Royal Society Report on
Large-Scale* Electricity Storage

Personal Summary

*meaning storage that can meet a significant fraction of demand, i.e. covers small stores cycled rapidly as well as large stores cycled slowly

Chris Llewellyn Smith, Oxford Physics

Underlying assumption:

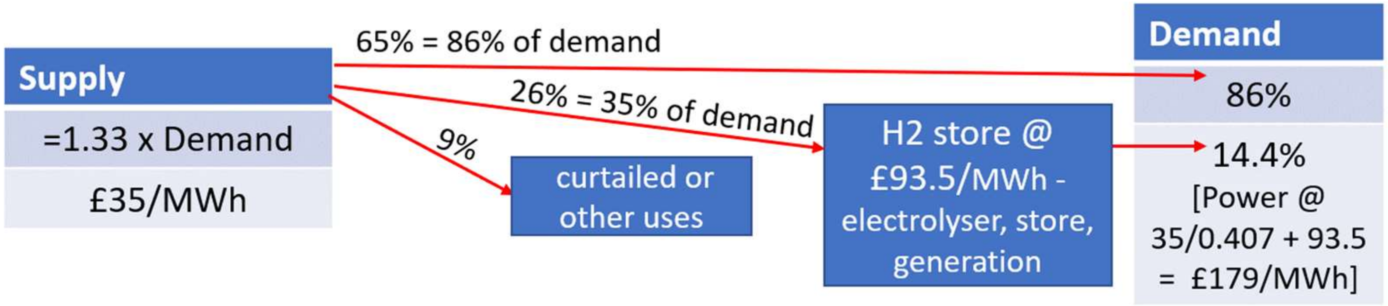
As Great Britain's electricity supply is decarbonised, an increasing fraction will be provided by wind and solar energy because they are the cheapest form of low-carbon generation

Acknowledgements especially due to: Tony Roulstone, Paul Cosgrove, Richard Nayak-Luke, Mike Muskett, Seamus Garvey, Nilay Shah, Phil Eames, Paul Shearing, Ian Metcalfe, Keith Bell, ...

- Wind and solar vary on time scales from minutes to decades → cannot meet all demand
  - times when there is none; times too much
- Must complement by storing excess for later use, *and/or* add large-scale low-carbon flexible sources
- Long-term variations in wind → **need to store 10s of TWh for many years/decades**: must have large component with low cost/energy stored - hydrogen is best option in GB
- First: study wind, solar and hydrogen storage (+ small amount of something - batteries? - that can respond very fast), which could do everything → benchmark against which to judge other options

  although adding some more expensive but more efficient storage probably lowers the cost, and there will be some nuclear, biomass, hydro, interconnectors
- With wind + solar supply ≈ 1.33 x demand, 86% of demand can be met directly with wind and solar

  the missing 14% must be met by making use of and storing most of the excess:



Average cost of electricity fed into the grid

£(1.33 x 35 + 0.144 x 93.5)/MWh ≈ £60/MWh

+ cost of transmitting wind and solar to store (£3/MWh) & batteries (£1/MWh)

Relatively insensitive to cost of storage

- Whatever complements wind and solar must be able to meet full demand when wind + solar ≈ 0

  → very low load factor → ***alternatives to storage more expensive***
- Will investors be willing to fund the (essential – but expensive) large-scale storage that will be needed?

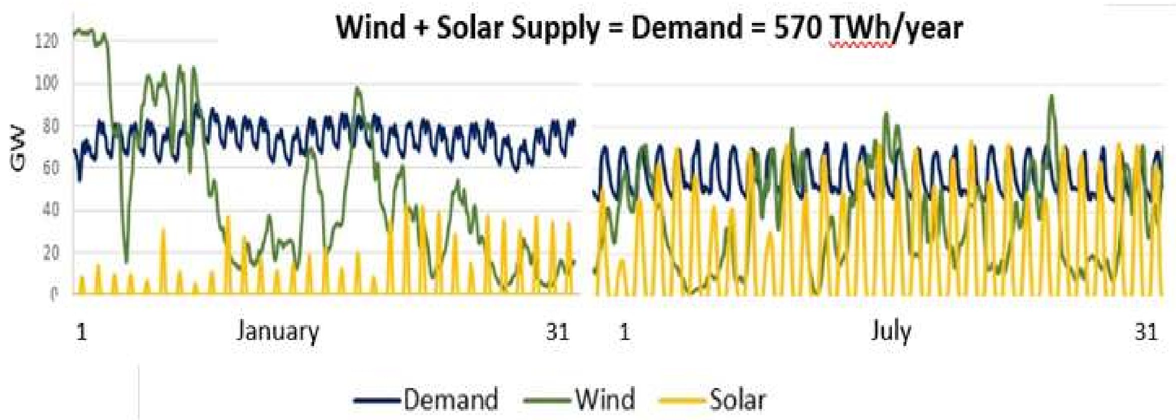
Volatility:

