

Hydrogen and Energy Storage

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Hydrogen is being widely discussed

It could conceivably play a role in providing space heating

It is likely to play a role in

- Providing industrial (process) heat
- Parts of Transport
- Reducing iron ore to iron

and **large-scale storage of electricity**

Energy systems need storage to buffer mismatches in supply and demand

For UK electricity, the buffer has mainly been provided by natural gas (15 TWh in store in 2018) but it's going, while *mismatches will increase as the roles of wind and solar grow*

Major growth in wind and solar expected because

- they are cheap: for 2050, will assume £35/MWh (the weighted average of BEIS's low 2040 projection for the mix of wind – on and off shore – and solar used)
- in the UK there are only three other large-scale low carbon sources of electricity:
gas + CCS (Fugitive CO₂ & CH₄? Limits scale), nuclear (Cost?) , BECCS (Resource?)

Outline: focus mainly on Power ↔ Hydrogen

- **2050 outlook for full system costs of***

- Power → hydrogen: electrolyzers
- Hydrogen storage in salt caverns
- Hydrogen → power: gas turbines, fuel cell, four-stroke engines

- **How much storage will be needed?**

Analysis** based on 37 years of hour-by-hour wind and weather data and an hour-by-hour model of 2050 demand: easy to say how much energy will have to come from store, *but volume of store depends on how rapidly it can be filled, the demand for power to be met and efficiencies*

Methodology → cost of powering the UK securely with renewable energy + hydrogen storage in 2050 with/out base load (nuclear?)

- **Cost with batteries, Adiabatic Compressed Air Energy Storage*** and hydrogen**

- **Open issues**

* work with Nilay Shah and Mike Muskett as part of Royal Society study of large-scale storage

** work begun, as part of RS study, with Tony Roulstone and Paul Cosgrove: after slide 8 results are new

*** ACAES costs studied with Phil Eames, as part of RS study

Power → Hydrogen. Electrolysers*:

Alkaline	Polymer Electrolyte Membrane	Solid Oxide
Commercially available for many years Can load follow	Commercially available but still potential for improvement Can follow v fast transients < 1 sec	Not yet demonstrated at scale 700-800 C. Ability to load follow depends design. Ceres steel backed cells - operate at somewhat lower temperature - can do so
Full systems cost (with rectifier, balance of plant) some \$900/kW _e		

Future: PEM cells uses iridium catalyst – expensive/supply limited: urgent need to reduce Ir content or find alternative. Platinum probably (?) not a serious concern

Long-term values IEA	Alkaline	PEM	SO
Efficiency % (LHV)	70-80	67-74	77-90
Capex/kW _e	200 -700	200 -900	500 -1000

Following literature review, decided to **use 74% efficiency and \$450/kW_e in 2050 costings**

* thanks to Marcus Newborough (ITM) and Mark Selby (Ceres) and others for discussions

Salt Cavern Stores

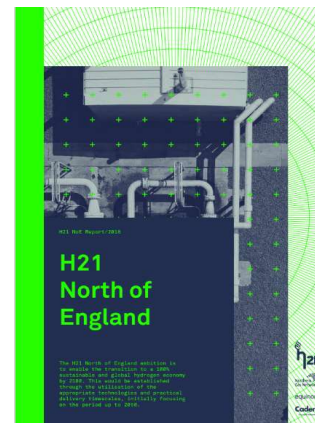
- Is the potential big enough? Yes, by a very large margin

Recent British Geological Survey report (thanks to John Williams et al for early sight) → theoretical estimate of 1875 TWh in the East Yorkshire region, 812 TWh in the Wessex Basin and 284 TWh in the Cheshire Basin

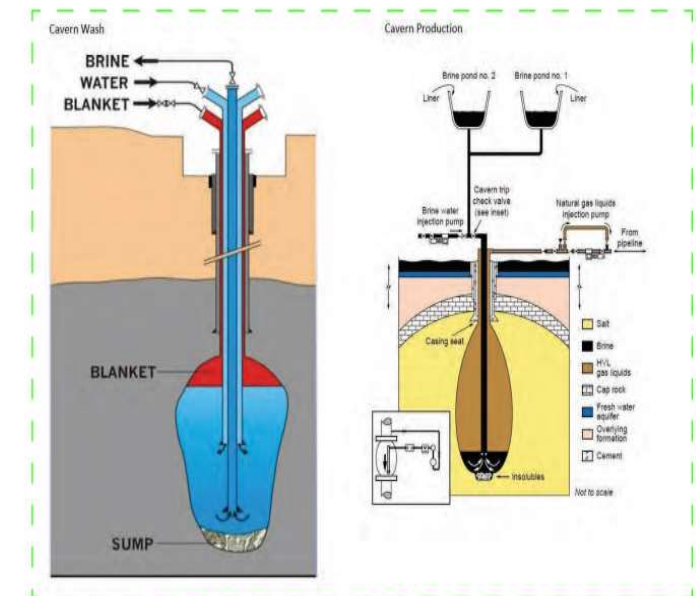
- What will it cost?

