Large-scale Electricity Storage

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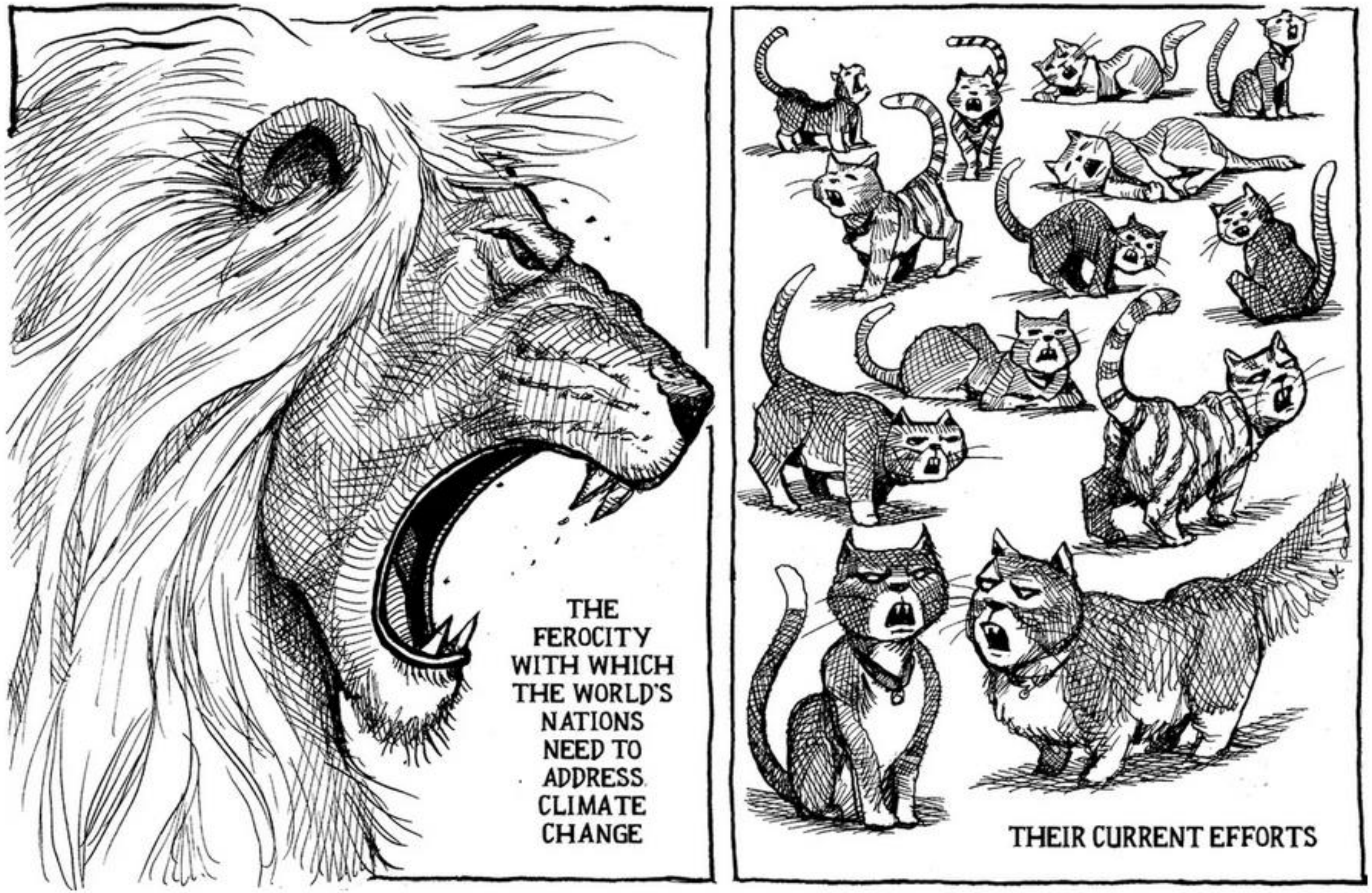

The Economist
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Large-scale* Electricity Storage

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

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- Context
- Highlights of the Royal Society study of Large-Scale Electricity Storage
  - which is available at royalsociety.org/electricity-storage
- More on Methodology
- More on Technologies
- More on Markets/Governance
- Conclusions

Context 1

- **We use final energy to** Provide heat ~ 48%
  Power transport ~ 32%
  And in the form of Electricity ~ 20%

  Allowing for inefficiencies, the calls on of primary energy are ~ 40% electricity, 35% heat, 25% transport