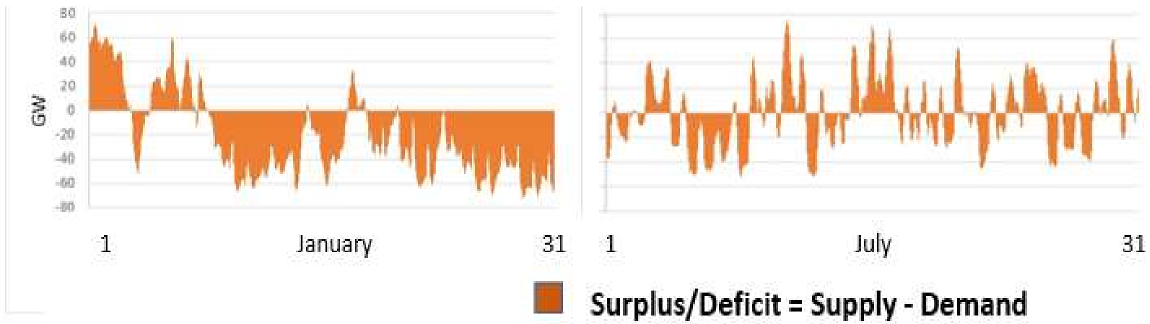
Variability of wind and solar in the

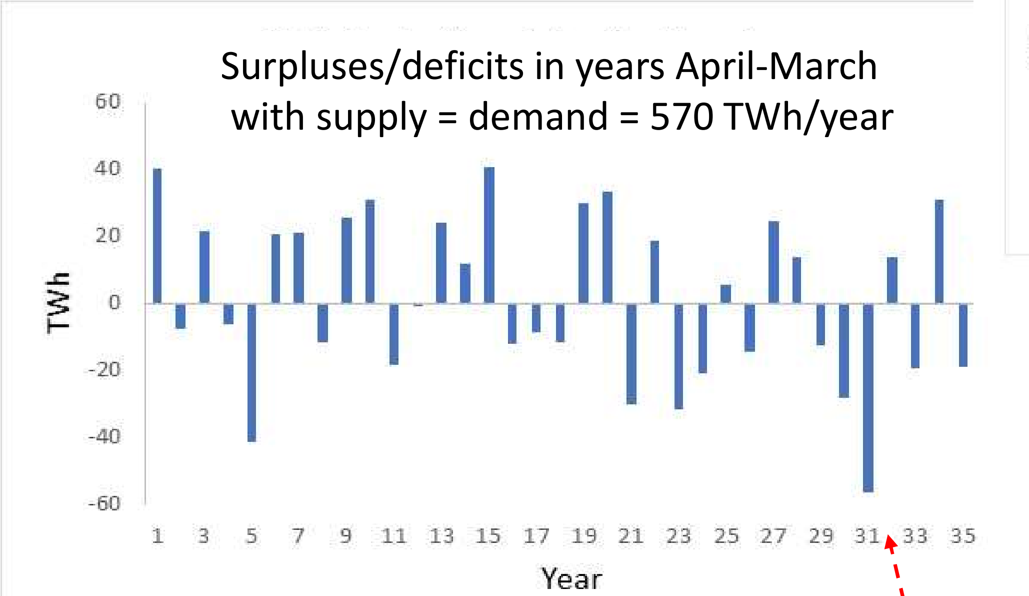
- short term:

and

- long-term:







storage that supports high wind + solar must include a multi-TWh component able to store energy for many years

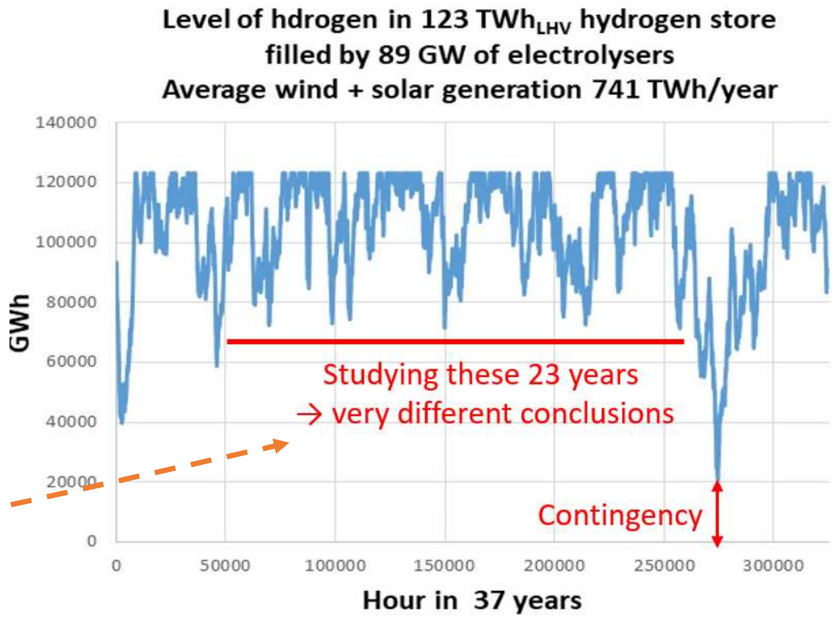
For model of 570 TWh/year 2050 demand → next slide