538 page report (thanks to Dan Sadler for discussions) and provides a detailed analysis of the costs

Ten 300,000 m³ salt caverns, with a common surface facility, at depths of 1,700-1,800 m at up to 240 bar, which together would house 1.44 TWh of hydrogen (not including 0.7 TWh cushion gas) would cost £325M, or **£226/MWh_{LHV}** for the useable 1.44 TWh_{LHV}



describes how caverns are made



Hydrogen → Power. Options:

2020	SO Fuel Cells	PEM Fuel cells	4-stroke ICE	OC GT	CC GT
Fuel flexibility	H ₂ / CH ₄ / NH ₃	H ₂ only	H ₂ / CH ₄ /NH ₃	H ₂ / CH ₄ / NH ₃	H ₂ / CH ₄ / NH ₃
Load following response	Seconds	Milli-secs	Secs	Secs	Secs
Cost per kW [\$]*	900	900	400	713	1084 ^l
Efficiency	55% (H ₂)	55%	46%	34% ^l	54% ^l
Maintenance % of capital p.a.	1.0%	1.0%	3.0%	2.00%	2.00%
Lifetime [hours]	60000	100000	80000	80000	80000
Scale today [MW]	0.1-1.0	1.0	10 to 100's	100	1000
Fuel to power efficiency	55%	55%	45%	34%	55%
*for H ₂ with SOFCs, CH ₄ or H ₂ with 4-stroke ICEs, and CH ₄ with OCGT or CCGT. The cost would be higher with other fuels, perhaps by 25%for 4-stroke ICEs designed to run on NH ₃ .					

2050	SO Fuel Cells	PEM Fuel cells	4-stroke ICE	OC GT	CC GT
Fuel flexibility	H ₂ *	H ₂ only	H ₂ / CH ₄ / NH ₃	H ₂ / CH ₄ / NH ₃	H ₂ / CH ₄ / NH ₃
Cost per kW [\$]	425	425	300	713*	1084*
Fuel to Power Efficiency	65%	55%	52%	34%	58%
*Can also operate with CH ₄ , a H ₂ /CH ₄ mixture and NH ₃ , but at slightly higher cost and slightly different efficiencies					

- 4-stroke engines (increasingly used with natural gas – very flexible: 600 MW plant in Jordan) likely (?) to dominate in medium term (thanks to Richard Pearson, BP, for discussions), then fuel cells
- **In 2050 costings: assume \$425/kW_e, 55% efficiency**
- Reversible SOFCs could be a game changer: maybe 30% more expensive (rectifier..) but provide at least 2 kW of electrolyser power/kW of FC power (thanks to Mark Selby for discussions).

