The case for Medium-Duration Energy Storage
- and some varieties thereof.

SEAMUS D. GARVEY

A seminar at University of Oxford, Jan. 15, 2025

SOME STRIKING FINDINGS FROM THE R-S REPORT

c.f. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/large-scale-electricity-storage/

The *baseline case* in the Royal Society Report has …

100% Generation from R.E. … with ~30% over-genn.

Wind:Solar … approximately 80:20 mix by energy.

Storage mainly via H_2 in caverns … >50 days consmptn.

Storage input power … ~5% above mean generation.

Storage output power … ~peak power consumption

Storage	R.E. £35/MWh	R.E. £40/MWh	R.E. £45/MWh
Hydrogen in Caverns	£57.83 /MWh	£64.48 /MWh	£71.10 /MWh

(Using costs and performance levels thought most likely. $\eta_{RT} = 40.7\%$, £0.71/kWh (e))

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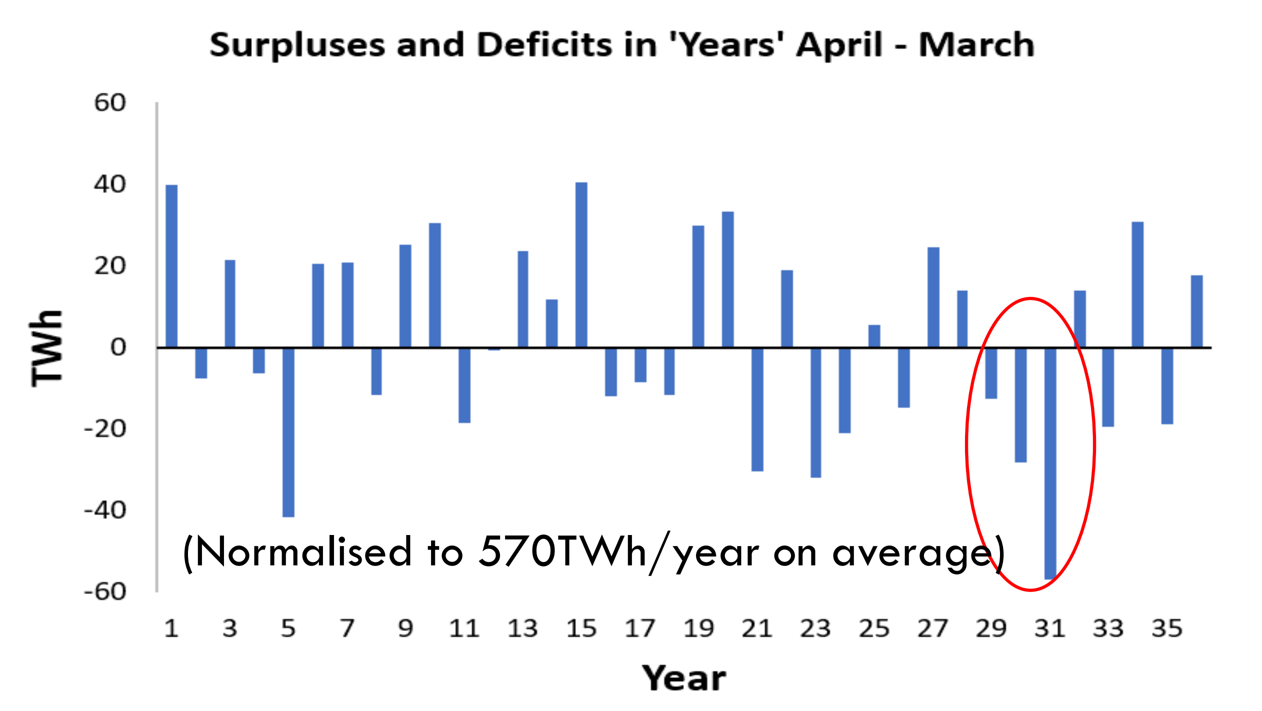
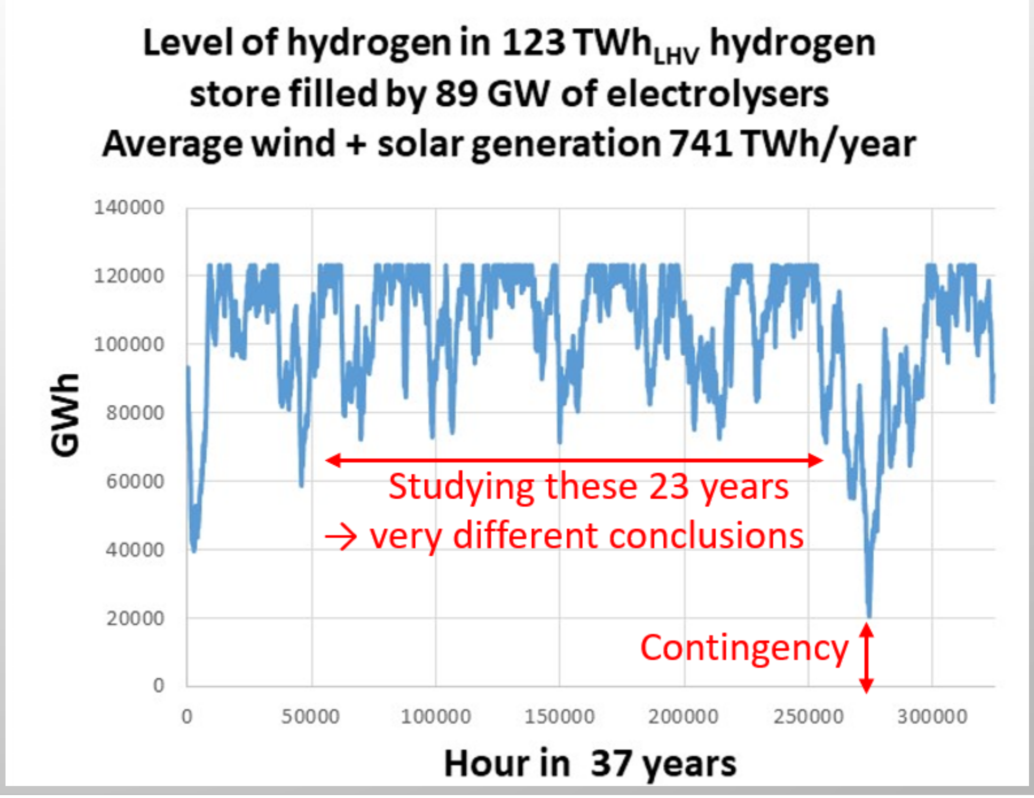
SOME STRIKING FINDINGS FROM THE R-S REPORT



A major finding has been that we need to look at variability of renewables (especially wind) over very long timescales.



The Met Office has indicated that even 37 years may not be sufficient … >60 years.

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SO WHAT?

* UK should already be preparing large salt cavern storage capacity
* Several GW of electrolysers and hydrogen-fired engines needed
* These are essential and “no-regret” actions.

It is tempting to think that we have found “the answer”. It is <u>AN answer</u>.

<u>Enter “MDES”: *Medium Duration Energy Storage.*</u>

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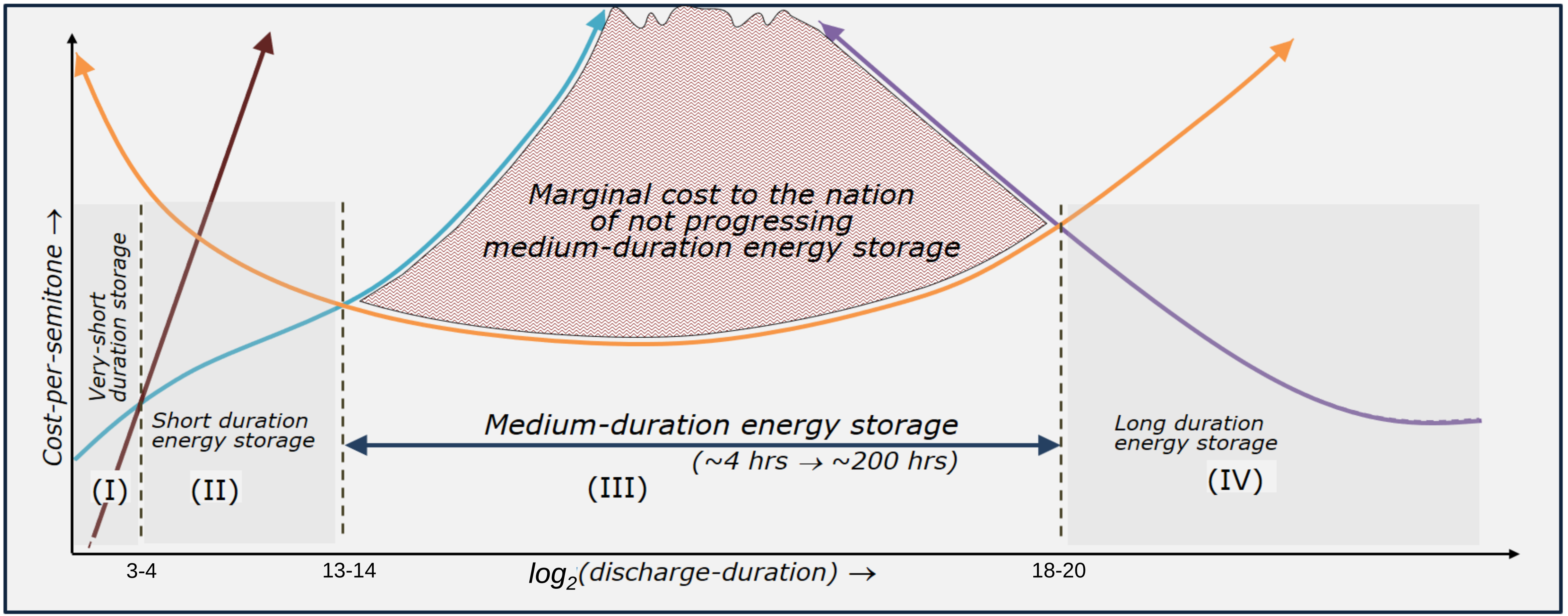
FOUR MAIN STORAGE DURATIONS



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THREE SECTIONS IN THE REST OF THIS TALK.

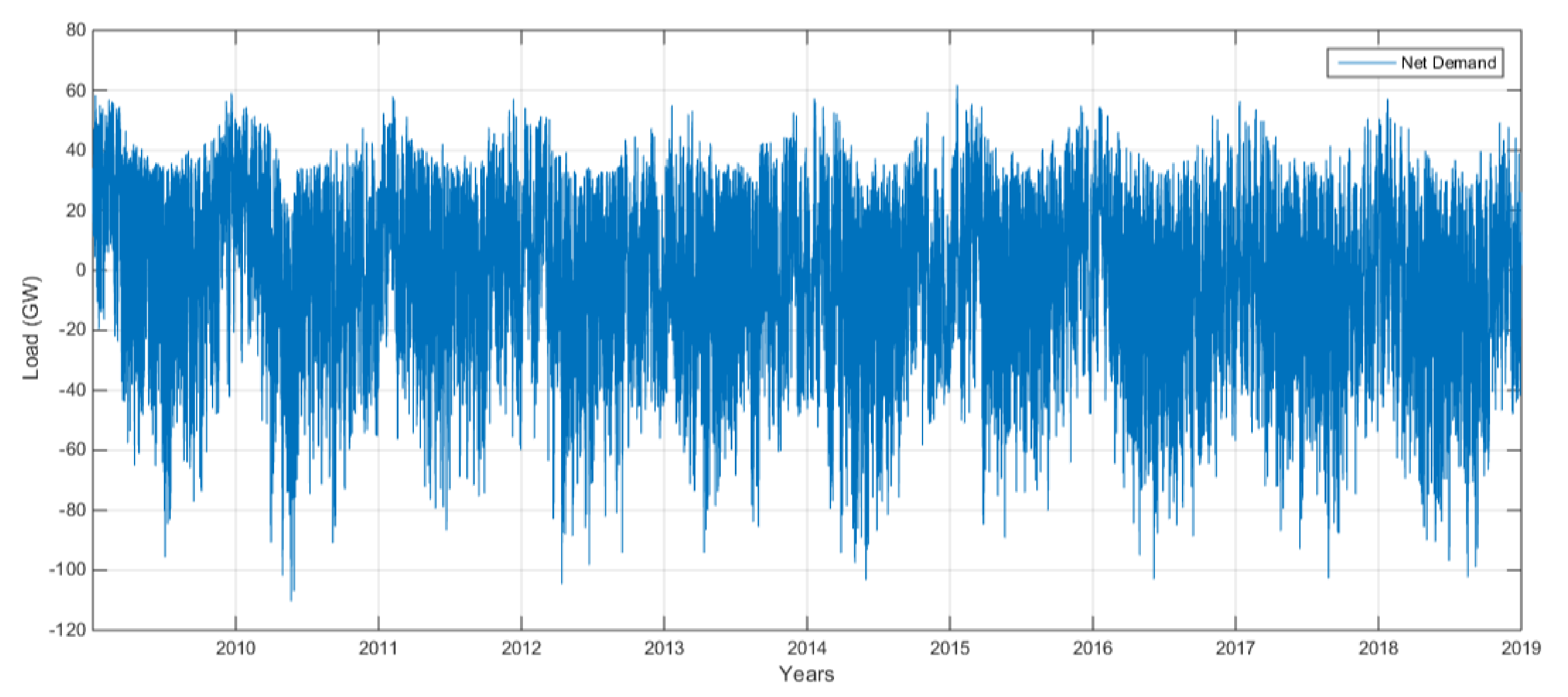
(1) The durations of continuous discharge for storage in the future

(2) Optimising a system with multiple stores for lowest cost

(3) A glimpse into *Wind Integrated Storage*.