Wind (80%) & solar (20%) based on real GB weather data (details → next slide) for

1992 – Above

1980-2016 - on left

Modelling



Need: hour by hour (best resolution available) models of

- wind + solar supply ← Ninja Renewables data for 1980-2016
  mix wind/solar – 80/20
- demand ← AFRY model of 570 TWh/year: into the grid, without electrolysis

Issues

Supply: is 37 years enough? **No** – Met Office +
→ add 20% contingency (→ + £1/MWh)
Climate change: effect uncertain - hope covered by contingency

Demand: repeat 37 times, so no detailed weather/demand correlations (models → effect small)

Level - models with 440/700 TWh/year (with very different profiles): cost of power changes < 2%

Procedure:

- trade-off: size of store/rate of charging
- scheduling with several types of store: later

Large-Scale Electricity Storage Technologies

Technology	Unit Capacity	Round-trip Efficiency	Technology Readiness Level + Comments
Cycle time: minutes to hours – limited by need to recover investment			
Batteries	Largest today 1.6 GWh	$\lesssim$ 90%	Lithium-ion + some other chemistries - TRL 9
Cycle time: up to weeks, in some cases months			
Flow batteries	Single battery many GWh	70-80%	TRL 7-8
ACAES	Single cavern $\lesssim$ 10 GWh	$\lesssim$ 70%	Compressors, Expanders, storage caverns and thermal storage TRL 9. Complete systems 7-8.
Carnot battery	GWh	$\lesssim$ 45%	TRL 7 with resistive heating
Pumped Thermal	< GWh	50%	TRL 4-6
Liquid Air	< GWh	$\lesssim$ 60%	Systems in operation - TRL 8. Larger/more advanced systems – TRL 7
Able to provide months or years of storage			
Synthetic fuels	Single tank ~ TWh	$\lesssim$ 30%	TRL 7-9 - outclassed by ammonia and hydrogen for electricity storage
Ammonia	Single large tank ~ 250 GWh	$\lesssim$ 35%	Production and storage - TRL 9. Conversion of pure ammonia to power – TRL 5. More expensive than hydrogen, but could be deployed across GB
Hydrogen	Single large cavern 200 ~ GWh	~ 40%	Electrolysers, storage caverns and PEM cells - TRL 9. Conversion to power by 4-stroke engines TRL 6-7. Potential onshore storage sites limited to E Yorkshire, Cheshire and Wessex.

details follow

Hydrogen 1 – Electrolysers

2050 assumptions from IEA, IRENA, industry sources

	Alkaline		Polymer Electrolyte Membrane		Solid Oxide	
Availability	Commercially available for many years		Commercially available but potential for improvement		Not yet demonstrated at scale	
Load following	Can follow		Can follow v fast transients < 1 sec		Ability depends on the design	
	IRENA	IEA	IRENA	IEA	IRENA	IEA
Efficiency Today	43-67%	63-70%	40-67%	55-60%	61-74%	74-81%
IRENA 2050/ IEA Future	> 74%	70-80%	> 74%	67-74%	> 83%	77-90%
Cost $\$/\mathrm{kW}_e$ **Today**	500 - 1000	500 -1400	700-1400	1100 – 1800	> 2000	2800 -5600
2050/Future $\$/\mathrm{kW}_e$	< 200	200-700	< 200	200-900	< 300	500 - 1000
**** In their simulations, IEA assume a future cost** $\$450/\mathrm{kW}_e$ **and efficiency of 74%**						
Lifetime today (1000s of operating hours)	60	60-90	50-80	30 -90	< 20	10-30
2050/ Future	100	100-150	100 -120	100 - 150	80	75-100
Output Pressure – bar. Today	< 30	1-30	< 70	30-80	< 10	1
2050/ Future -bar	> 70	-	> 70	-	> 20	-

Could be reversible

Limited by availability of iridium

Alkaline: need to operate above 20% of min. current + switch on/off frequently: probably not an issue

Assume 74% (results not v sensitive)

Full system costs: v dependent on module size + scale of manufacture
Assume $450/kW +/-50%

~ find 30% load, so these #s → 30 years

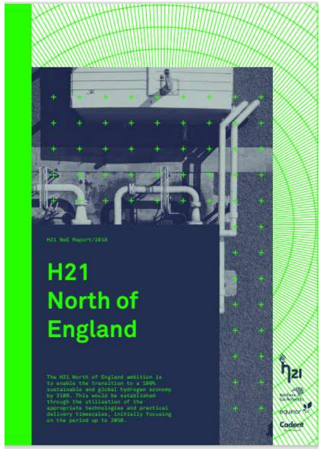
Assume 30 bar (impact on compression needed pre-storage)

