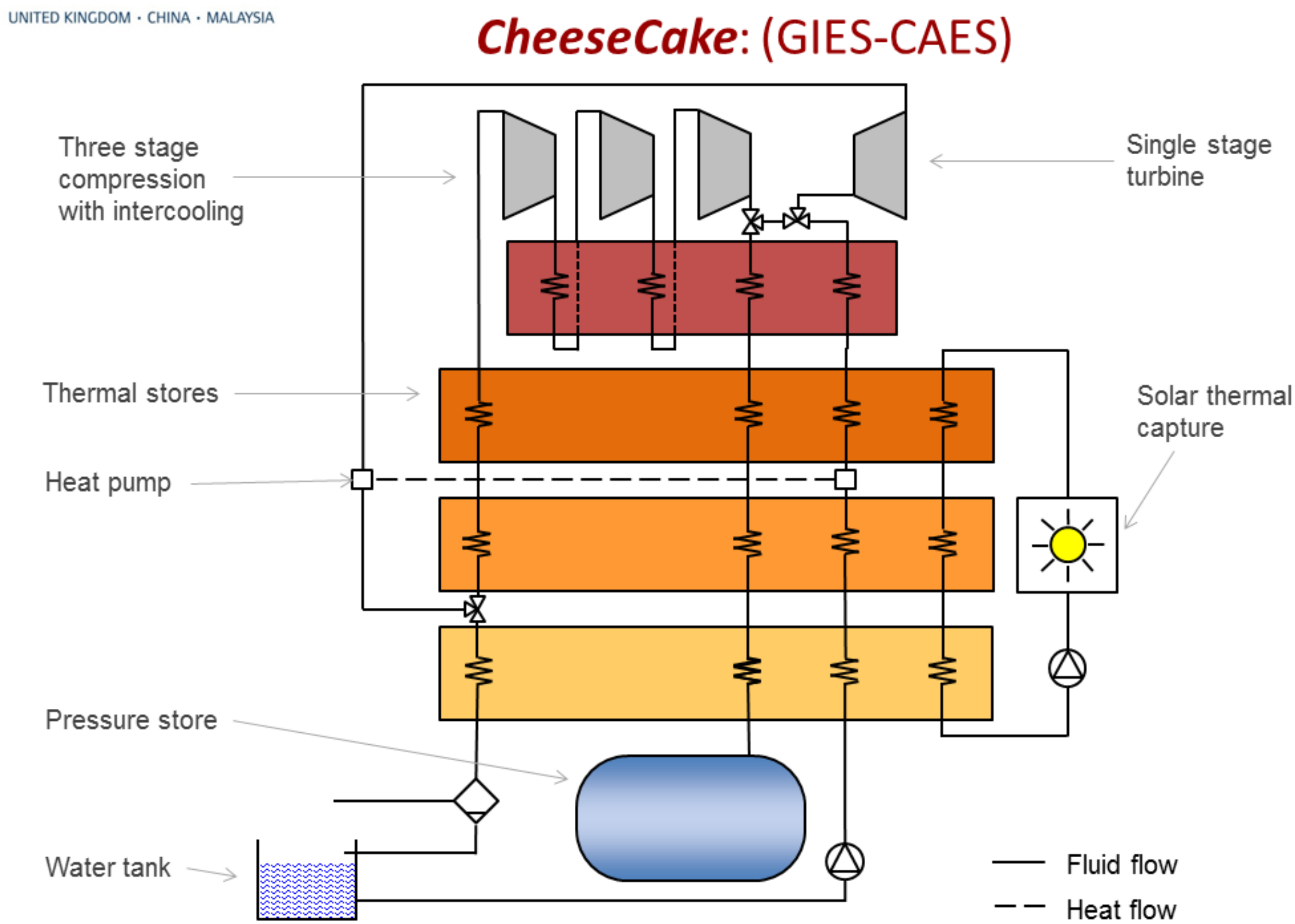
A new concept in Hybrid ES

Hybrid Energy Storage System Combines Flywheel Energy Storage with Fluid Power: Power flows following instruction to "release power into the AC system



2015 concept now a Spinout

CheeseCake Energy Ltd.



CheeseCake.