Section #1

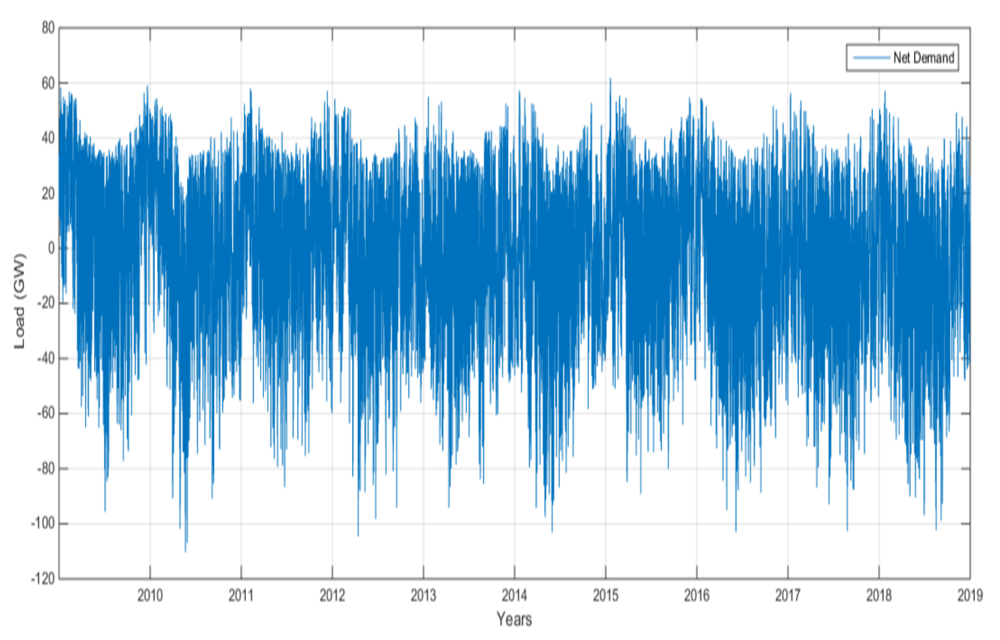
STORAGE: DURATIONS OF CONTINUOUS DISCHARGE

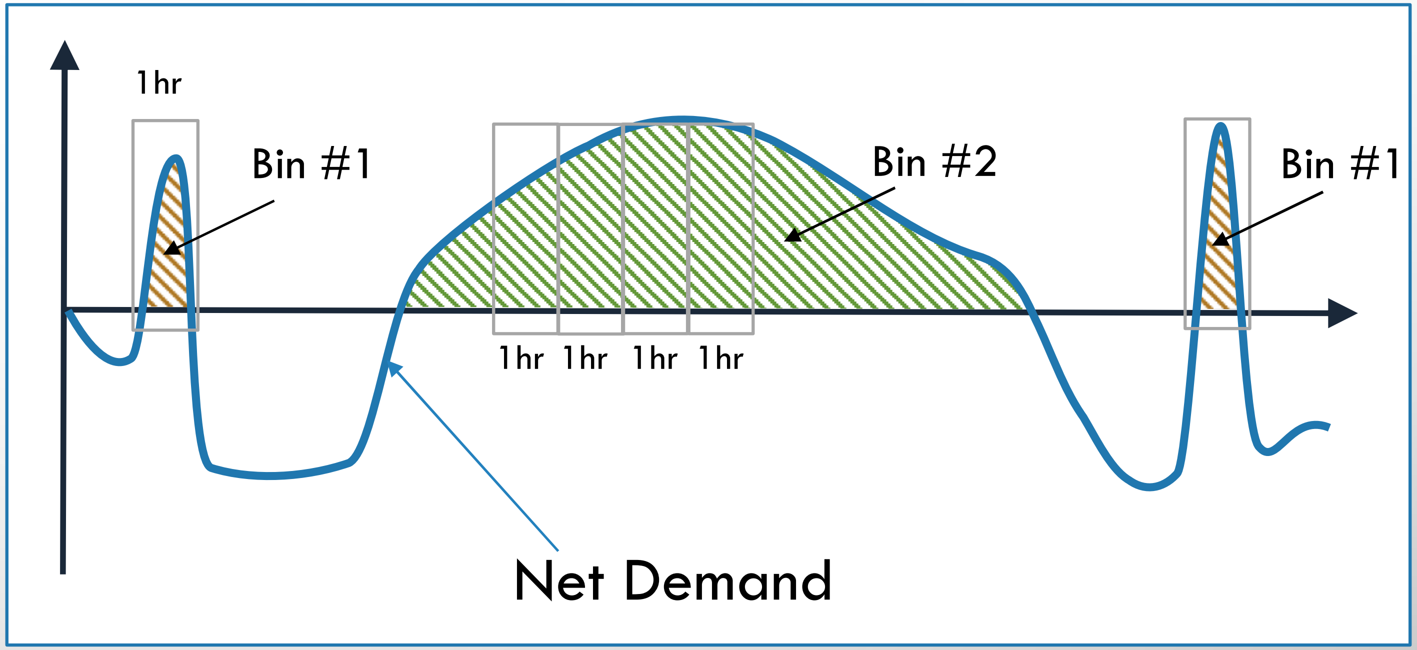


Net Demand *for the UK (2009-2019) with 75% of generation from wind, 25% generation from PV and 10% over-capacity (i.e. the average value of Net Demand here is slightly negative).*

Section #1

STORAGE: DURATIONS OF CONTINUOUS DISCHARGE





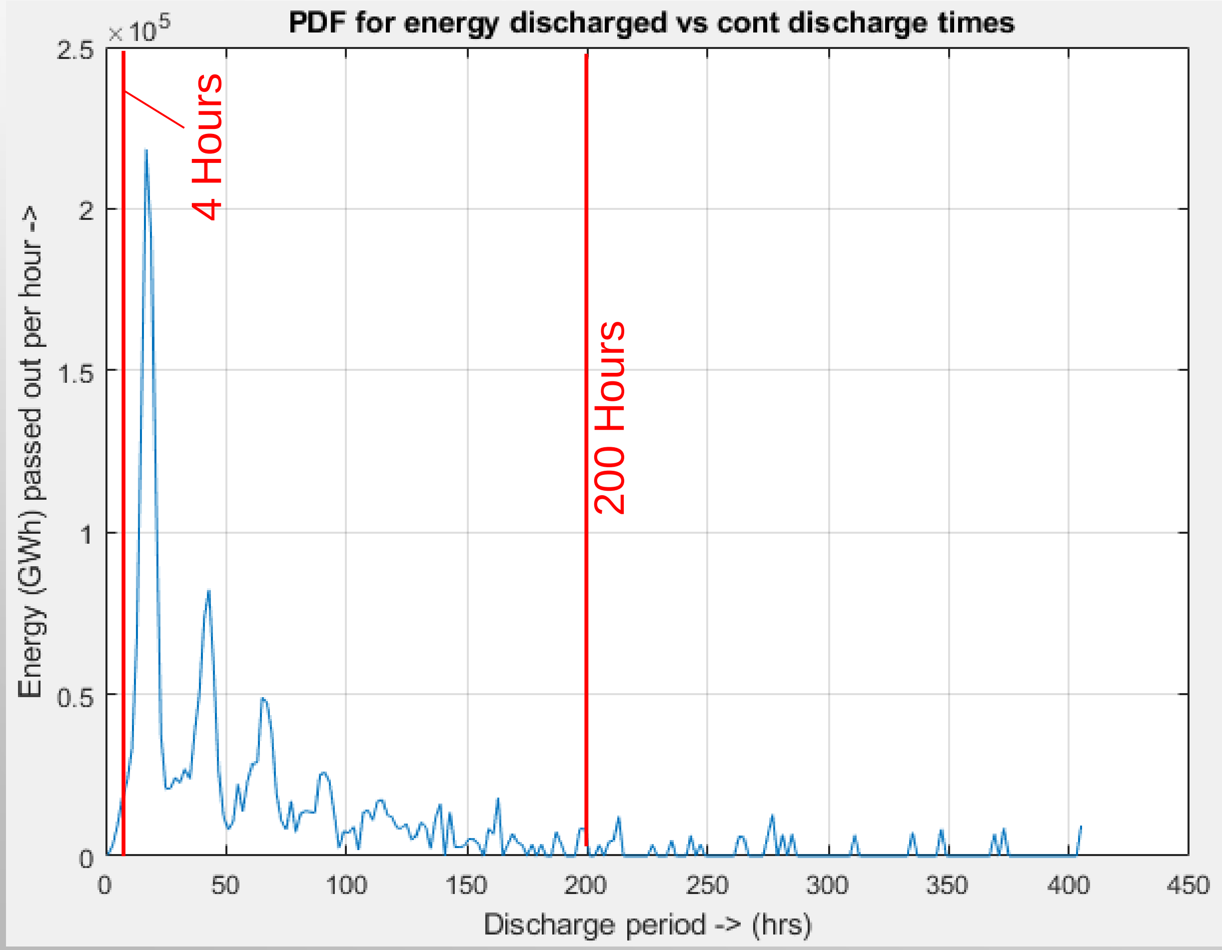
Examine each continuously-positive section in turn and sort these into 3 different "Bins"…

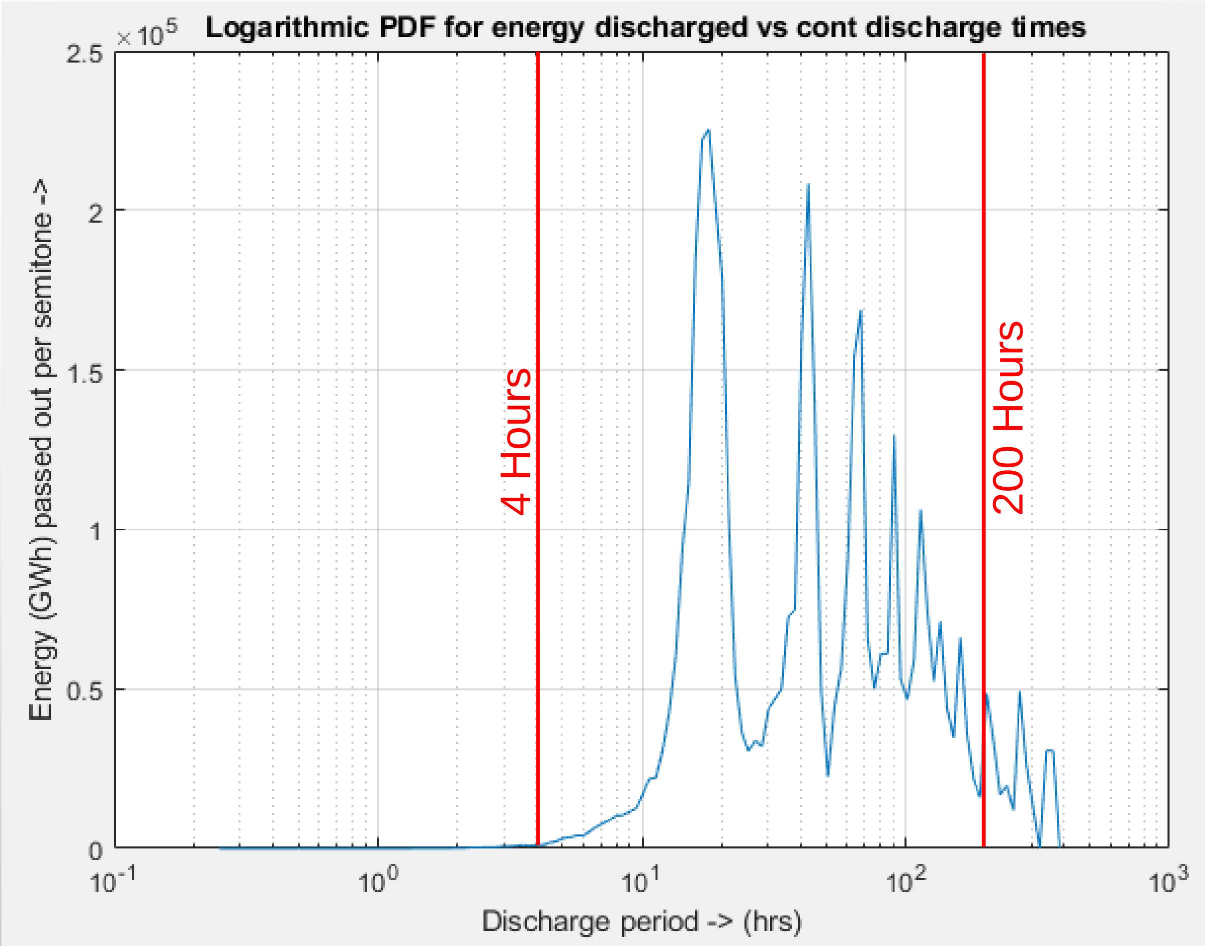
$T_{Discharge}$ <4hrs:	**SDES.**	(Batteries)	<1% of energy from storage
4hrs < $T_{Discharge}$ < 200 hrs:	**MDES.**	(CAES, LAES, PTES. …)	~92% of energy from storage
$T_{Discharge}$ > 200 hrs:	**LDES.**	(Hydrogen , Ammonia, …)	~7% of energy from storage

Section #1

STORAGE: DURATIONS OF CONTINUOUS DISCHARGE

If we use many more “bins”, we obtain a Probability Density Function (PDF).