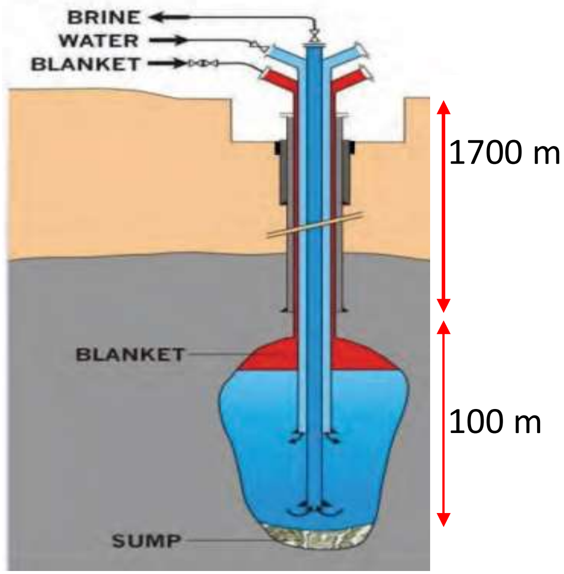
Hydrogen 2 Underground Storage

Costs from H21 NE study of clusters of 10 x 300,000 m^3 of solution-mined salt caverns in E Yorkshire (sharing common surface facilities)

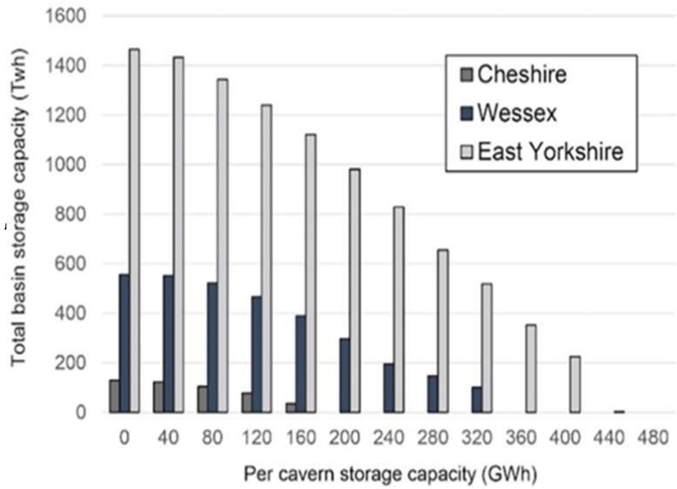
→ each cluster stores 1.22 TWh$_{LHV}$ of usable hydrogen at £247/MWh$_{LHV}$

Given lack of recent experience + underground hazards, assume low/base/ high values of £247/371/494/MWh





Potential capacity much more than adequate:



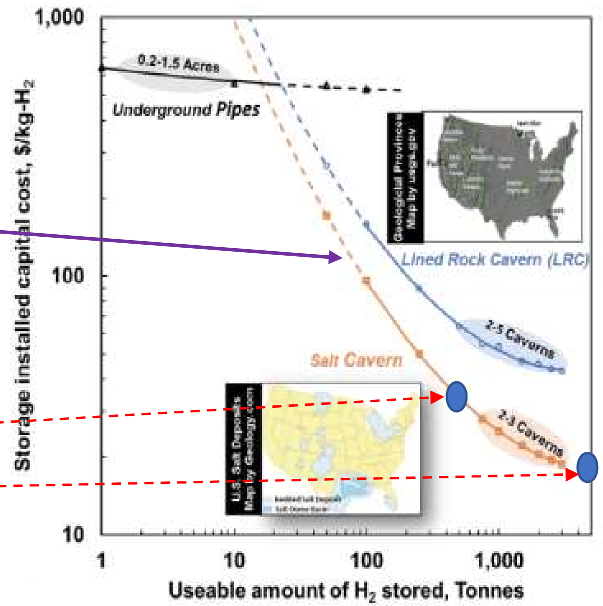
Comparison with other estimates difficult - cost depends on geology, geography (distance to brine disposal), and **size:**

£/mass stored ~ 1/√(mass stored)

[Argonne study for DoE – almost only one with enough detail to allow comparison]

This accounts for apparent differences in literature - MIT study

- H21 NE



Hydrogen 3 Conversion to power

- **PEM cells**

DoE → cost of 237 kW_e stacks designed for use in heavy goods vehicles, produced at a scale of 20 GW/year, could fall to \$86/kWe

Cells designed for use in power generation will be more expensive - won't be manufactured at such a large scale, balance of plant costs have to be added, and different constraints

Less work on cells for power generation:

NREL→ future low/medium/high costs of \$340/425/528/kW_e (including 50% mark up and 25% for installation)