Hour by hour models of

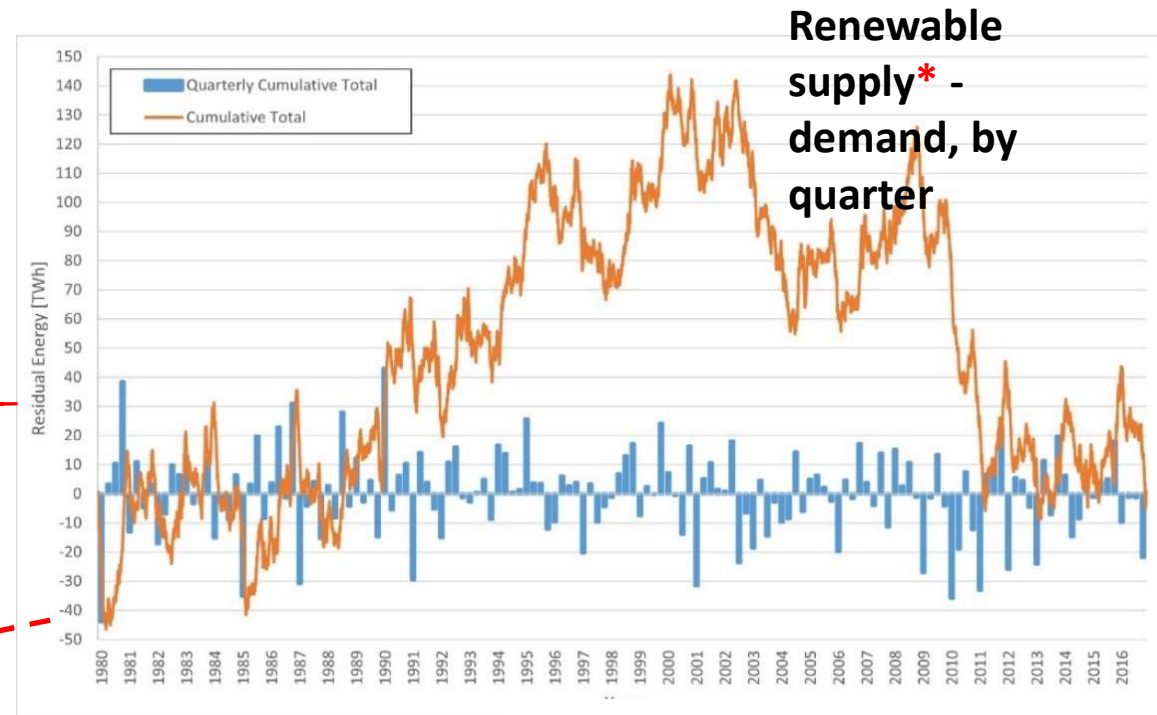
- **Wind + Solar***

Ninja renewables data 1980-2016

20% solar + 80% wind (3/7 on/offshore)
maximises power directly to the grid,
does not necessarily minimise cost (see later)

- **Demand**

Model of 2050 demand (570 TWh),
provided by AFRC/Poyry, repeated 37 times
- *correlation of weather and demand neglected*



One decade not enough

- are 37 years enough? No according to special study by Met Office: needs more work, meanwhile *include contingency*
- **what about climate change?** Experts not in agreement, except that interannual variability will increase → *more contingency*

*scaled to average 570 TWh/year over 37 years

Figure shows demand could be met over 37 years by renewables plus a 100% efficient, 190 TWh store, cycled very infrequently, with 122 GW electrolyser power (enough to store all surpluses)

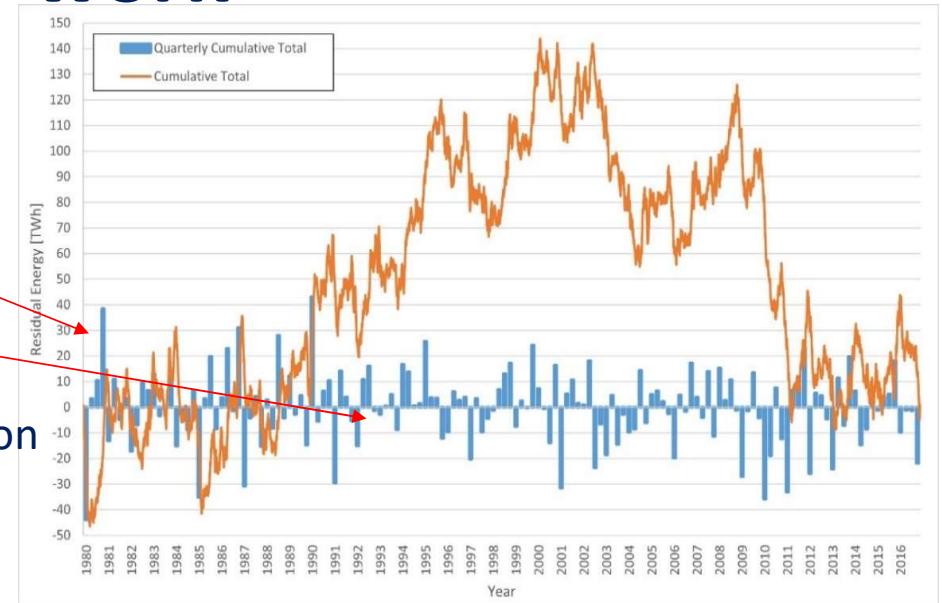
Need to increase level of renewable generation, to deal with inefficiencies, use store more efficiently, and reduce required electrolyser power

For 100% renewable system to work

- Need to increase renewable supply until
 $\sum \text{surpluses} = \sum \text{deficits} / (\text{round trip efficiency})$

requires hour by hour study of how surpluses increase and deficits decrease, some becoming surpluses

With the 75% x 55% efficiency assumed for hydrogen, this happens at 703 TWh/year average renewable generation not sensitive to demand model: scales with level of demand