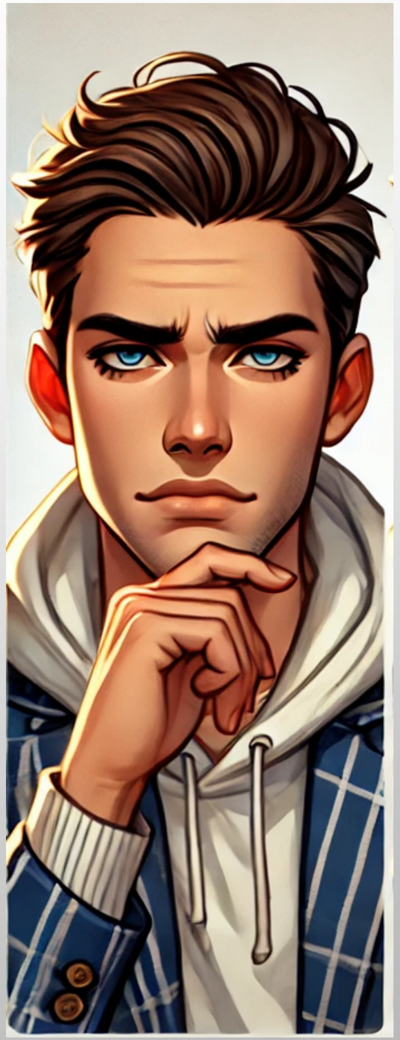
Using the same supply data and demand data (over 37 years) as was used in the R-S report

Section #1: Complete

STORAGE: DURATIONS OF CONTINUOUS DISCHARGE

Hmm! So most of the energy supplied by storage in Net Zero UK will emerge in periods of continuous discharge in the "MDES range" (4hrs – 200hrs). I get that.

However, that does not necessarily mean that this energy should not be supplied by hydrogen or batteries!



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Section #2

OPTIMISING A SYSTEM WITH *N* ENERGY STORES

A tool called [*NStore_sim*] provides the capability: www.era.ac.uk/resources/NStore_sim

[*NStore_sim*] is a set of MATLAB functions with some example main scripts showing how to use these functions for specific problems. The link above contains 4 x 30-minute videos explaining the underlying logic and methodology. It also contains basic documentation.

The central concept is that we create a cost-function that depends on system parameters (held in a vector, $\boldsymbol{p}$) and then we use a standard (unconstrained) optimisation to search for minimum cost by exploring the space of all plausible $\boldsymbol{p}$.

$$Cost = f(\boldsymbol{p})$$

Section #2

OPTIMISING A SYSTEM WITH *N* ENERGY STORES

For each different storage type, we should know …

Cost per unit¤ of rated input power	(£/kW(e_{input}))
Cost per unit¤ of rated output power	(£/kW(e_{output}))
Cost per unit¤ of storage capacity (volume)	(£/kWh(e_{output}))
Round-trip efficiency	(%)
Cost per unit of energy-fill reduction¥ (end – start)	(£/MWh)

¤ These costs comprise both CapEx and OpEx components

¥ This matters only for very long-duration store types (including fossil-fuelled generation)

Section #2

OPTIMISING A SYSTEM WITH 1 ENERGY STORE

A single-store energy system has 4 parameters of which 3 are independent.

- Rated storage input power | G | (GW(e_{input}))
- Rated storage output power | H | (GW(e_{output}))
- Storage capacity (volume) | V | (GWh(e_{output}))
- Over-generation factor* | X | ( )

If parameters (G, H, V) lie within reasonable bounds, then there will be some minimum value of X such the system is *acceptable* ($X = X_{min}$).

$$\boldsymbol{p} := \begin{bmatrix} G \\ H \\ V \end{bmatrix} \qquad Cost = f(\boldsymbol{p})$$

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* X=1.2 indicates that the total quantity of electrical energy generated in the record exceeds the total quantity of electrical energy consumed by a factor of 1.2.

Section #2

OPTIMISING A SYSTEM WITH 1 ENERGY STORE

We can test whether a particular 4-tuple (G, H, V, X) is acceptable by doing the following:

- Initialising the energy in store at some value such as 0.7×V
- Stepping through each (1-hour?) period in the record and …
- If supply exceeds demand, put (some of?) the excess into store
- If demand exceeds supply, draw (some of?) the shortfall from store
- Adjust the energy level in the store according to what has gone-in / come-out.

There is no “scheduling” problem here and no value or purpose for “forecasting”

We essentially use “interval-bisection” to find X_{min} starting with an interval like [1.0   1.6]

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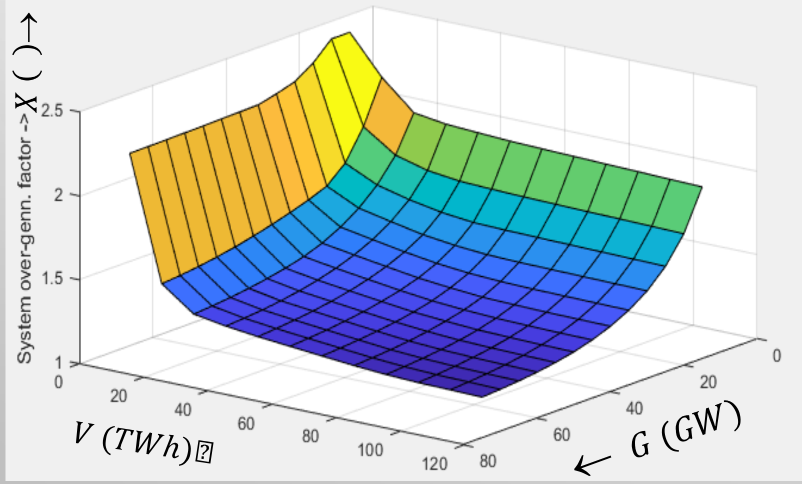
Section #2

OPTIMISING A SYSTEM WITH 1 ENERGY STORE

The optimisation explores the 3D space of points (*G*, *H*, *V*), computing costs for each one.

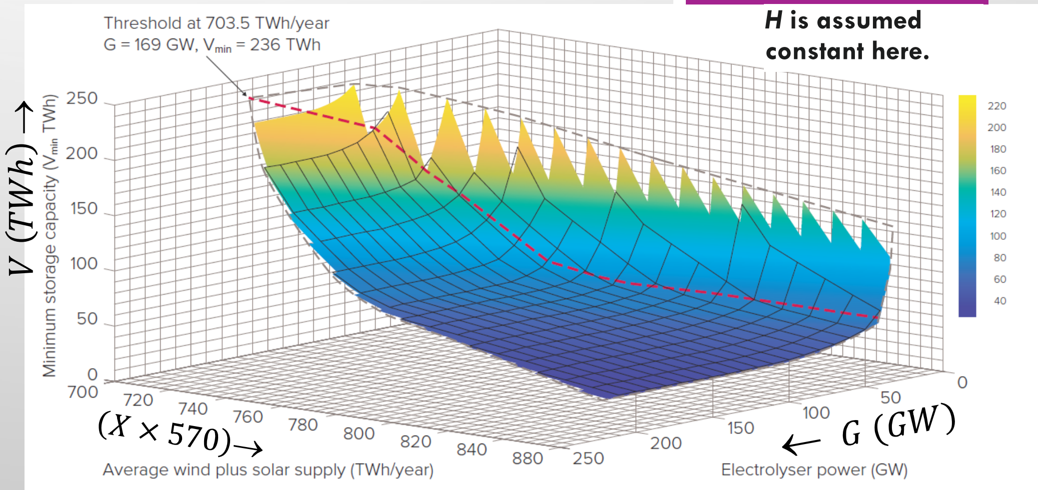
For “manual” approach to this, you can assume that the output power, *H*, is constant (it can never exceed maximum demand) but this is not necessary in [*NStore_sim*].



From [*NStore_sim*] (<demo_02.m>)

FIGURE 12

***H* is assumed constant here.**



From the Royal Society report

Section #2

OPTIMISING A SYSTEM WITH 2 ENERGY STORES

Now there are 7 distinct parameters determining system cost and whether that system is *acceptable*

- Rated input powers G_1, G_2 (GW(e_{input}))
- Rated output powers H_1, H_2 (GW(e_{output}))
- Storage capacities (volumes) V_1, V_2 (GWh(e_{output}))
- Over-generation factor* X ( )

If parameters (G_1, G_2, H_1, H_2, V_1, V_2) lie within reasonable bounds, then there will be some minimum value X for which the system behaviour is acceptable ($X = X_{min}$).

$$\boldsymbol{p} := [G_1 \quad G_1 \quad H_1 \quad H_2 \quad V_1 \quad V_2]^T \qquad Cost = f(\boldsymbol{p})$$

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* X=1.2 indicates that the total quantity of electrical energy generated in the record exceeds the total quantity of electrical energy consumed by a factor of 1.2.

Section #2

MODELLING A SYSTEM WITH 2 ENERGY STORES

We can test whether a particular 7-tuple (G_1, G_2, H_1, H_2, V_1, V_2, X) is acceptable by doing the following:

- Initialising the energy in each store at some value such as 0.7×V
- Stepping through each (1-hour?) period in the record and …
- If supply exceeds demand, put (some of?) the excess into store
- If demand exceeds supply, draw (some of?) the shortfall from store
- Adjust the energy level in the store according to what has gone-in / come-out.

Now some “scheduling” is needed to decide which store has priority for charge or discharge.

[*NStore_sim*] can:

(i) Determine whether one 7-tuple, (G_1, G_2, H_1, H_2, V_1, V_2, X) delivers an *acceptable* system

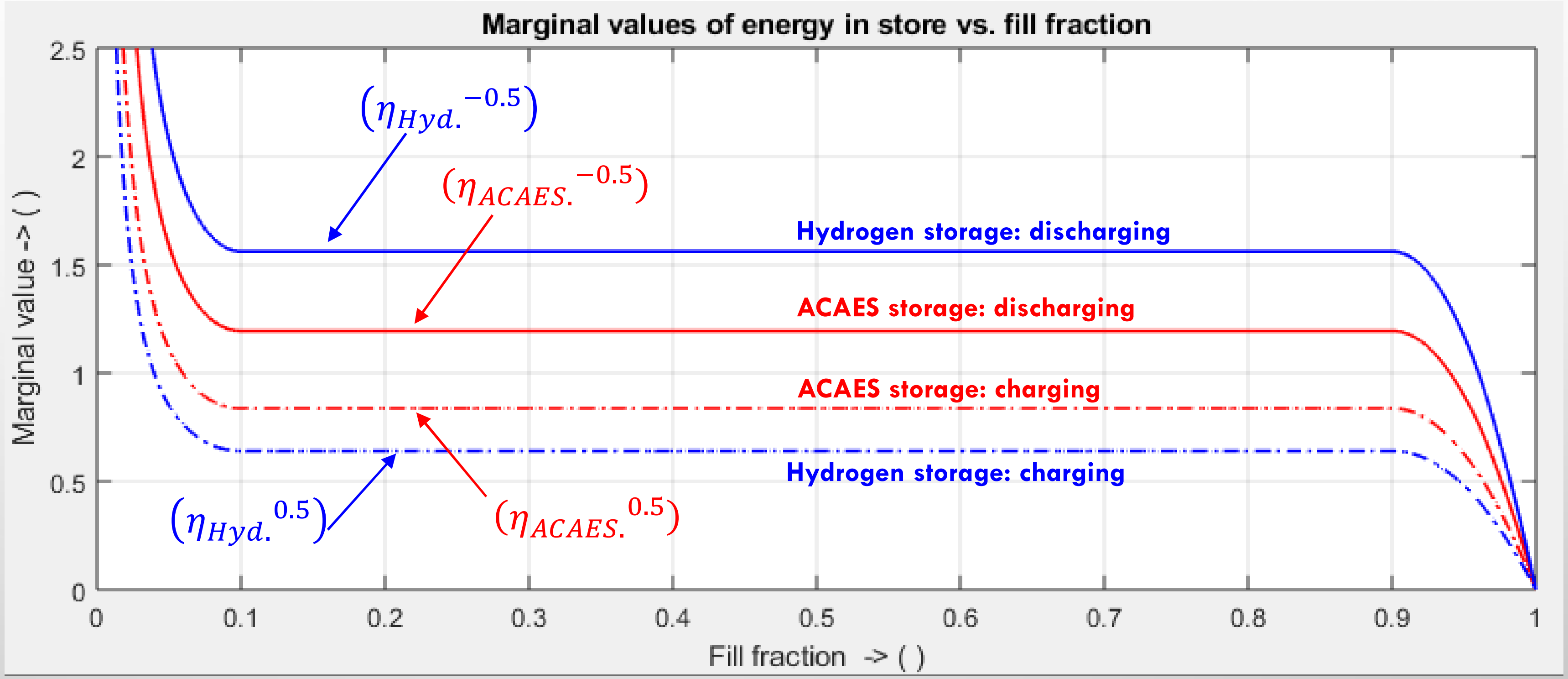
(ii) Determine smallest X for which (G_1, G_2, H_1, H_2, V_1, V_2, X) delivers an *acceptable* system

Section #2

OPTIMISING A SYSTEM WITH 2 ENERGY STORES

A good scheduling approach for the operation of multiple stores in a system is described by Zachary et al. [1]

The scheduling algorithm is *greedy*.