cheaper than turbines

- **4-stroke engines**

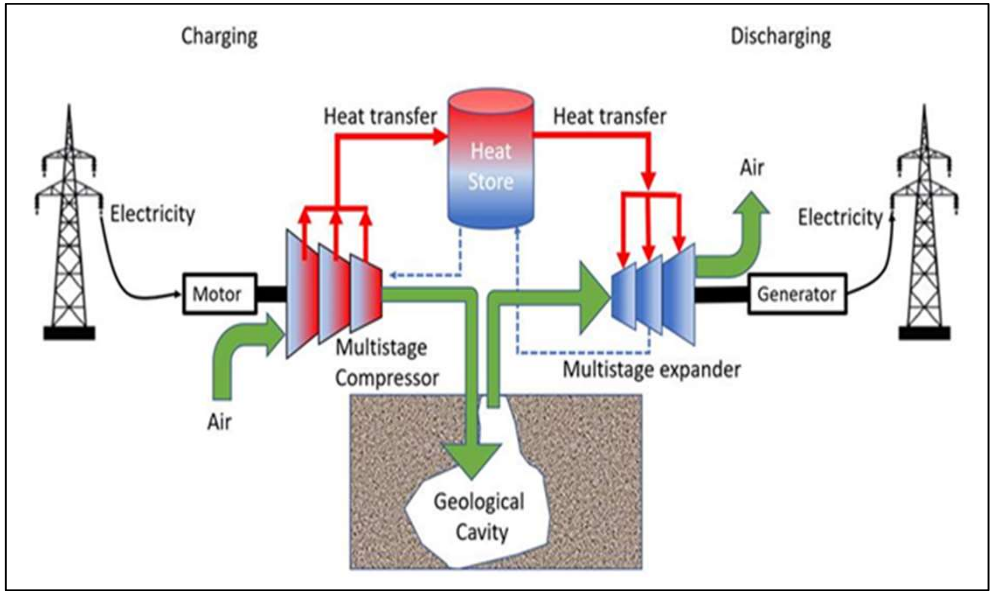
Could be cheaper that PEM (input from expert at BP + discussions with JCB)

Assume 55% efficiency, low/medium/high costs of \$300/425/637/kW_e

ACAES – studied in own right + as exemplar of class of stores

Two grid-connected ACAES plants now in operation in China

- 40 MW_e/300 MWh_e plant (operating since May 2022)
  air stored in a salt cavern, heat in thermal oil
- 100 MW_e/300 MWh_e plant (operating since September 2022)
  air stored in a mined cavern, heat in supercritical water



Cannot give generic cost: depends on

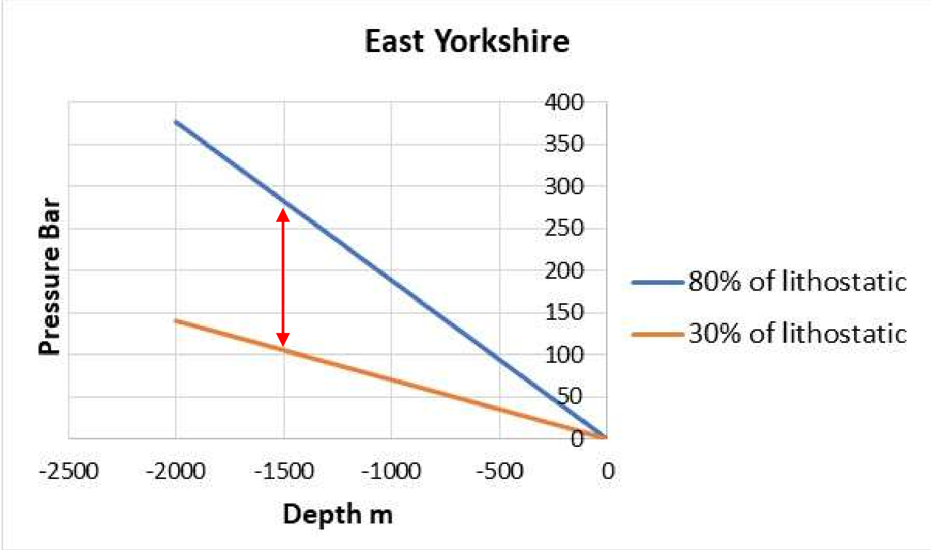
- **pressure range** (~ depth, unless in solid rock or container)
- **design:** # of stages of compression and expansion, how heat (*stores most of energy: compressed air mainly stores exergy*) is stored

  assume multistage compression → limits temperature rise → store heat of compression in water (much cheaper than molten salts)
- **size of compressors:** rule of thumb → cost ~ (power rating)$^{0.6}$

Underground capacity in GB

Perhaps enough for ACAES that would deliver 20 TWh_e/year – but this would start to encroach on other needs for underground storage

ACAES – Modelling and Cost Assumptions



Model 300,000 m^3 (H21) **caverns at 1000 m & 1700 m depth**

Split difference: each cavern absorbs 10 GWh work of compression in 6 stages. Expansion in 6 stages, supported by 7.5 GWh of thermal storage can deliver 6.8 GWhe