- **As fossil fuels are phased out** (in transport, space heating, providing industrial heat...)
  - an increasing share of the world's growing demand for energy will be provided by electricity and as electricity supply is decarbonised
  - an increasing fraction will be provided by wind and solar

According to (e.g.) **the International Energy Agency's *scenarios* in 2050**

	Stated Policies	*Announced Pledges*	*Net-Zero*
Electricity/all final energy, 20% today →	28%	39%	52%
Wind + solar/all electricity, 11% today* →	46%	61%	71%*

*+ 11% hydro, 8% nuclear, 4% **B**io **E**nergy with **CCS**, geothermal 2%, 2% gas & coal + CCS, 2% H2 & NH3

*In 2022: in UK Wind 26.7%, Solar 4.4%; in the EU Wind + solar 22%

Conclude: decarbonising electricity is key to decarbonising the energy system

- wind and solar will play a vital role

Context 2

- Wind and solar vary on time scales from minutes to decades. Can install more than enough to meet demand on average, **but** *there are times when there is none*
- Electricity supply and demand must *exactly* balance at all times – or the lights go out
- Must complement large-scale wind & solar by storing excess for later use

  and/or adding large-scale zero or low-carbon flexible sources (nuclear, BECCS, gas + CCS*****, hydro in some countries, ...) *not zero emissions: fugitive CO_2 + upstream methane leakage

  aim for a minimum-cost genuinely net-zero electricity system (if possible – *it is*)

  - reserve off-setting for harder to abate sectors
- Wind + solar cheapest form of generation – but storage is expensive
- The need for, and provision of, storage depends on climate, geography, and geology

Focus first on storage in Great Britain* in 2050

– although methodology and conclusions on technologies are general

- Approach: start by identifying essential large-scale storage needs for zero carbon power in 2050, before considering how to get there. Working forward may not lead to the right destination.

*not UK; N Ireland's electricity grid is integrated with the Republic of Ireland's

The Need for Storage 1

- To evaluate the need for flexible supply/storage: must **compare** hour by hour (best resolution available) **models of**

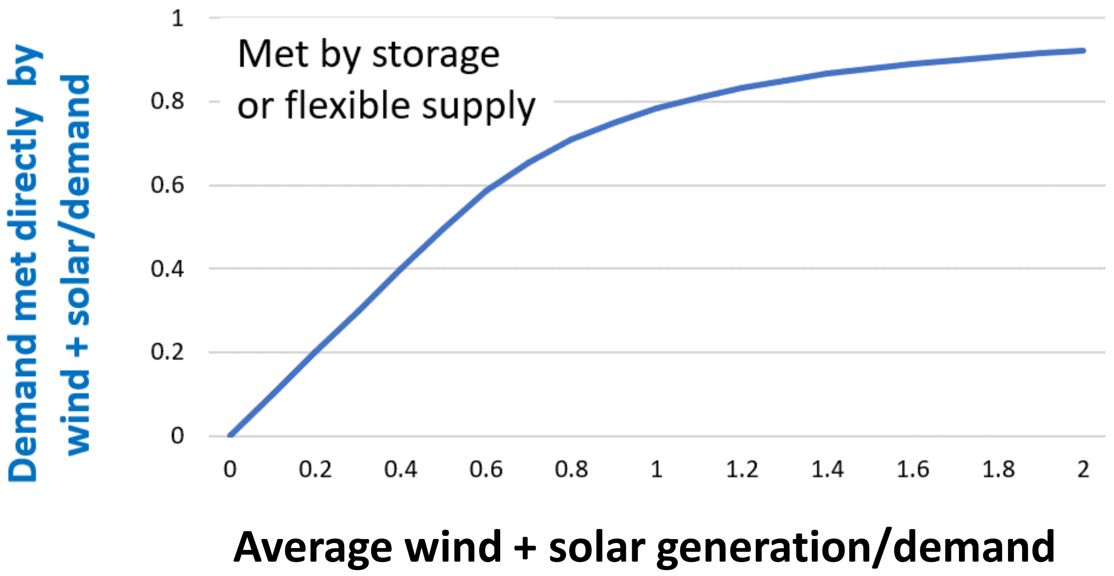
  - wind + solar supply (Ninja Renewables data for 1980-2016*, 80% wind/20% solar - minimises curtailment)

  and

  - demand (AFRY model of 570 TWh/year ≈ 2 x today: with higher and lower levels find very similar average costs of electricity)