Within constraints, energy is preferentially put into the stores with highest marginal value and energy is preferentially withdrawn from stores with lowest marginal value.

[1] Zachary, S. Scheduling and dimensioning of heterogeneous energy stores with application to future GB storage needs. In review. https://arxiv.org/abs/2112.00102.

Section #2

OPTIMISING A SYSTEM WITH *N* ENERGY STORES

Any given N-store system is described by the ($3N$+1)-tuple, ($G_1 \dots G_N$, $H_1 \dots H_N$, $V_1 \dots V_N$, X).

We can test whether this system will be acceptable by …

- Initialising the energy in each store #i at some value such as $0.7 \times V_i$
- Stepping through each (1-hour?) period in the record and …
- If supply exceeds demand, spread (some of?) the excess into stores
- If demand exceeds supply, draw (some of?) the shortfall from stores
- Adjust the energy levels in the stores

Given particular values for the $3N$ independent parameters, we can trial different values of X with the above procedure to find what minimum value of X produces an acceptable system.

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Section #2

OPTIMISING A SYSTEM WITH *N* ENERGY STORES

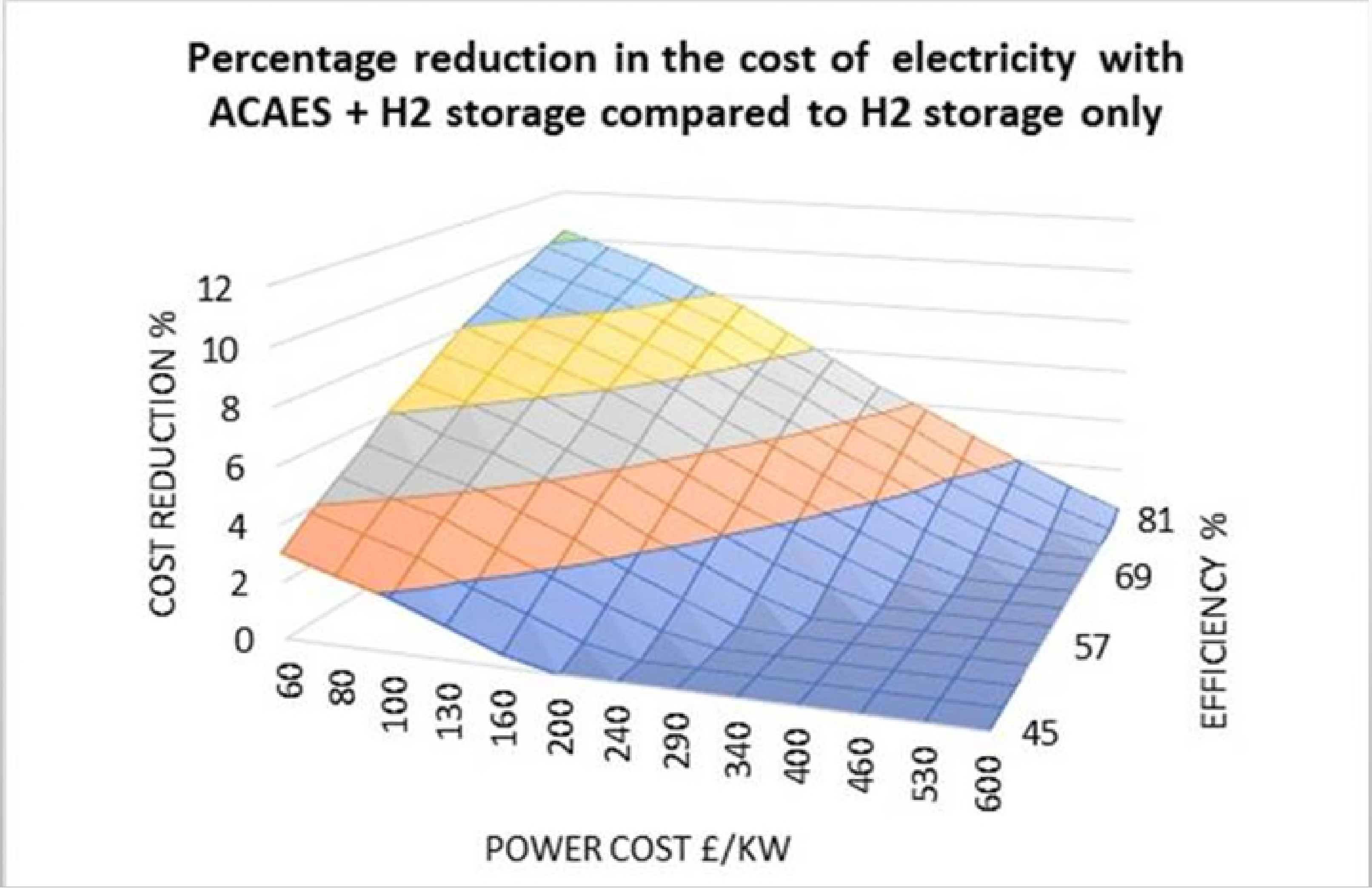
This simple approach is very revealing:

- Blends of wind and solar matter a lot: ~80:20 to balance between Winter and Summer on average – but wind suffers much greater year-to-year variability than solar power!
- Nuclear power can be examined. It is “almost a theorem” that the cost-per-MWh for a system based on R.E.+storage sets an upper limit for acceptable cost for nuclear power!
- Including nuclear shifts the optimal blend of wind:solar. With nuclear providing >40%, we would want to have 0 solar power! More nuclear <=> less solar!
- Gas-fired generation (with/without CCS) can be treated as storage and put into the optimisation. Using realistic cost assumptions … the cost-optimal UK system burns 0 gas!
- Under realistic cost assumptions about Adiabatic Compressed Air Energy Storage (ACAES), reductions in whole-system cost of >5% are credible relative to the baseline system using hydrogen and batteries to provide all storage.

Section #2

OPTIMISING A SYSTEM WITH *N* ENERGY STORES

Depending on what you believe about future power costs and roundtrip efficiency of ACAES …



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Section #2

OPTIMISING A SYSTEM WITH 2 ENERGY STORES

Some interesting observations:

- Most energy from storage will pass out from MDES, not from H_2
- Over-generation factor reduces from 1.3 to 1.2
- Spend on MDES is similar to that on H_2 – although the MDES stores have much smaller capacity.
- ~15% of all energy consumed comes out of storage.

  (~25% of all gen^n goes into storage)

```
Store #1:  Total energy (in,out)=(2975.91,2022.24) (TWh)
Store #2:  Total energy (in,out)=(3463.36,1402.59) (TWh)
```

Storage cost components (NPV) listed here

	Store #	Element	Value	Cost (£bn)
ACAES	1	IP Power	43.54 (GW)	16.18
	1	OP Power	32.31 (GW)	15.28
	1	Energy Cap.	5.07 (TWh)	18.53
	1	Enrgy Dfct.	-1.09 (TWh)	-0.07
Hydrogen	2	IP Power	36.24 (GW)	19.21
	2	OP Power	60.84 (GW)	30.50
	2	Energy Cap.	47.21 (TWh)	37.55
	2	Enrgy Dfct.	6.84 (TWh)	0.45

Generation costs given now

Element	Value	Cost (£bn)
Genn. to meet demand	21090.00 (TWh)	391.91
Losses & Curtailment	4748.87 (TWh)	88.25

Section #2: Complete

STORAGE: DURATIONS OF CONTINUOUS DISCHARGE

OK. The cost-optimisation outcomes do seem to suggest that there could be a role for MDES.

It's a pity about the high degree of uncertainty on costs and performance.

Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

Numerous solutions compete in the standalone MDES space: (E-I-E-O)

- Flow batteries.
- Pumped Hydro Energy Storage, PHES.
  (Very mature. Limited by geography. ~80% RTE. Very long lifetime.)
- Compressed Air Energy Storage, CAES.
  (UK has a lot of bedded salt! High RTE. Integrate with transmission?)
- Liquid Air Energy Storage, LAES.
  (Siteable anywhere. UK spearheaded. Medium RTE. Integrates with heat, cold, xmssn)
- Pumped Thermal Energy Storage, PTES.
  (Siteable anywhere and potentially very low cost per kWh capacity).
  - CO_2 battery. (Excellent concept – if there is a cheap & reliable "dome"!)

Thermo-mechanical solutions.

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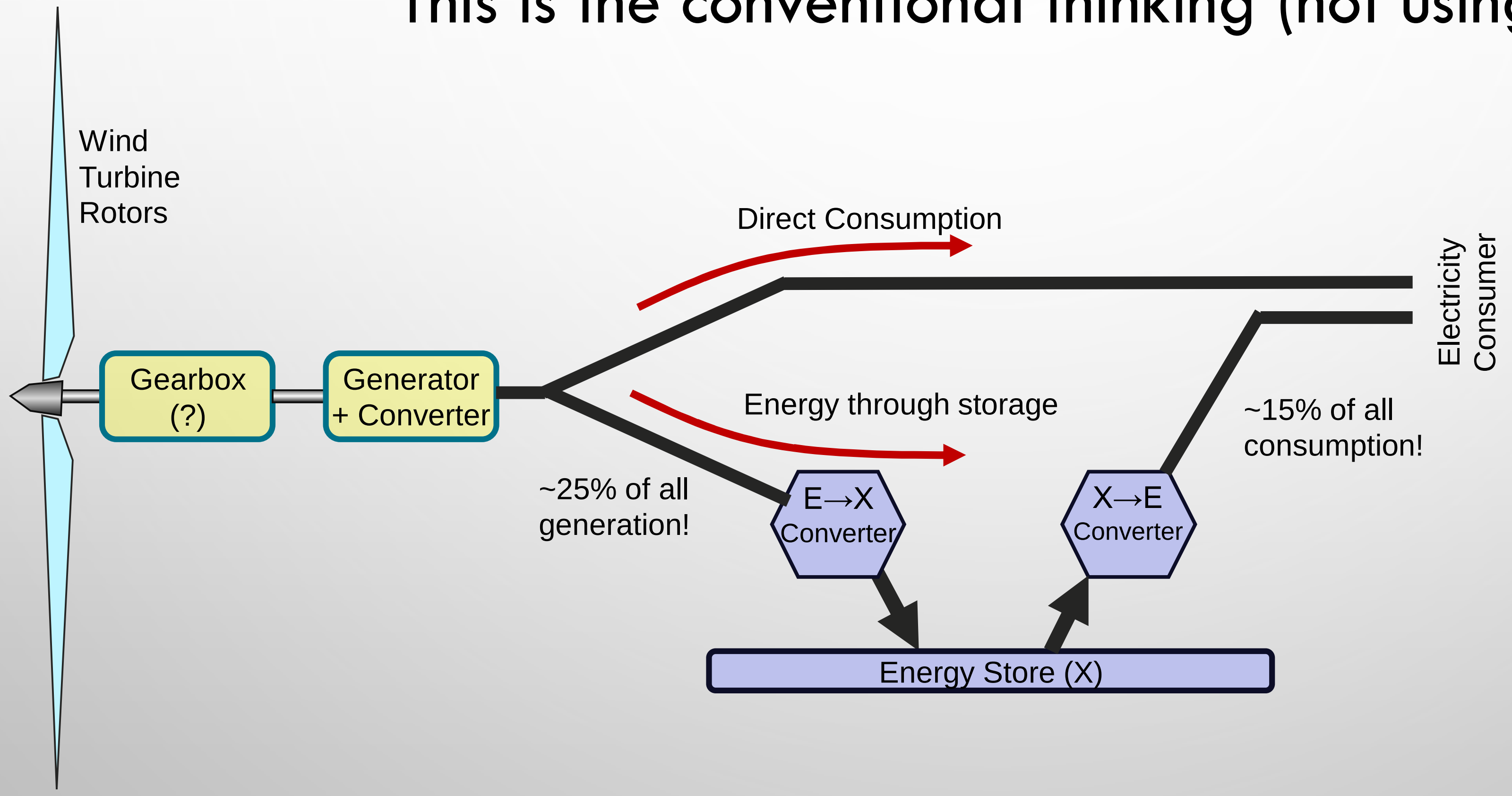
Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