Costs - huge jump from 300 MWh to 6.8 GWh

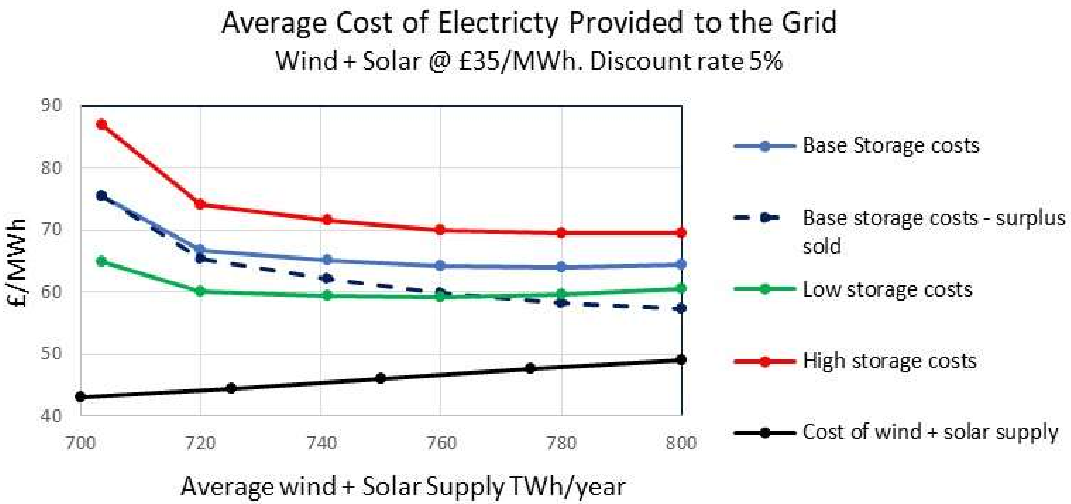
- **1.5 x H21 cost for clusters of caverns**, without H2 related costs
- **Water pit storage**: based on actual (full) costs from Denmark
- **Compressors/expanders**: have quotes from suppliers of $200/kW$_e$ for complete/crated 1 MW$_e$ systems (but not for UK safety standards)

  But want costs (which will fall when manufactured at scale) for six-stage ~ 60 MW systems, including cost of buying/preparing site, installation, share of management costs,...
- **Assume £(100-500*)/kW for ~ 60 MW**

  **conservative if 0.6 law holds – for very different systems, over range 1 to 60 MW*

+ 4%/year O&M

Results – H2 (+ battery storage) only



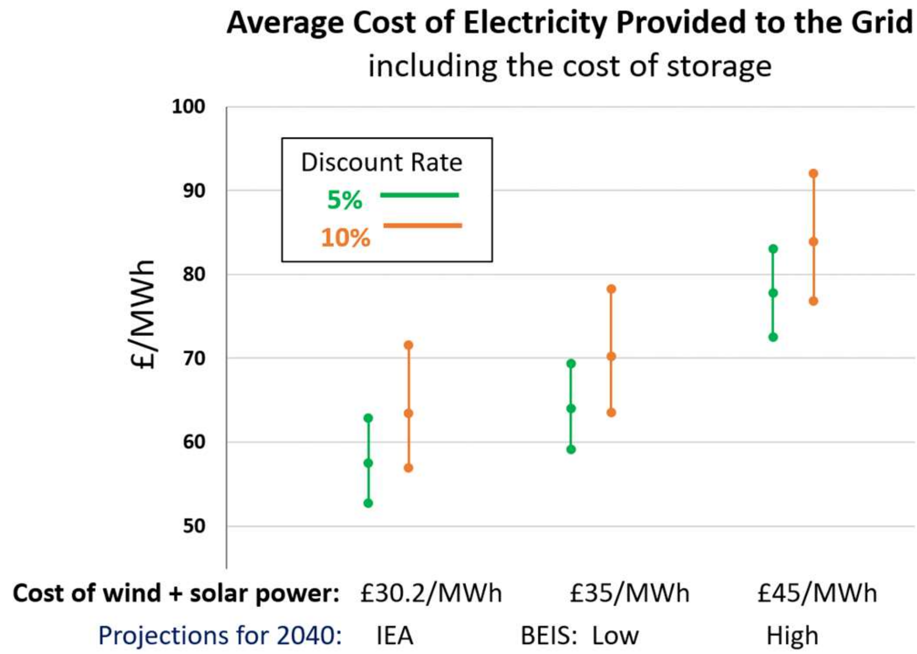
Includes £1/MWh for batteries → grid services + £3/MWh for transmission from wind/solar farms to stores + 20% contingency in size of store (adds ~ £1/MWh)

'Surplus sold' assumes 100% valued at £35/MWh - unrealistic & increasingly improbable as generation increases

Shown to indicate the scale of possible savings from co-production of H2 for multiple purposes or finding other uses

With other Wind + Solar costs

+ 5% & 10% discount rates:



Comparison: wholesale price around £46/MWh in last decade

Over £200/MWh in most of 2022

2021 prices

H2 (+ battery → rapid reponse) + baseload

Adding baseload will increase the average cost of electricity ***unless*** it costs *less* per MWh than the average cost per MWh without it. True of nuclear baseload, and of nuclear cogeneration (electricity when needed, otherwise hydrogen from steam assisted SO Electrolysers)

Ammonia only

Averge cost of electricity higher than with H2 only by > £5/MWh

ACAES only

More expensive than H2 only by 10 % or more + storage capacity probably not available + loss of stored heat

Hydrogen + ACAES - more efficient but higher volumetric storage cost

Need a procedure for scheduling their use. Studies in the literature use hindsight/assume perfect foresight