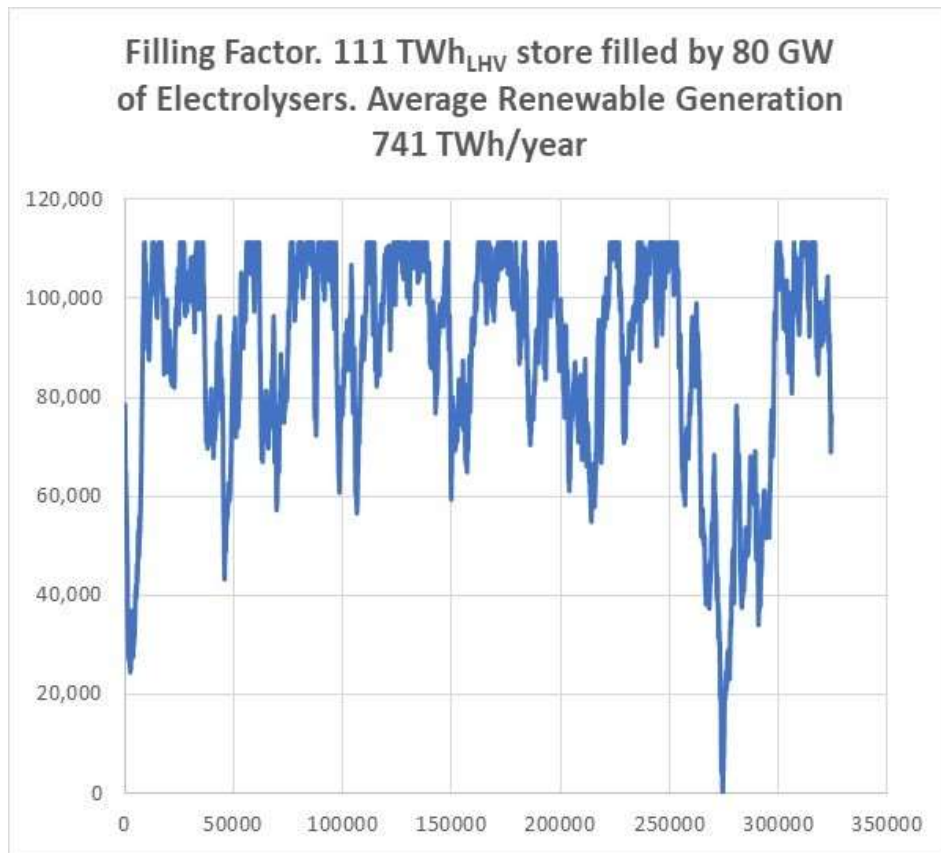
BUT

at the 'threshold' energy (703 TWh) the store is again cycled very unfrequently and need an unaffordable 168 GW of electrolyzers to absorb all surpluses

Need to go a bit higher in renewable energy

– will look at 741 TWh/year average = 1.3 x demand, 5.4% above threshold energy

Example with 741 (=1.3 x demand) TWh renewable generation in average year

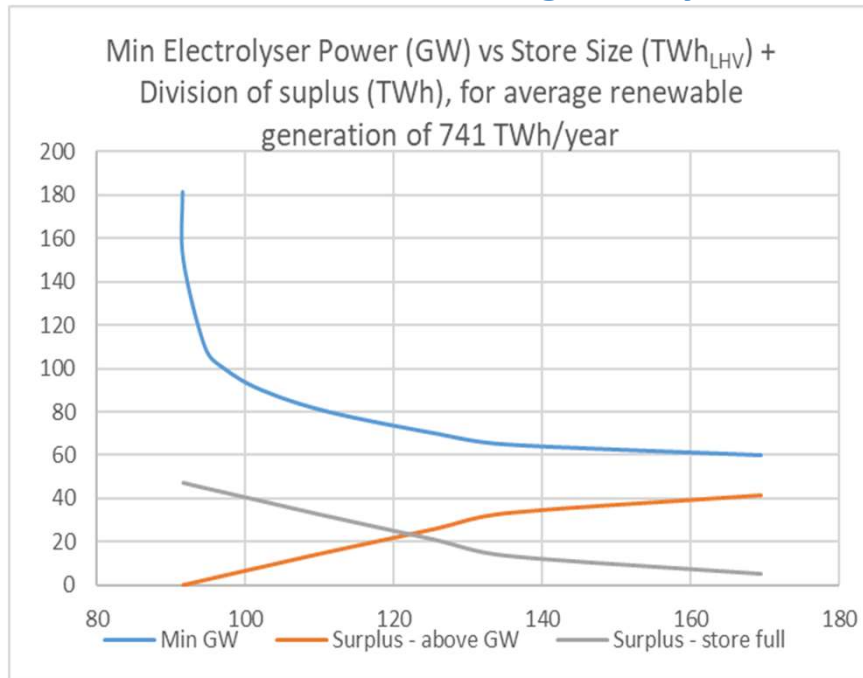


- Example shown with initial and final fillings the same – but would work provided store is initially > 47% full
- With less electrolyser power, filling could not keep up with depletion (at the rate needed to meet demand) during the ‘big fall’ after hour 250,000, *and it would **not** work.*
- If the store was smaller, the fall would start at a lower value *and it would **not** work* – **simple solution: make store bigger, by (say) 20%**

It also works for different combinations of Volume of store (V) and Electrolyser Power (G) – *choice should be based on costs*

Choice of Volume (V) and Electrolyser Power (G)

Need to be above blue line, given by model



Contribution to **average cost of energy** in £/MWh is (with 5% discount rate)

$$(18.1 * V \text{ TWh}_{\text{LHV}} + 26.7 * G \text{ GW} + 25.2 * P) / 570$$

P is power output (GW) – to meet maximum demand must be 100 GW without baseload; 82.9 with (e.g.) 150 TWh/year baseload