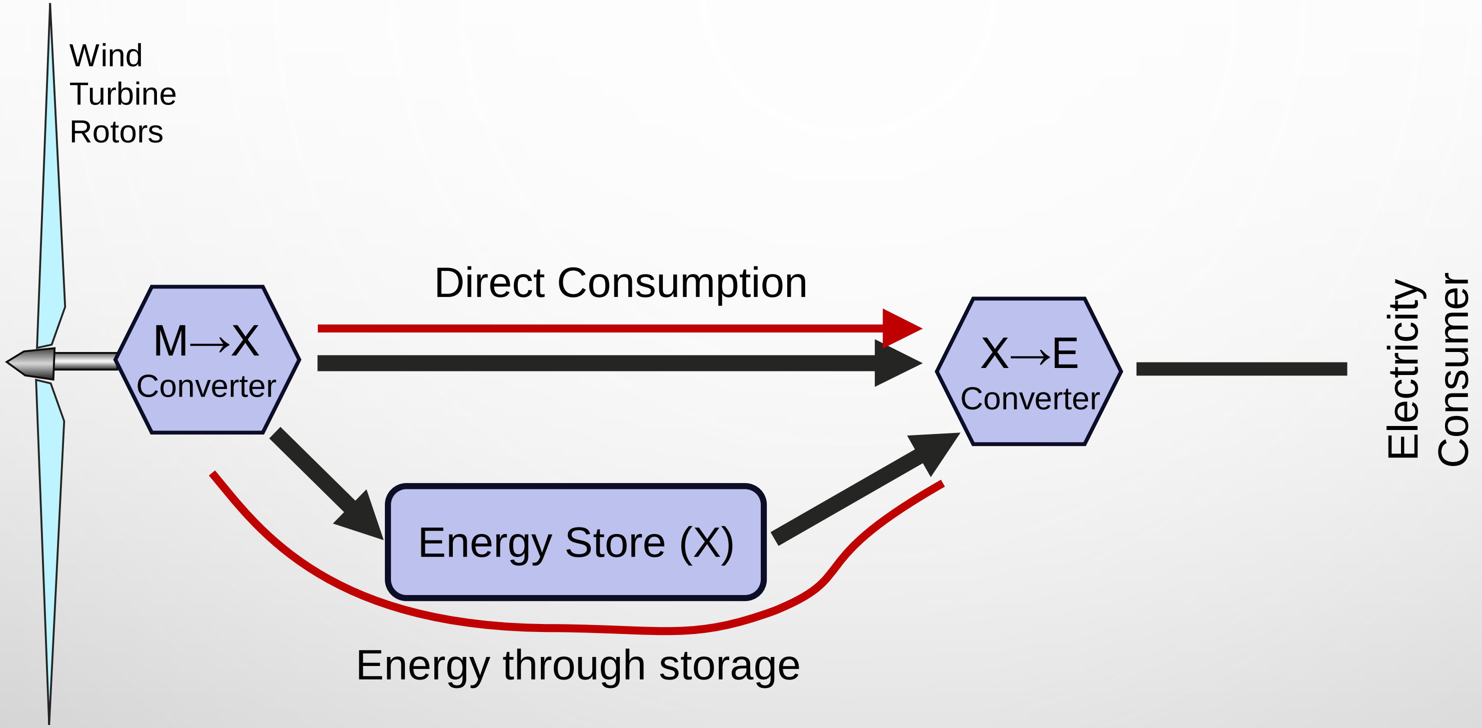
This is the conventional thinking (not using WIS)



~25% of all energy collected is transformed …
mechanical → electrical → mechanical → electrical

Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

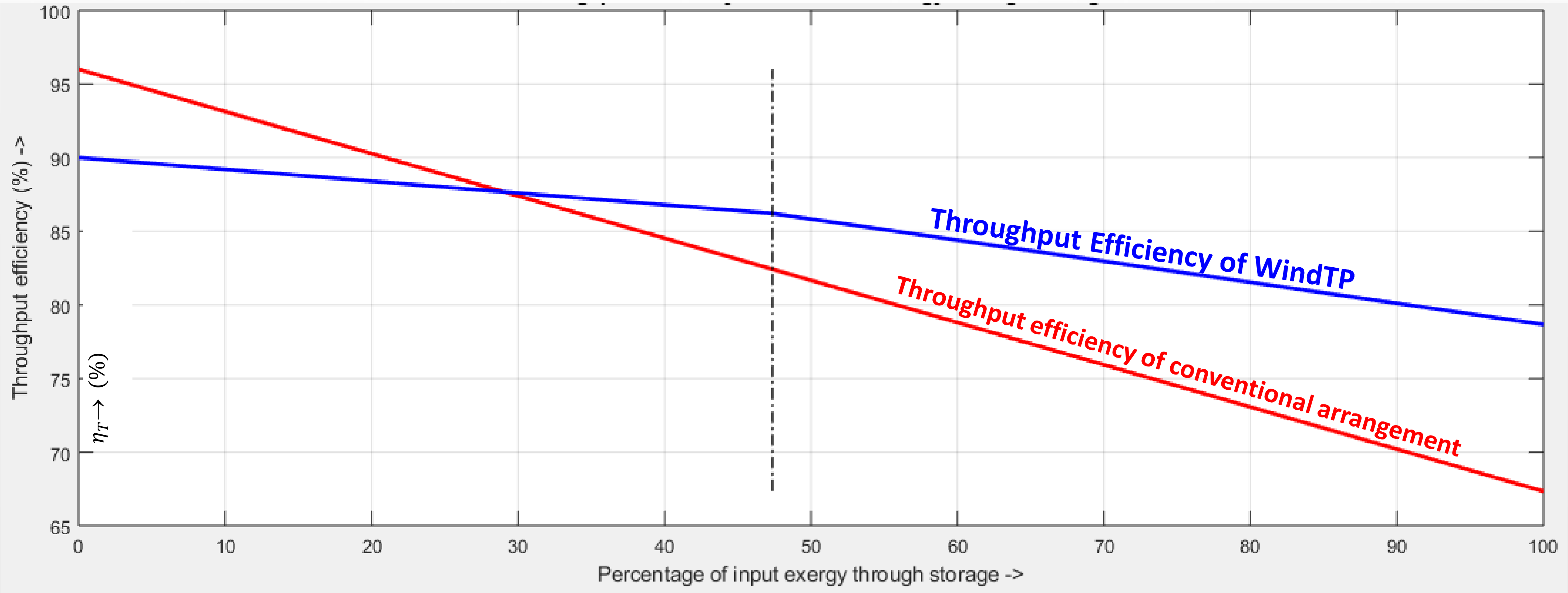


Wind Integrated Storage involves:

- Fewer energy transformations for energy through storage (losses ↓)
- Fewer pieces of power-conversion equipment (CapEx ↓)
- Improved utilisation of transmission lines (CapEx ↓)

Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)



WIS works well when a high fraction of all energy from the wind turbines passes through storage.

Garvey, Eames et. al., *On Generation Integrated Energy Storage*, Energy Policy 86, 2015, pp544-551 http://multiscience.atypon.com/doi/pdf/10.1260/0309-524X.39.2.149

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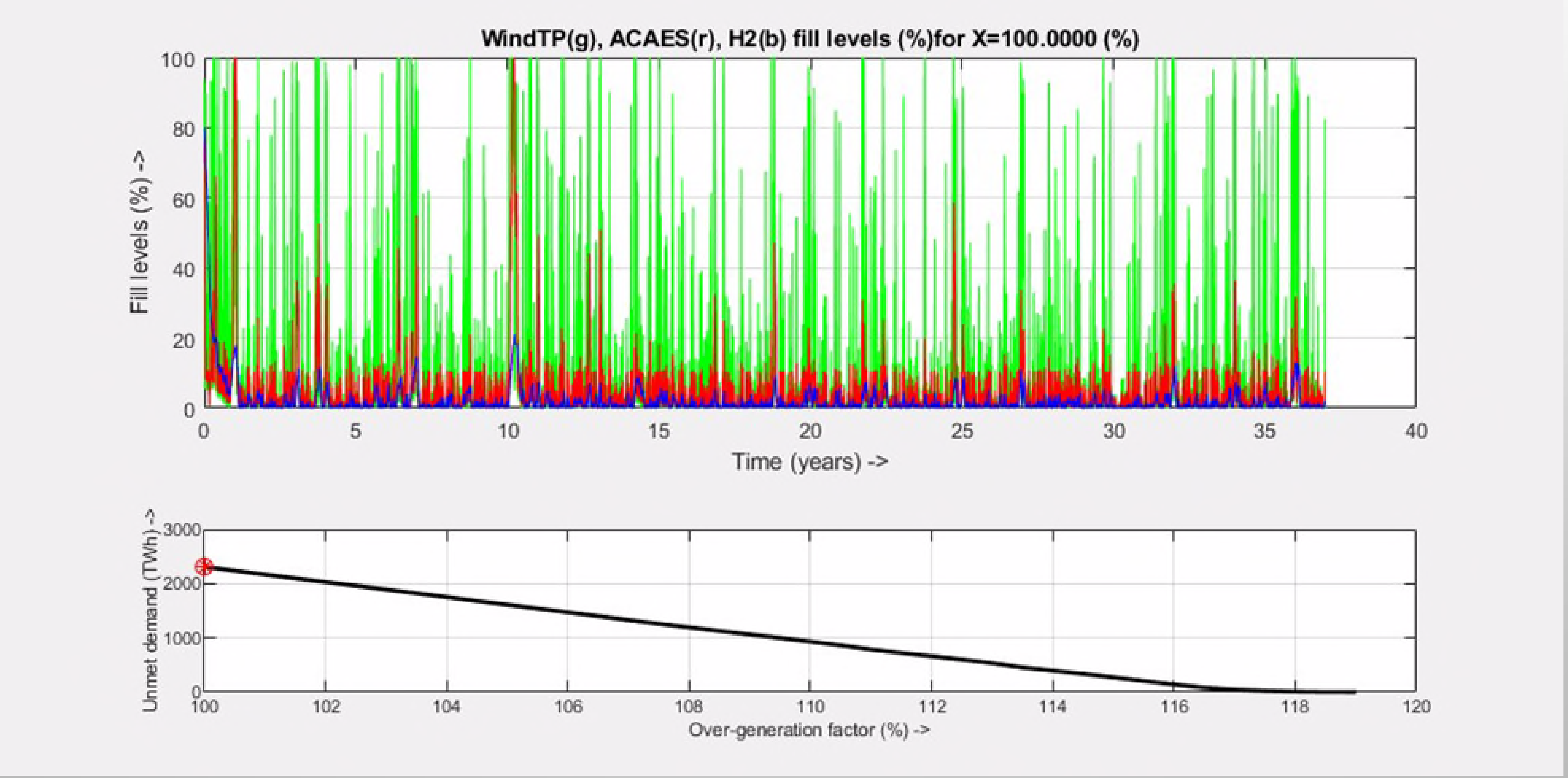
Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

#1: Wind-Integrated Storage. G_1=30GW, H_1=20GW, V_1= 1,050GWh, η_1=80%
#2: ACAES. G_2=15GW, H_2=10GW, V_2= 2,800GWh, η_2=65%
#3: Hydrogen Storage. G_3=37GW, H_3=65GW, V_3=80,000GWh, η_3=41%



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Section #3

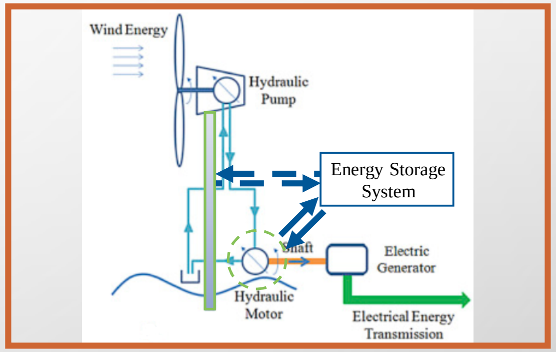
A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