Play *GIES-CAES-Illust* in VLC

Future of CAES Event

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Future of CAES Event

9:00 – 9:20	*Registration*
9:20 – 9:30	**Win Rampen**, University of Edinburgh "Chairman's welcome and opening remarks"
9:30 – 10:00	**Mark Byrne**, Gaelectric "Compressed Air Energy Storage (CAES) A key tool in managing a high renewables electricity system"
10:00 – 10:30	**Haisheng Chen**, Chinese Academy of Sciences "A 10 MWe, 40 MWh advanced CAES plant"
10:30 – 11:00	**Jasmin Lückert**, Dresden University of Technology "Advancement of Operational Performance of the Huntorf CAES"
11:00 – 11:30	**Gareth Lloyd-Jones**, BC&T Consultants "Offshore hard rock energy storage"
11:30 – 11:50	*Coffee & Tea Break*
11:50 – 12:20	**Andrea Burrato**, GE Oil & Gas "Large scale energy storage solutions at GE Oil & Gas"
12:20 – 12:50	**Shahab Natanzi**, Dresser-Rand "Future CAES – The Dresser-Rand Approach"
12:50 – 13:20	**Anthony Kitchener**, SVW Compression Pty "Bridging the pressure gap"
13:20 – 14:10	*Lunch*
14:10 – 14:40	**Paul Lowbridge**, National Grid "Future drivers for grid scale energy storage in the UK"
14:40 – 15:10	**Franc Mouwen** , Park-ID "The role of tunnel boring in CAES"
15:10 – 15:40	**David Evans**, British Geological Survey "Potential UK resource for underground CAES"
15:40 – 16:00	*Coffee & Tea Break*
16:00 – 17:00	**Discussion Panel**: A thought-provoking panel featuring delegates from distinguished stakeholders aimed at answering the question: CAES: where do we go from here?
17:00 – 17:10	Closing Words
17:10 – 18:00	**Networking Session**

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Debate in Parliament

WHY THE KEY TO SOLVING A FUTURE UK ENERGY CRISIS CAN BE FOUND IN OUR PAST – INTEGRATING ENERGY STORAGE WITH GENERATION

1100-1200 Committee Room 18

Antoinette Sandbach, MP. (Chairperson)
Baroness Brown of Cambridge (vice-chair of Climate Change Committee)
Phil Sheppard of National Grid (Director of System Operations)
Seamus Garvey of Nottingham University
Andrew Boston of ERP (Head of Analysis)
Gordon Waddington (CEO of E.R.A.)

Debate in Parliament

* There is an urgent need to remove constraints in energy policy, market structure and development planning where these exist – especially where there is evidence that such constraints may be against the interests of the UK energy consumer and taxpayer.

* There is also a dire need for the commissioning of energy storage demonstrators for learning. The point was made that we should explore 20 different technologies seriously with a view to seeing one or two of them serving us extremely well in providing future affordable flexibility services.

* If we expect private investment to provide the services needed to balance the electricity system, then the market must ensure that those parties who provide the service can reap sufficient reward to make it worthwhile. <u>This requires both clarity and certainty</u>. For at least some classes of energy storage technology still in development, it is not sufficient to plan to adjust the market in the future such that these will become commercially viable at scale. <u>It is necessary also to guarantee in advance that such a market will exist</u> in order that the necessary technology developments can be justified.

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Debate in Parliament

* We need today’s government to exercise more of a controlling mind than previous governments have been inclined to do – not picking winners but identifying areas in which services will have value both in the UK and abroad.

* There is a strong case for reviewing whether simpler approaches to the procurement of grid services can work – for example, real time localised energy pricing and a simple commission-based charge for grid usage. Such approaches would allow free market engagement with the provision of services and might indeed bring forward the “UBER of grid management”.

* We must take maximum advantage possible of improved weather and demand prediction and combine these with smart-grid technologies so that load can be shifted forwards in time as well as backwards and it can be re-distributed spatially. At the same time, it must be recognised that the balancing problem involves moving large amounts of energy in time and space and intelligence alone cannot solve every problem.

* The energy system is undergoing a revolution and it must learn from other sectors which have experienced revolutions. Lean manufacturing may have lessons of use.

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Debate in Parliament

* The UK has a strong international lead in non-battery energy storage.

* It is not sufficient for the UK to look inwards whilst decarbonising its own electricity grid. The UK can and must play a strong role in enabling other countries to also adopt carbon-neutral (or carbon-negative) electricity generation technology.

* When funding directions for future research and development are being determined, we should now be prioritising solutions that will still play a role in 2035 and beyond in electricity grids where generation comes almost exclusively from renewables and some nuclear power (and hydrocarbon combustion if coupled with CCS). Cost assessments should include all relevant elements – especially the balancing costs.

* The age of “LCoE” is gone.