Adding 20% contingency to V, **cost is minimised at point on blue line where $18.1 * 1.2 * V + 26.7 * G$ is least** (V= 111 TWh, G = 80 GW – case shown without 20% contingency)

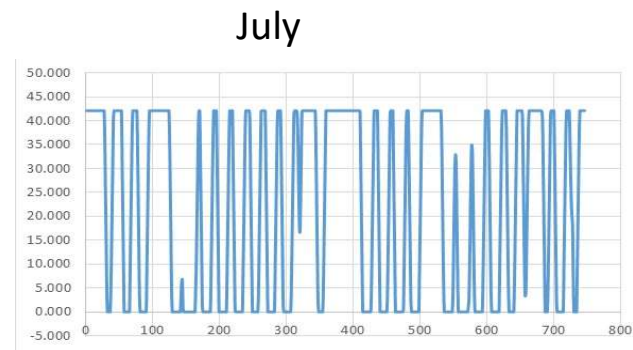
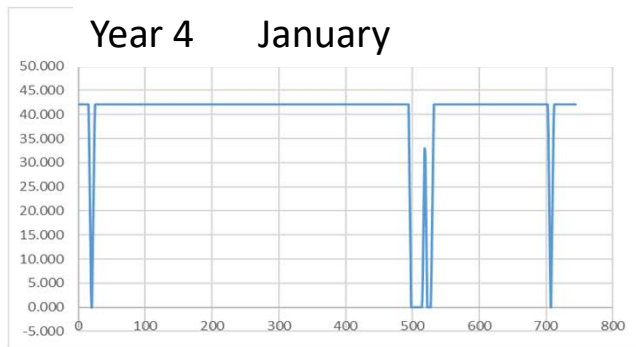
Average cost of power also depends on value (if any – for export, meeting demand that could arise to use it, making hydrogen for purposes other than storing electricity) of final surplus of

$$741 - 485 \text{ (demand met directly)} - 85 \text{ (residual energy at 741)} / 0.74 / 0.55 = 47.1 \text{ TWh}$$

Part of surplus that arises because store is full can be converted to hydrogen without additional electrolyzers

Choice of store Parameters

Hydrogen + Batteries - two parameters as power in and power out linked. Look at 40 GWh of 4-hour (i.e. 10 GW) batteries (1-hour battery 60% more expensive). Given priority in storing surpluses/filling deficits, with 741 TWh/year renewable generation, model → batteries deliver 6.94 TWh/year (174 full cycles/year) – out of 85 TWh needed from storage. Must reoptimize hydrogen parameters taking account of surpluses used/filled by batteries to get overall cost

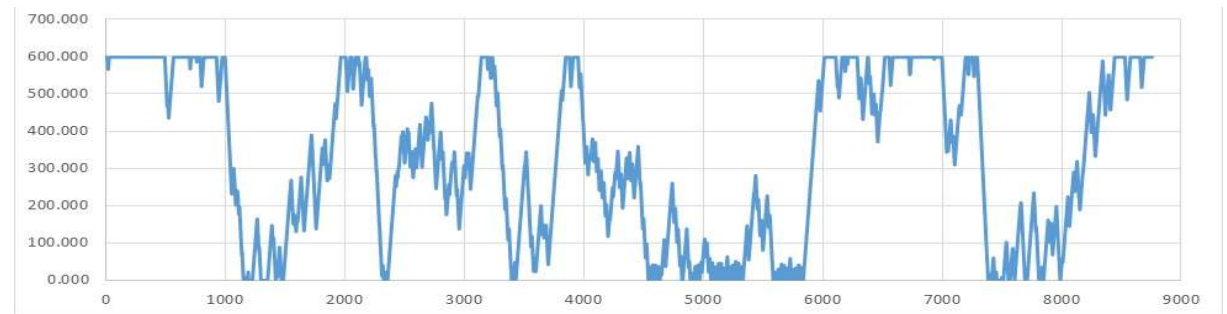


ACAES + Batteries – three parameters: volume, power in, power out – optimise with respect to P_{in} and P_{out} for a given V and then reoptimize hydrogen taking account of surpluses used/filled by ACAES → *will decrease in cost of hydrogen be larger than the increase from adding ACAES?*