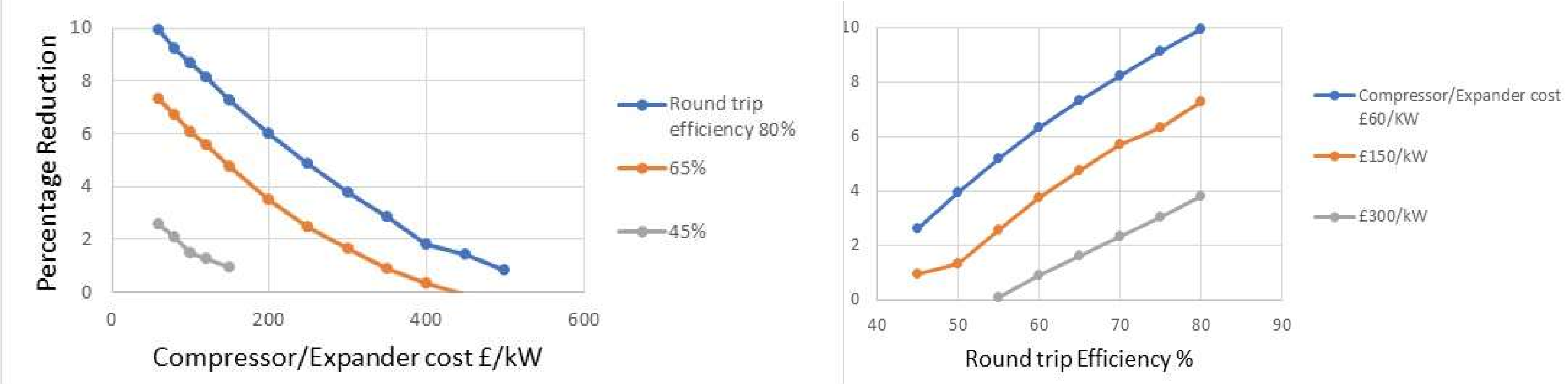
- Only worthwhile including ACAES if it lowers the cost of the H2 store by more than the amount it adds
- Most likely to happen if ACAES is normally* given priority in storing surpluses, and in discharging energy to fill deficits, since
  - *the more energy is stored in/delivered by ACAES, the smaller the size and cost of the hydrogen system*
  - *the lower the amount and cost wind and solar input as ACAES is more efficient*

* Following Zachary: when ACAES store is nearly full/empty shift priority in filling/discharging to H2 → small effect on the average cost of power, but changes demands on each store to absorb and provide power

ACAES + Hydrogen

- ACAES - *and other systems for which it acts as a proxy (with compressor/expander → power conversion)* - is cheaper than hydrogen alone for a wide range of possible costs and efficiencies:

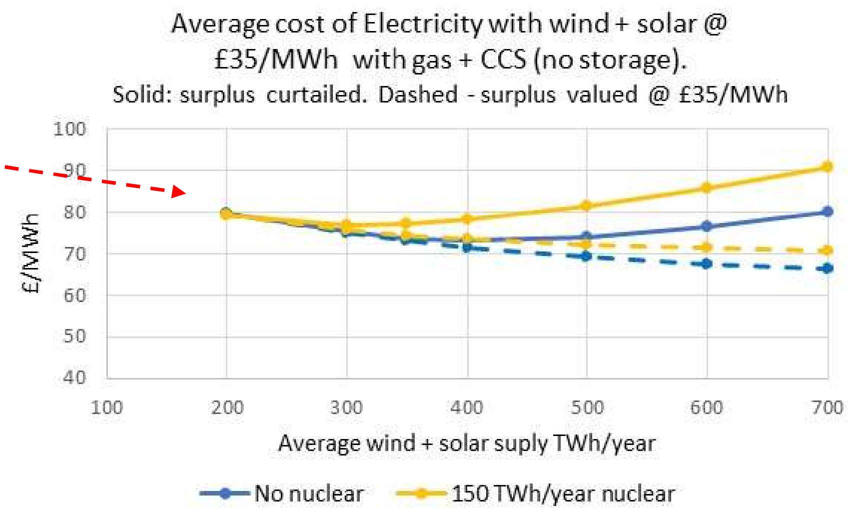
ACAES + Hydrogen Storage - Reduction in Average Cost of Electricity Relative to Hydrogen alone: for different ACAES Costs and Efficiencies