There are numerous distinct technology classes possible for direct integration of storage with wind power

i. Pump water uphill

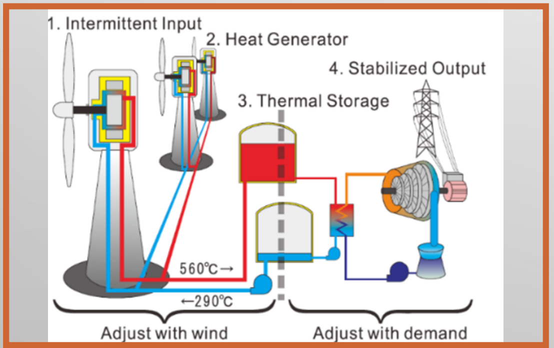
4 New Ways to Store Renewable Energy With Water, Spectrum, 2017

ii. Compress air directly



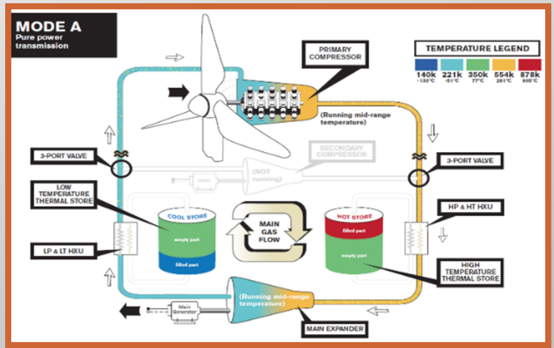
Chao Qin, *et al.*, 2016. Hydraulic-electric hybrid wind turbines: Tower mass saving and energy storage capacity. *Renewable Energy*, pp. 69-79.

iii. Convert rotor work to heat



Toru Okazaki *et al.*, 2015. Concept study of wind power utilizing direct thermal energy conversion and thermal energy storage. *Renewable Energy*, Volume 83, pp. 332-338.

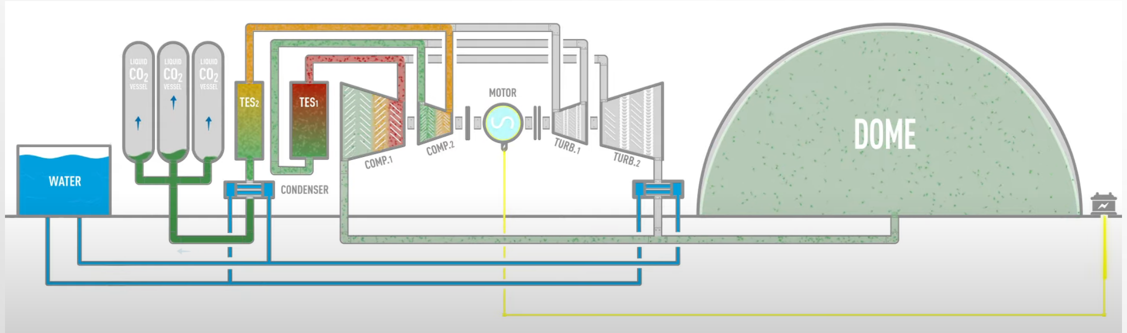
iv. Pump Heat



Seamus D Garvey *et al.*, 2015. Analysis of a Wind Turbine Power Transmission System with Intrinsic Energy Storage Capability. *Wind Engineering*, Volume 39, pp. 149-174.

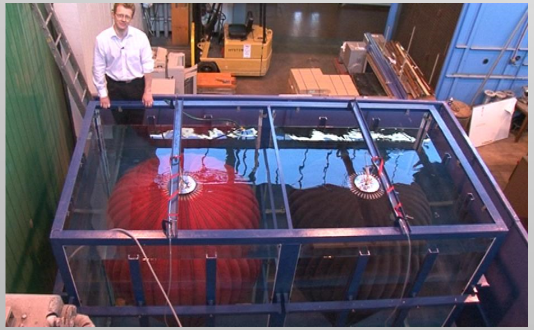
Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)



https://energydome.com/

Liquefy CO_2 to “charge” and expand it to “discharge”. Store the CO_2 in bags underwater?



https://highviewpower.com/

Liquefy air to “charge” (using rotor work to do the compression) and expand the liquid air again to “discharge”.

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A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

WindTP is WIS implemented using thermal pumping. Like all WIS, *WindTP* is a power transmission system for wind turbines that draws power directly from the rotor and delivers output power directly to grid.

WindTP employs reversible thermal pumping to enable the storage of ~100hrs of rated output capacity at marginal costs much below the cost of the wind turbine itself. This storage capacity with batteries would cost ~10 times as much as the wind turbine (£2/kW vs £200/kWh).

http://multi-science.atypon.com/doi/pdf/10.1260/0309-524X.39.2.149

WIND ENGINEERING Volume 39, No. 2, 2015 PP 149–174

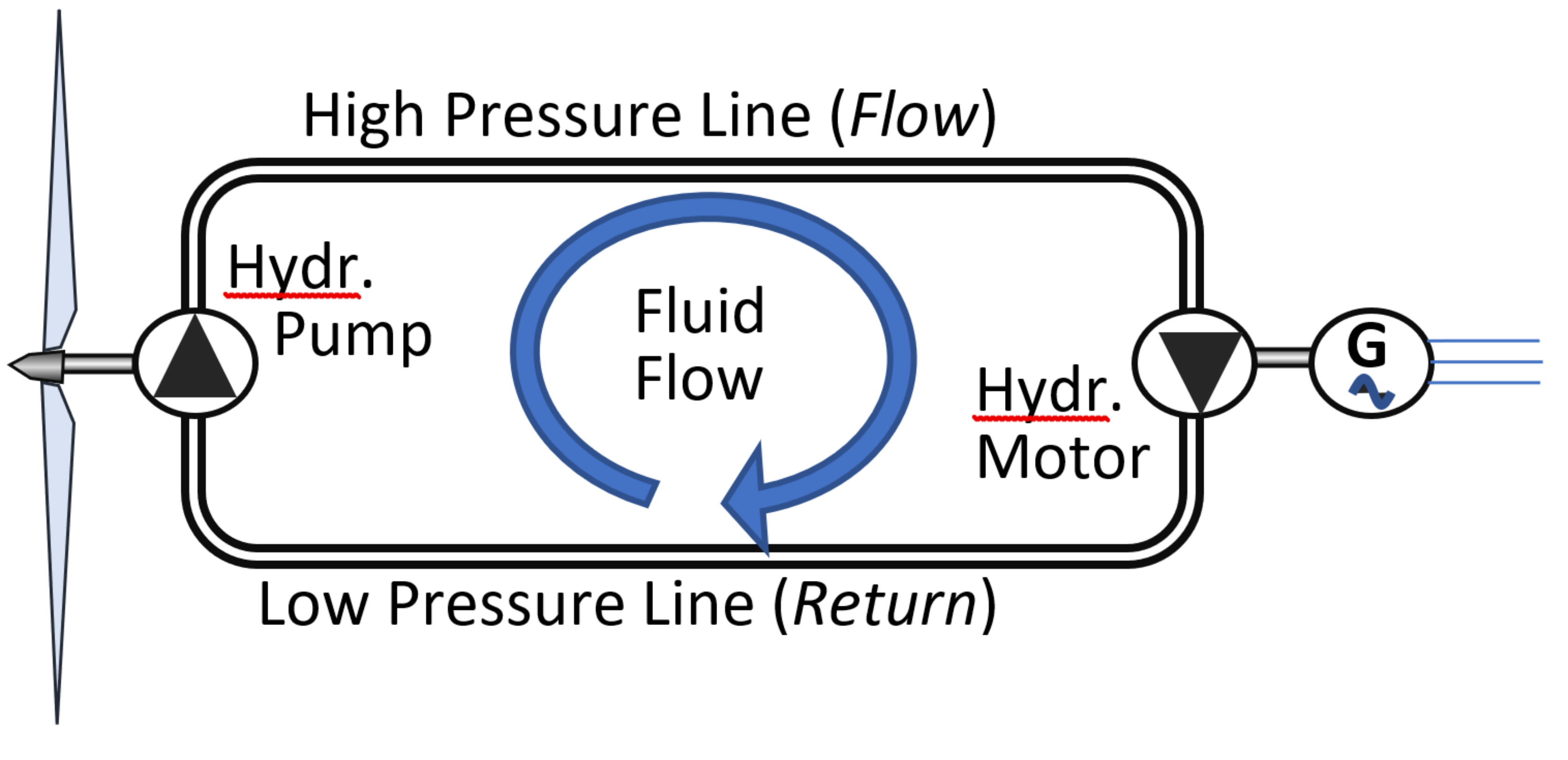
Analysis of a Wind Turbine Power Transmission System with Intrinsic Energy Storage Capability

Seamus D Garvey*[1], Andrew J Pimm[1], James A Buck[1], Simon Woolhead[1], Kai W Liew[1], Bharath Kantharaj[1], James E Garvey[2] and Barrie D Brewster[1]

Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

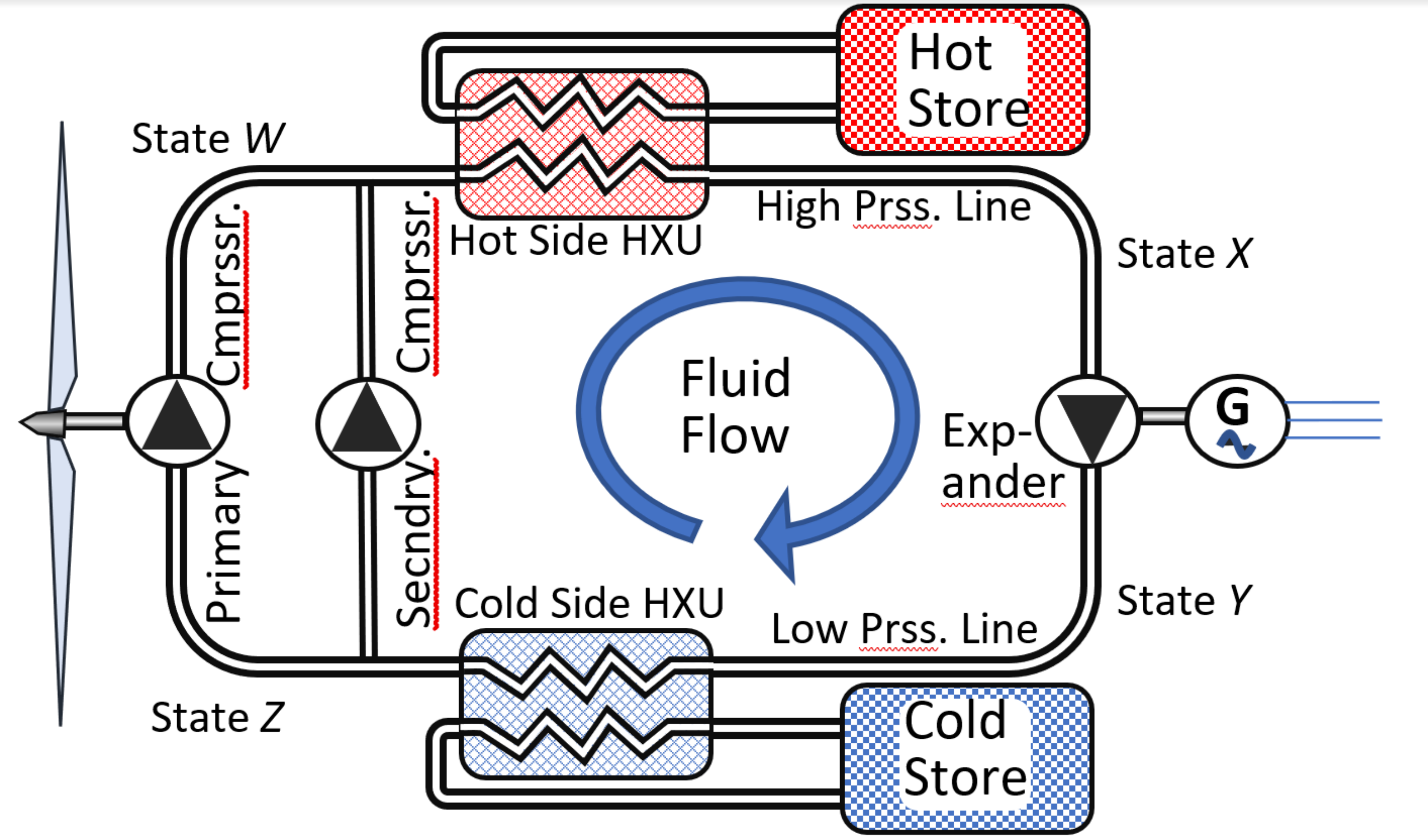
Start by understanding a hydraulic transmission between main rotor and generator with a high speed ratio (~×50) ...