1 TWh ACAES store
with $P_{in} = 10 \text{ GW}^*$, $P_{out} = 11 \text{ GW}^*$
delivers 25.5 TWh/year

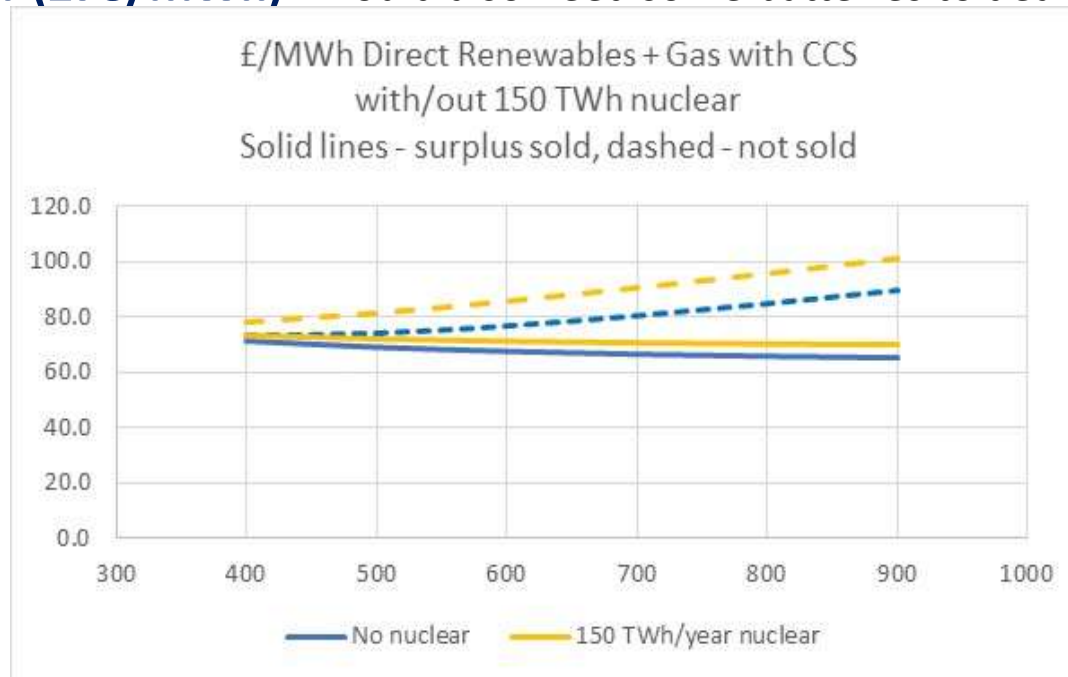
*pro rata: 50 MW, 55 MW for 5 GWh store

Year 4 **25.5 full cycle/year. Not fully optimised**



Average Costs - warm up

Direct renewables (no storage: surpluses curtailed) + gas with CCS (BEIS 240 costs)with/out 150 TWh/year nuclear (£78/MWh) - would also need some batteries to deal with short-term fluctuations



- Very sensitive to whether surplus sold (meaning: at assumed cost of £35/MWh) - sensitivity less with storage as part of surplus used
- Contribution to average of gas with CCS falls with renewable generation as part of cost is variable (fuel,...): fall also seen with storage as size of storage system falls

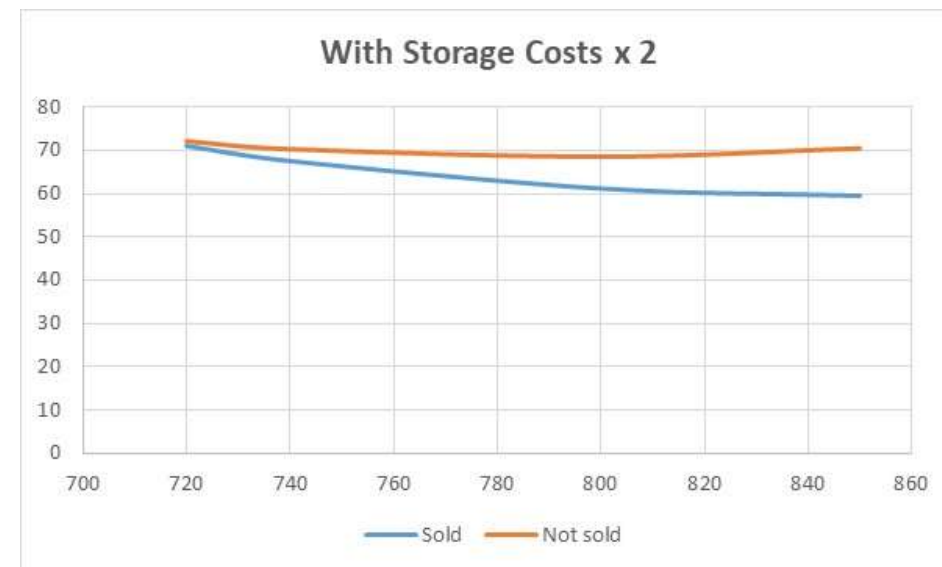
Costs – Hydrogen Store Only (will also need batteries)

Storage will also be used below threshold at which it can do everything – see later



Sensitivities

- 10% discount rate would increase cost by £7.8/MWh with 741 TWh/year renewables
- 20% → 40% contingency in store size → + £0.85/MWh with 741 TWh/year renewables!
- If storage costs used in plot on left too low by factor of two:



With Nuclear or Other Baseload

Lowers threshold for storage to work. Addition to average cost

X TWh/year nuclear adds $\text{£}(X \cdot 78 / 570) / \text{MWh}$

With $X = 150$: $\text{£}(\text{nuclear} + \text{hydrogen}) > \text{£hydrogen}$, but for $X = 50$ TWh costs similar at 741 TWh/year renewables

Suggests that a modest amount of nuclear may have a role. Should be considered together with the effects of adding other stores.