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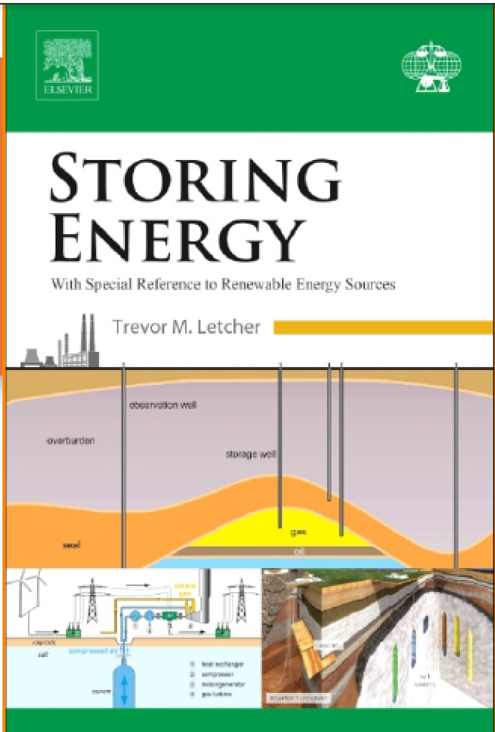
A new book in 2016 …

S. Garvey is co-author of 3 chapters in this new book.



Storing Energy

with Special Reference to Renewable Energy Sources

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

ELSEVIER

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

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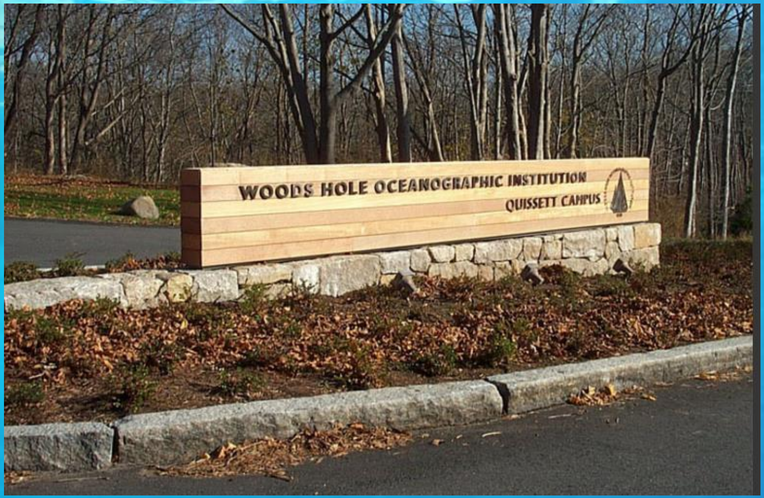
A conference next year …

OSES2014: Windsor, Canada, OSES2015: Edinburgh, UK
OSES2016: Malta, OSES2017: WHOI, Boston



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THE UNIVERSITY of EDINBURGH

UNIVERSITY OF MALTA
L-Università ta' Malta

University of Windsor

UNIVERSITY OF LEEDS

Other Presentations

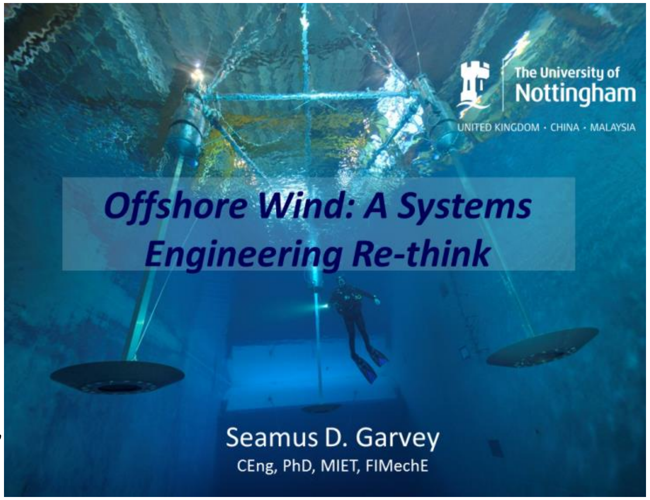
Other major presentations at:

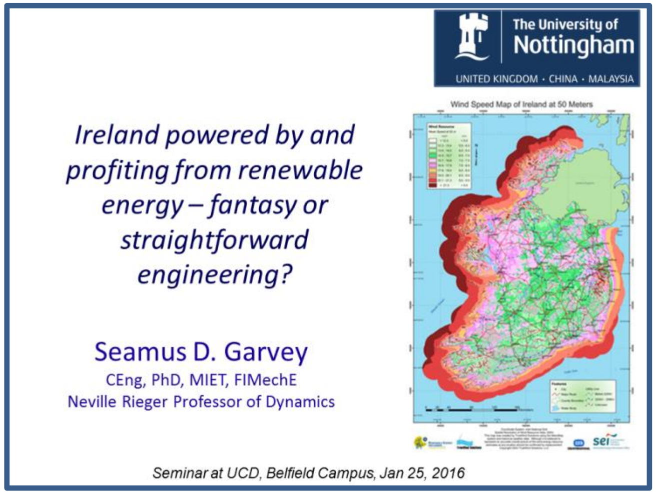
Offshore Engineering Society, Jan 6, 2016.

Offshore wind: a systems engineering rethink

University College Dublin, Jan 25, 2016.

Ireland powered by and profiting from renewable energy:
- fantasy or straightforward engineering





FactSheets drafted for EERA JP on ES. (CAES and GIES).

Thanks for listening.

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