<u>Note: hydraulic transmissions are the natural design choice for *Torque Machines!*</u>

Section #3
A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

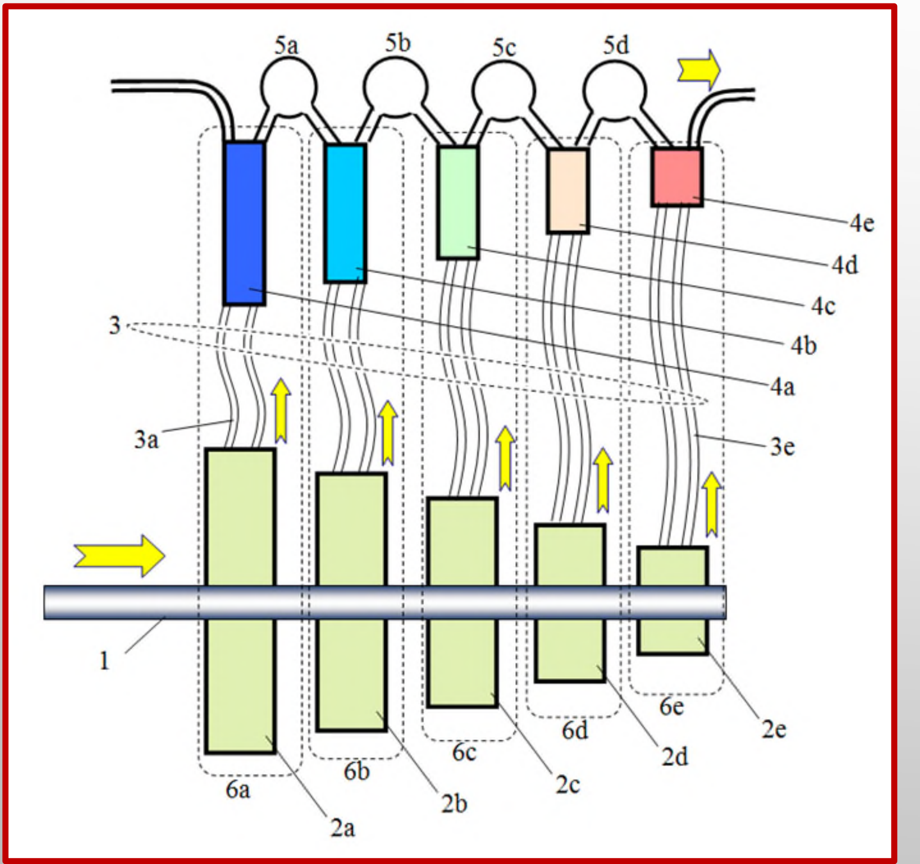
… and then swap the hydraulic fluid for a gas – the *working gas* … Helium!

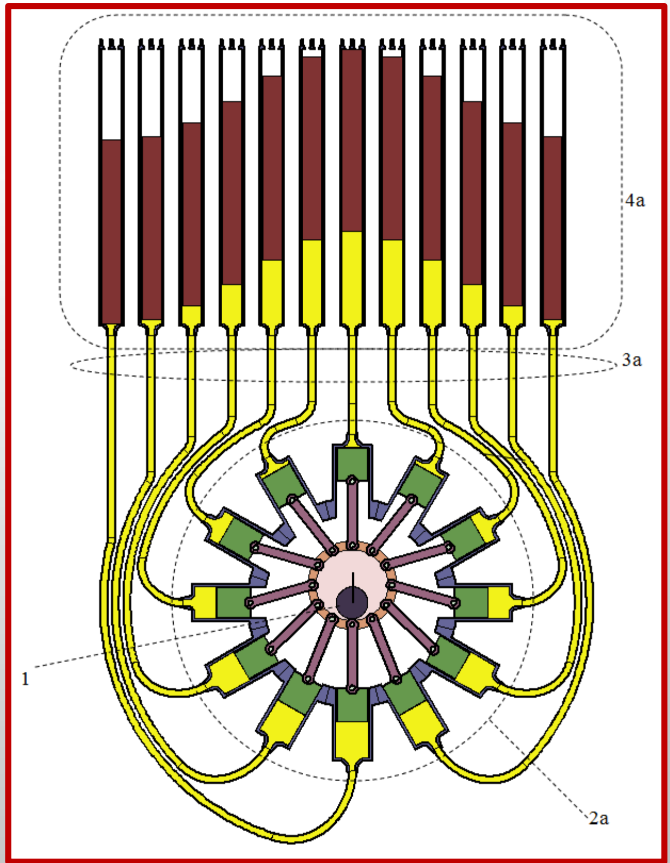


Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

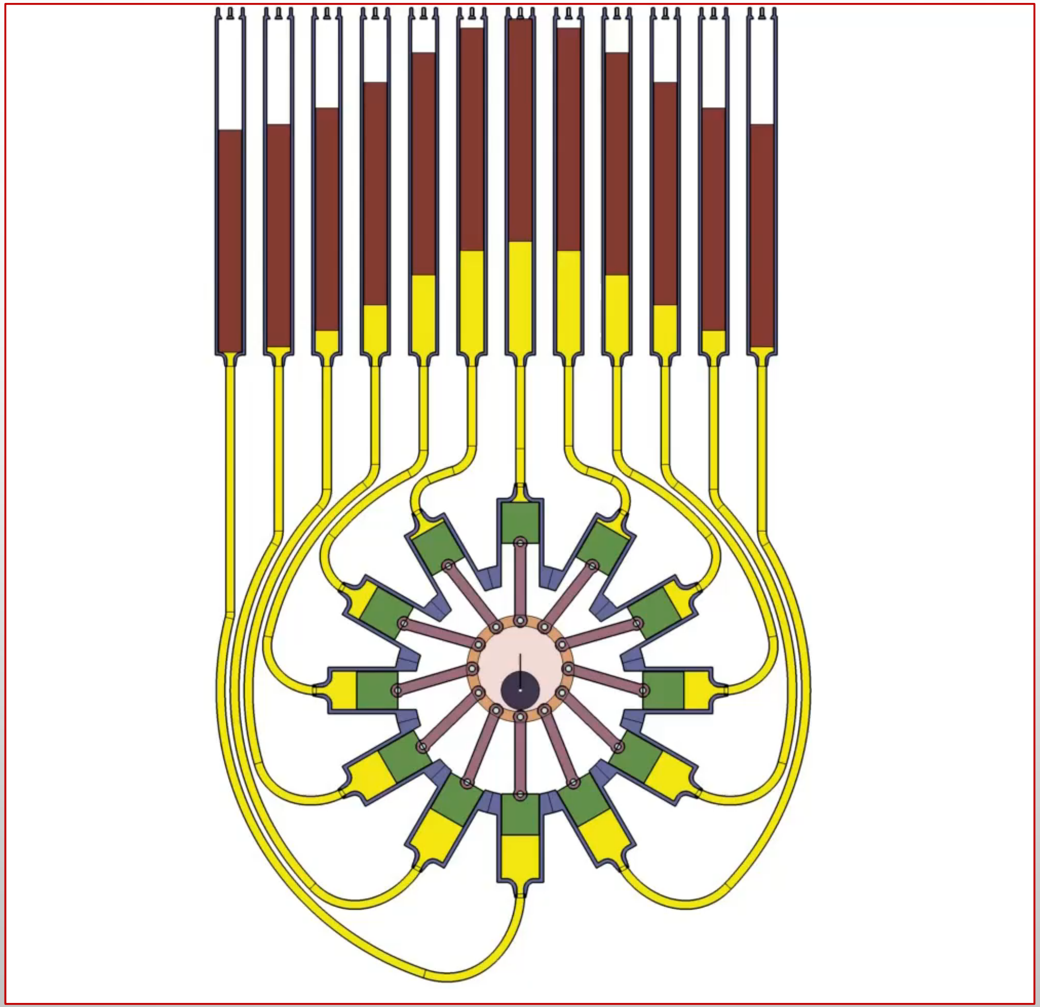
MULTI-STAGE MACHINE. EACH STAGE SIMILAR RATIO, DIFFERENT TEMPERATURE.



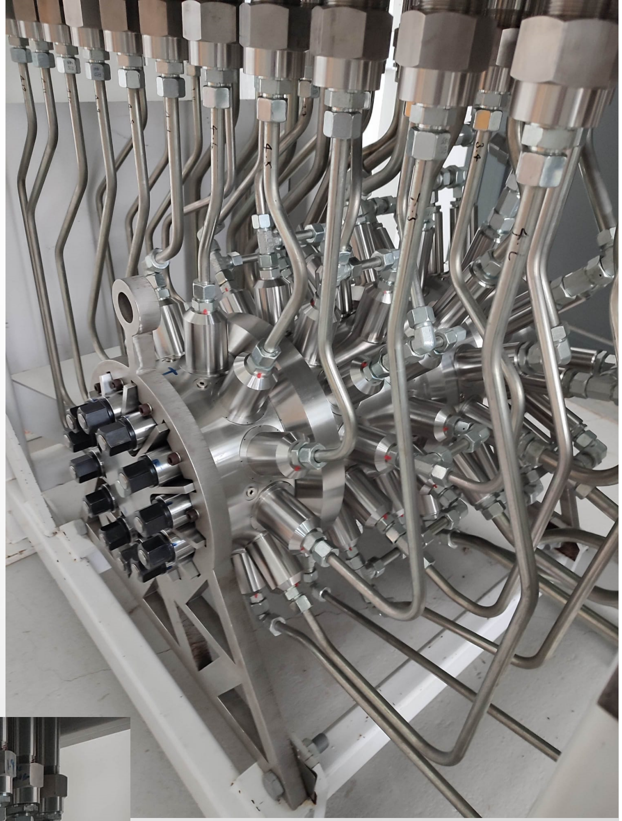


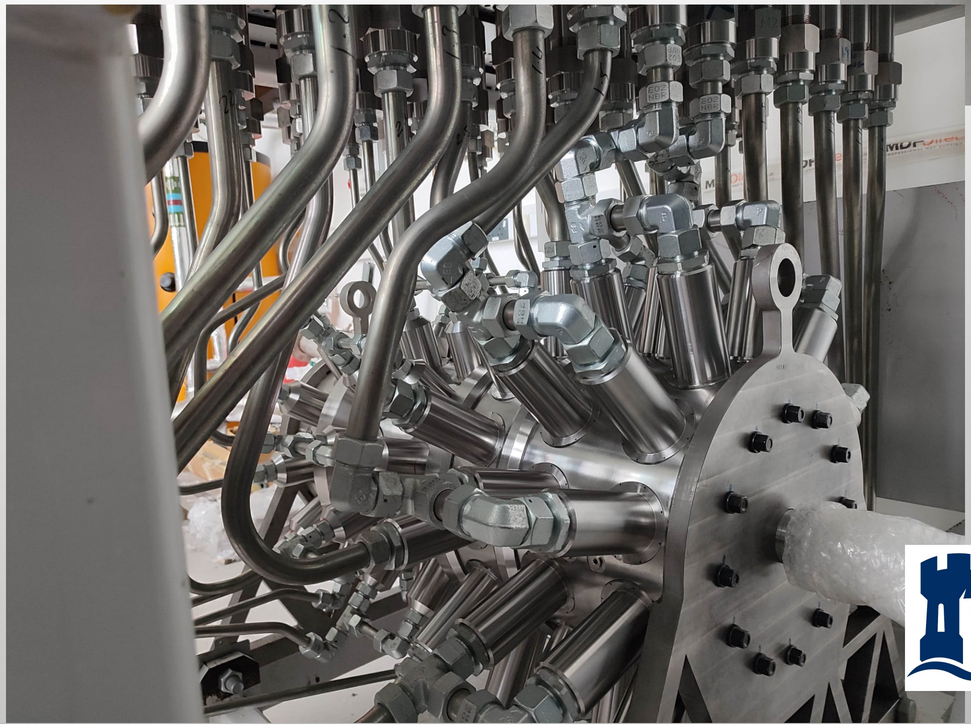
Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)



The machine consists of two parts. The lower half is the displacer, and the upper half is the converter.
We have oil in the lower half to move backward and forward within pipes and this oil compress the air in the converter pipes.