With other stores: results at 741 TWh/year renewables

- **Batteries + Hydrogen**

40 GWh* 4-hour battery (which delivers 6.94 TWh/year) changes average power cost by

$\$([1.2-1.5] \text{ batteries}^{**} - 0.76 \text{ hydrogen} - 0.8 \text{ if surplus sold}^*)/\text{MWh}$ *higher efficiency → larger surplus

* Nat Grid's 4 FESs have 56, 21, 23, 50 GW ** using our 2050 values, allowing for fade,....

- **ACAES + Hydrogen**

1 TWh ACAES storage, which delivers 25.5 TWh, changes average power cost* by

$\pounds(+ 1.7 \text{ ACAES} - 1.34 \text{ hydrogen} - 1.6 \text{ if surplus sold}^*)/\text{MWh}$ *higher efficiency → larger surplus

* with our (v uncertain) estimates of cost of: cavern (air mainly provides exergy) + heat store + compressors & expanders.

Actual cost £39 [89]/MWh without [with] cost of input power at 5% discount rate (55 [105] at 10%)

Maybe cheaper with larger store, but more interesting to look at:

- **Batteries + ACAES + Hydrogen**

Batteries + ACAES → bigger impact together than separately. At 741 TWh/year, average cost of power

Hydrogen alone £54.3 [57.2]/MWh if surplus sold [not sold]

Batteries + ACAES + Hydrogen £53.6 [58.5]/MWh if surplus sold [not sold] *with storage cost x 2: 66.5 [71.4]*

Won't show more results – exploring dependence on renewable generation, ACAES size, addition of nuclear, other merit orders (here: batteries > ACAES > hydrogen) *+ all needs an independent check*

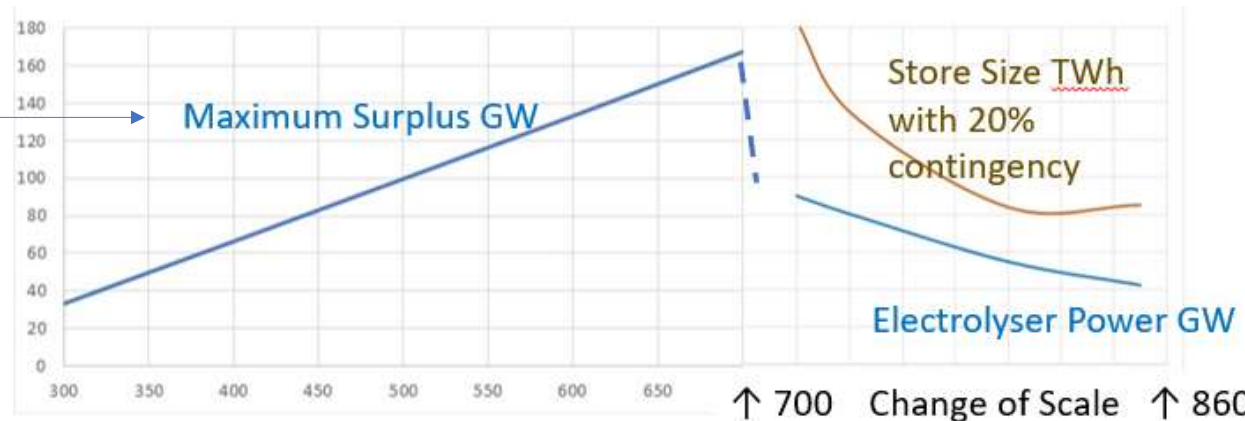
Below threshold for storage to do everything

- plots with 570 TWh/year demand, although demand and renewables will grow to 2050 level in parallel

- **Store all surpluses as hydrogen?**

Impractical – huge electrolyser capacity

Expect storage volume/electrolysers will build up slowly as gas is phased out to level at which storage can bear the brunt, e.g. in all renewable case 133 TWh_{LHV} store + 80 GW electrolysers at 741 TWh/year renewables (cost on next slide)