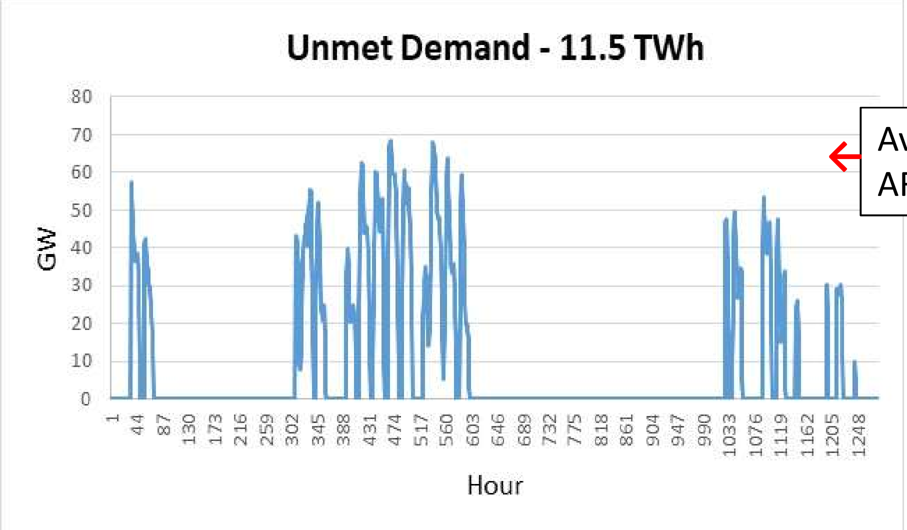


- Although the ACAES system has a much smaller capacity, it delivers more energy than hydrogen because it is cycled much more frequently, e.g. case in which H2 → 37 TWh_e /cycle, 36 TWh_e/year; ACAES → 2.4 TWh_e /cycle, 55 TWh_e /year
- Current markets could not deliver the degree of coordination between generators and operators of storage that will be needed to schedule the use of storage optimally

Additions and Alternatives?

- Li-ion batteries likely to be needed for rapid response, but for peak shaving/short term arbitrage they will be outclassed by ACAES & hydrogen when they are available (not necessarily true of flow batteries,...)
- Using Gas + CCS rather than storage to complement wind + solar → more expensive
- What if need for storage had been underestimated, and instead of building 20% extra storage (adding £1/MWh) 20% less had been built(saving £1/MWh)?





Average demand in AFRY model

Hard to cope with this. With long-term forecasts able to anticipate prolonged periods of low wind, 'preventive demand management' could help stop the store emptying: IEA gives examples, e.g. saving 14% over 9 months in California in 2002

Further steps

- **Whole-system modelling that take account of**
  - location of demand, supply and storage → implications for the grid
  - contributions of nuclear, hydro, biomass, interconnectors
  - other needs for green hydrogen (on which opinions differ widely) - requires model of temporal profile & flexibility. Will lower cost.
- **Work on**
  - markets that will incentivise the deployment of large-scale storage & insure it's there when needed
  - scheduling with several types of store and flexible sources: use long-term (as well as weather) forecasts,...
  - scale of the need for contingency (need to take better account of correlations between weather and demand)
  - cost estimates: need underpinning by detailed engineering estimates
- **Better estimates of investments & timing:** in 'only hydrogen' case with 570 TWh/year demand:
  - ~ £210 bn for wind (130 GW)+ solar (150 GW) - BEIS projections for 2040 commissioning in 2040:need before CO_2 emitting sources are switched off: looks possible by 2050 but rate of installation will have to increase
  - ~ £100 billion in hydrogen production, storage, conversion
  - ~ £100 billion (according to the National Grid) to enlarge and strengthen the grid

Further Steps (continued)

R&D

- 'New science' can't make a major contribution by 2050, but important for the long term, e.g. cheap direct synthesis of ammonia from air and water would be transformative
- Meanwhile
  - Huge scope for improving existing technologies, and combining them in new ways, e.g. in wind-integrated-storage, reversible electrolysers/fuel cells and compressors/expanders
  - Reduce/eliminate iridium in PEM electrolysers (only [?] fundamental resource issue),...

Demonstrators → identify and solve integration issues

Start construction of large-scale hydrogen storage now. UK well positioned:

- **Electrolysers:** INEOS → alkaline electrolysers for hydrogen production. ITM - PEM electrolysers. Ceres - design of Solid Oxide Electrolysers
- **Underground storage*:** H21 NE - poised in E Yorkshire. INOVYN - planning permission for a cluster of seventeen 350,000 m^3 salt caverns in Cheshire to store natural gas; applying for permission to store H2
- **Power generation:** Johnson Matthey + many other UK companies in supply chain for PEM fuel cells (and electrolysers). Ceres - design Solid Oxide Fuel Cells (could be reversible). JCB - have produced a prototype four-stroke hydrogen engine

* currently not justifiable commercially: need encouragement/recognition of need for large-scale storage. **Meanwhile** ACES Delta (with $500 million of debt financing from the DOE) → 'world's largest renewable energy hub' in Utah: will store 5,500 tonnes of hydrogen (in a salt cavern), with over 450 t/day provided by over 1 GW of electrolysers

Conclusions

GB’s 2050 electricity demand could be met largely (even wholly) by wind and solar supported by large-scale storage, at a cost that compares very favourably with cost of using the only large-scale low-carbon alternatives - natural gas generation with CCS and nuclear (both expensive - especially if operated flexibly)

Need

– **Government to recognise the need for large-scale storage & provide the incentives/guarantees required to incentivise investment**

– **Get on with it**

Wind + solar + hydrogen storage

→ **upper bound.** Adding other types of store very likely → lower cost, as will coproduction of hydrogen for all purpose