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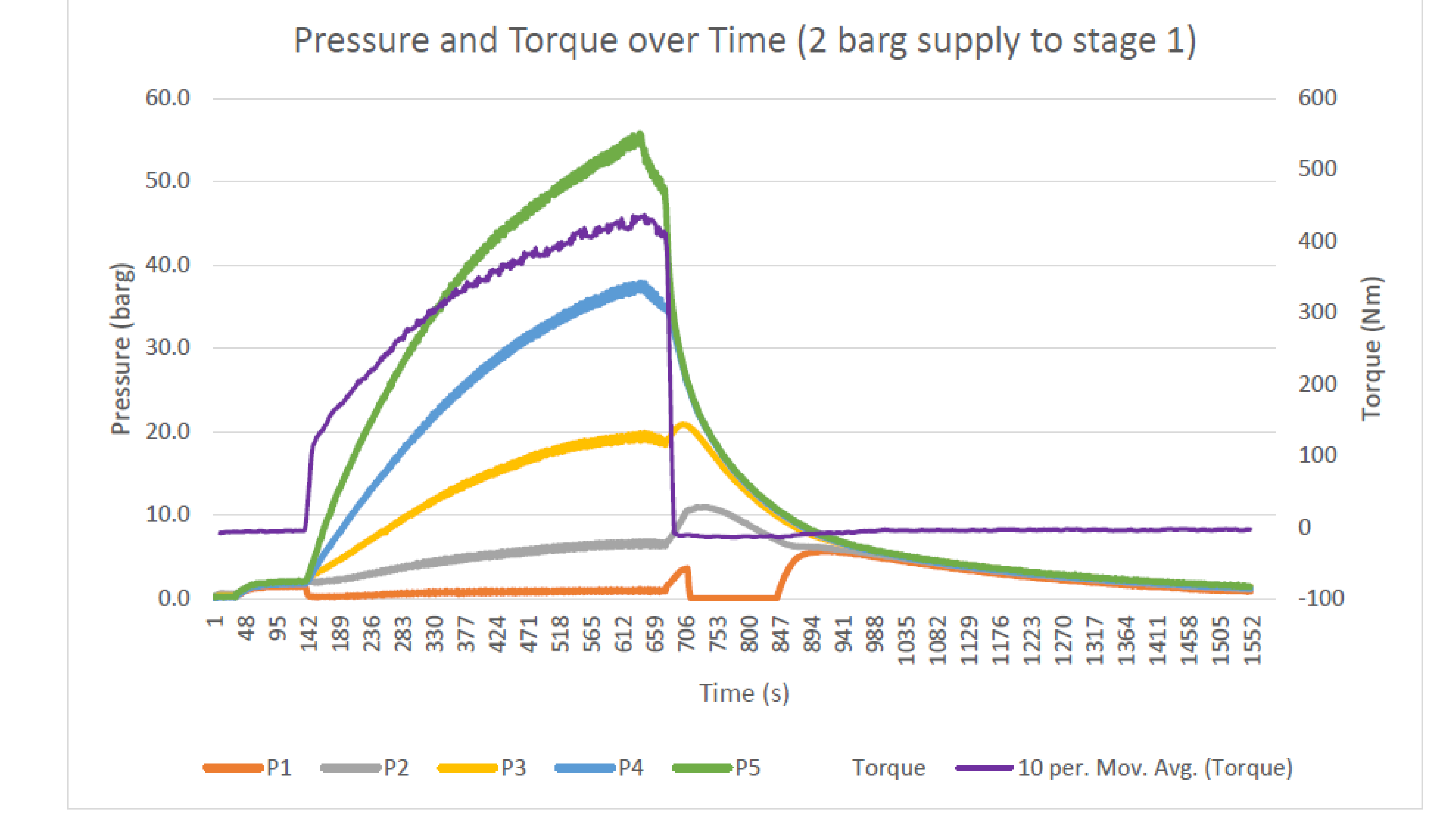
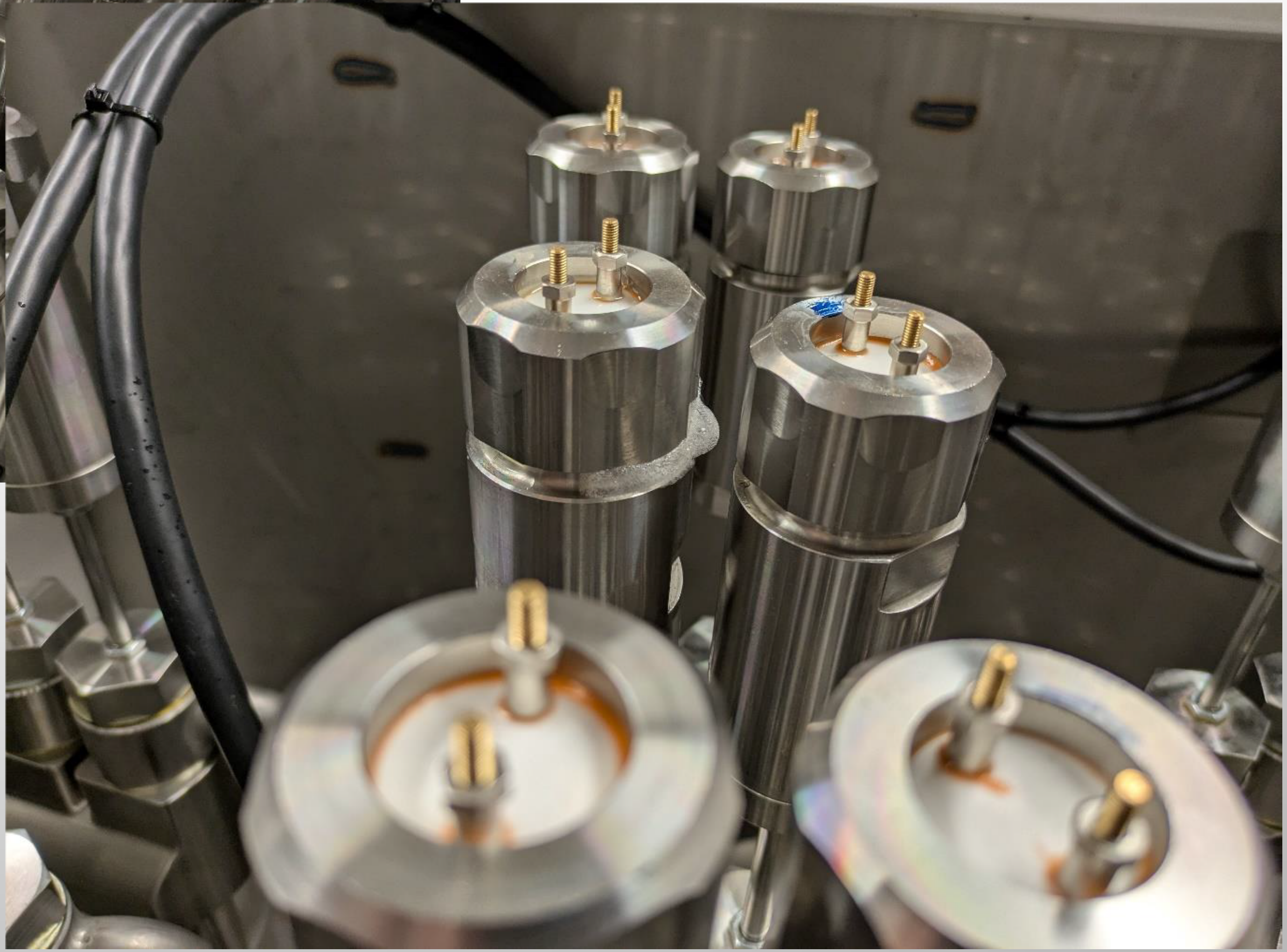
Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)



LEAKAGE!



Section #3

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

With very credible assumptions, *[Nstore_Sim]* shows that *WindTP* could account for overall savings of >£1/MWh. on total system costs relative to the next least expensive system (which already includes a substantial utilisation of ACAES based on salt caverns!

The savings increase as the cost of wind increases because the high achievable turnaround efficiency of *WindTP* causes a reduction in the level of over-generation required. Reminder: the biggest cost in our future Net Zero UK will be the cost of primary generation.

Section #3: Complete

A GLIMPSE INTO WIND-INTEGRATED STORAGE (WIS)

Hey! If that £1/MWh saving on all electricity was real, that would be quite a big deal. I heard that we could be consuming 1000 TWh per year by 2050. That would be £1bn/year !!

It it was as good as that, surely DESNZ would already be looking into it seriously?

CONCLUDING REMARKS

- Much H_2 storage in caverns needed for Net Zero UK.
- Medium duration energy storage (discharge durat^{ns} between ~4hrs & ~200hrs) will do the heavy lifting for future integration of 100% renewables.
- Standalone MDES solutions like ACAES might provide`>5% relative to H_2 only
- Wind Integrated Storage (WIS) could be a major economic opportunity for UK
- *WindTP* is one attractive form of WIS that can be implemented anywhere.
- Tools exist to elucidate the role of MDES … www.era.ac.uk/resources/NStore_sim

energy storage
IEA Technology Collaboration Programme

https://iea-es.org/task-42/

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MORE ABOUT MDES & OFFSHORE STORAGE

- www.era.ac.uk/Medium-Duration-Energy-Storage-event
- www.era.ac.uk/Medium-Duration-Energy-Storage-2022
- www.era.ac.uk/MDES2024

https://www.osessociety.com/

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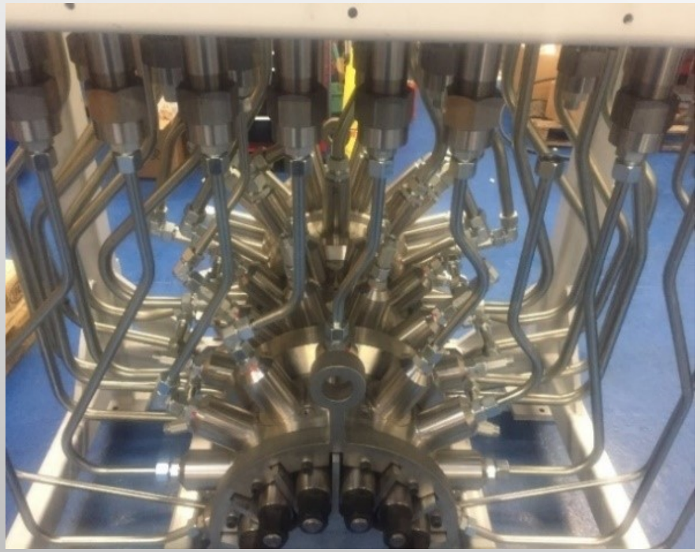
Thanks for listening. **Seamus.Garvey@Nottingham.ac.uk**

For more info. about Wind Integrated Storage:



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https://docs.google.com/presentation/d/1jhBAuYzkNj7UzMXq0MWcSCECW0-mQxoW/edit?usp=sharing&ouid=104407450146476914335&rtpof=true&sd=true

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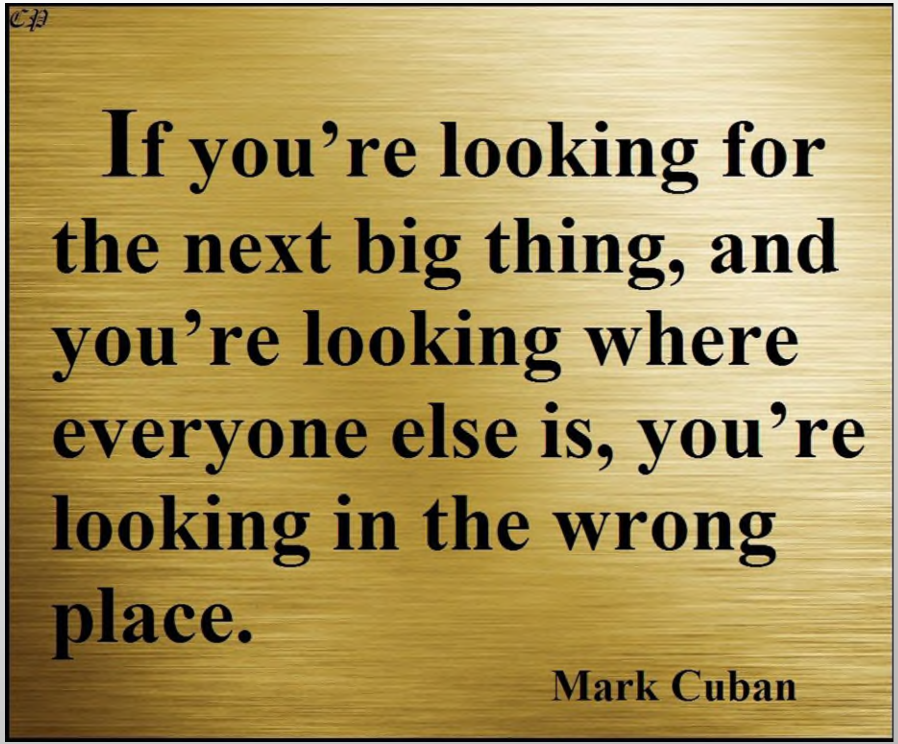
A presentation made to BEIS on Feb 4, 2020 supporting the request that an independent study should be carried out into wind integrated storage and its importance to the UK.



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