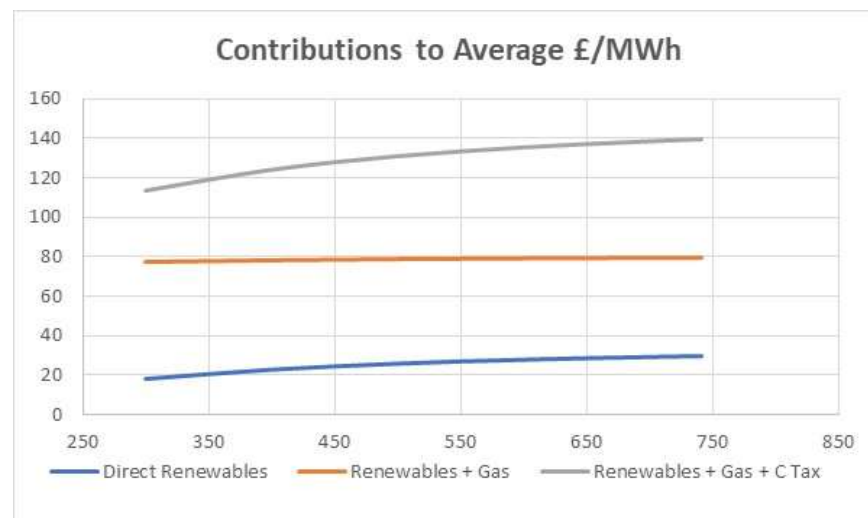


- **Curtail all surpluses?** ‘Business as usual’

Direct Renewable supply + unabated gas,
assumed fully flexible

**BEIS 2040 costs for gas
which include £190/t-CO₂ tax**

*Designed to discourage; could fund offsets,
but strong competition for limited capacity*



Could we get there by 2050?

- **Storage**

- **Technical barriers?** Location of storage relative to supply and demand, architecture of grid...
- **Financial barriers?**

Cumulative investment* to reach 80 GW electrolyzers** + 133 TWh store** + 100 GW generation

£(27 Electrolysers + 35 Store + 31 Generators) billion = £93 billion

5 x original (2016) Hinckley point estimate – spread over 30 years

**more than needed above 741 TWh – but would provide ability to turn most of surpluses into hydrogen for other uses and store it as necessary

With all Reversible fuel cells 133 → 110 TWh, £93 bn → £70 bn + ability to electrolyse all surpluses

* to link this to figures above note that they assumed a 30 year financial lifetime with 5% discount rate, and fixed O&M of 1.5% of Capex

- **Renewables**

To reach (e.g.) 741 TWh in 2050, 80% wind – 60 GW on shore, 75 GW off shore, 20% solar – 150 GW:

Wind: government aiming for + 30 GW by 2030 - need to increase rate by 50%

Solar: today adding about 1.5 GW/year - need + 5 GW/year

Investment (using BEIS projections for 2040) **£210 bn**

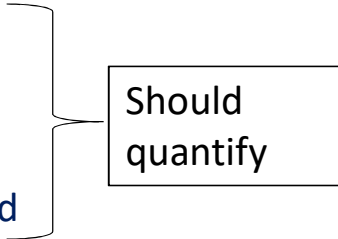
Issues/Questions 2

- **Different wind/solar mixes**

Looked at 10%, 20% (optimises use of renewables) and 30% solar. As expected, storage cost is (slightly) higher at 10% and 30%, but as solar energy will be cheaper 30% is cheapest (by a small margin) *if* surplus has no value

- **Contingency**

- Larger store
- North sea gas → power using 4-stroke engines or fuel cells already in place: needed rarely, so ignore CO2 – but expensive to keep gas supply open for rare use
- Feed imported ammonia* directly from tanker anchored offshore to SOFCs and 4-stroke engines
- Keep store of iron and use it to make hydrogen (by adding water), but as needed rarely keeping infrastructure for conversion expensive
- Import hydrogen from places (e.g. N Africa) where it will be very cheap to make, but importing as H2 expensive; if imported as ammonia need to keep infrastructure for conversion to hydrogen – expensive as rarely used
- Demand management – discussed in report: not practical for long periods



Should quantify

- **See forthcoming RS report for**

How the grid can cope with such high levels of renewables, market reforms/measures needed to increase coordination (investment and operational decisions) and encourage necessary investment

* Not favoured for storage of UK surplus electricity [$\text{£power/efficiency generation} \geq \text{hydrogen}$, £storage similar (maybe a bit less), *provided salt caverns available*; $\text{£power/efficiency production} > \text{hydrogen}$]

Conclusions

Note of caution – work in progress: checks needed, much more to do ...

- **Results** are **not** scenarios: they are inputs for scenario building, which provide encouragement by **suggesting that costs will not prevent powering the UK largely with wind and solar supported by storage**
- **Important future steps include:**
 - ❖ Building scenarios of transition from where we are today (2018: 352 TWh - 37% gas, 20% wind + solar, 18% nuclear, 11% bio & waste, 5% net imports...) to higher levels of renewables meeting growing demand with storage (batteries, ACAES or..., and hydrogen), supported by unabated gas (phasing out) nuclear and maybe some gas + CCS and BECCS, taking account of need to strengthen the grid...
 - ❖ Considering effect of geography – location of demand, renewable supply, storage facilities: note that I did not include interconnectors – will help cope with variability, but unlikely to lower the need for storage given the possibility of prolonged pan-European periods of low wind and sunshine