* Studies based on less than several decades of wind and solar supply seriously underestimate the need for storage *and* overestimate the need for wind and solar and other flexible supply

- However much wind and solar are installed they can never meet all demand directly:

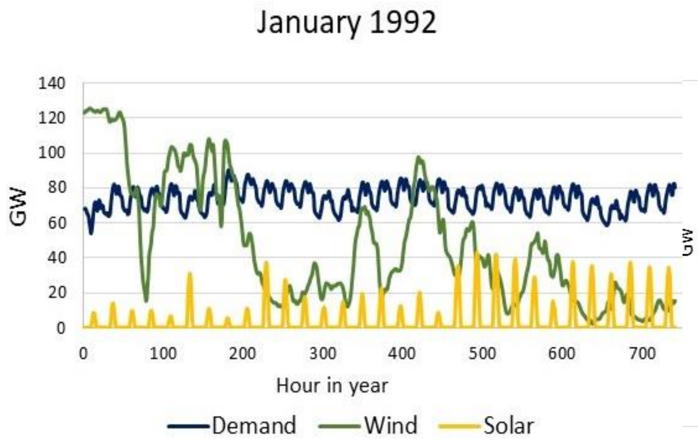


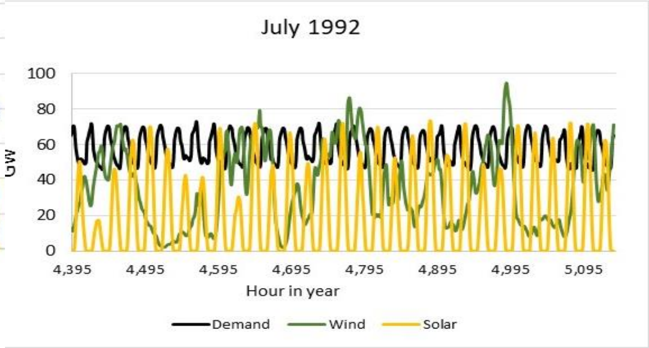
The Need for Storage 2

Storage is needed to cope with the variability of wind and solar

With average wind (80%) + solar (20%) supply = demand = 570 TWh/year:

- in the **short/ medium term**:



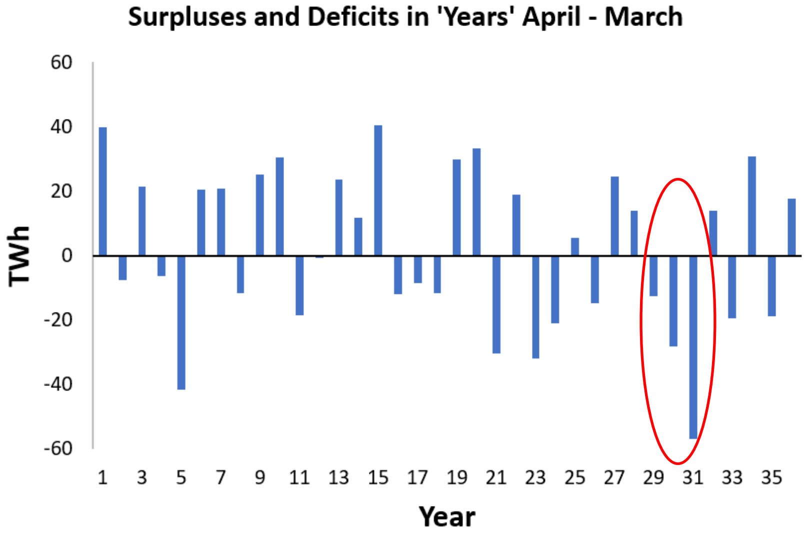


- this is the focus of most studies of storage

- in GB with 80/20 wind solar, the winter and summer deficits are *both* ≈ 0 averaged over 37 years.

Volatility, not seasonality, is the issue.

- in the **long term**:



Wind varies on scales of decades, depending on the phase and size of the North Atlantic Oscillation

Need to store tens of TWh for decades (true also with inefficiencies)

→ ***large amount of storage with low cost/energy stored** - **hydrogen stored in solution-mined salt caverns is the best option in GB***

Could not conceivably be provided by batteries

1000 times more that GB's pumped hydro capacity

Start modelling storage in ‘**Benchmark Model**’

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 for 2050**

although (see later) adding some higher capital cost but more efficient storage may lower the cost, and there will be some nuclear, biomass, hydro, interconnectors, and perhaps gas with CCS

Energy is lost in converting electricity to a storable form, e.g.

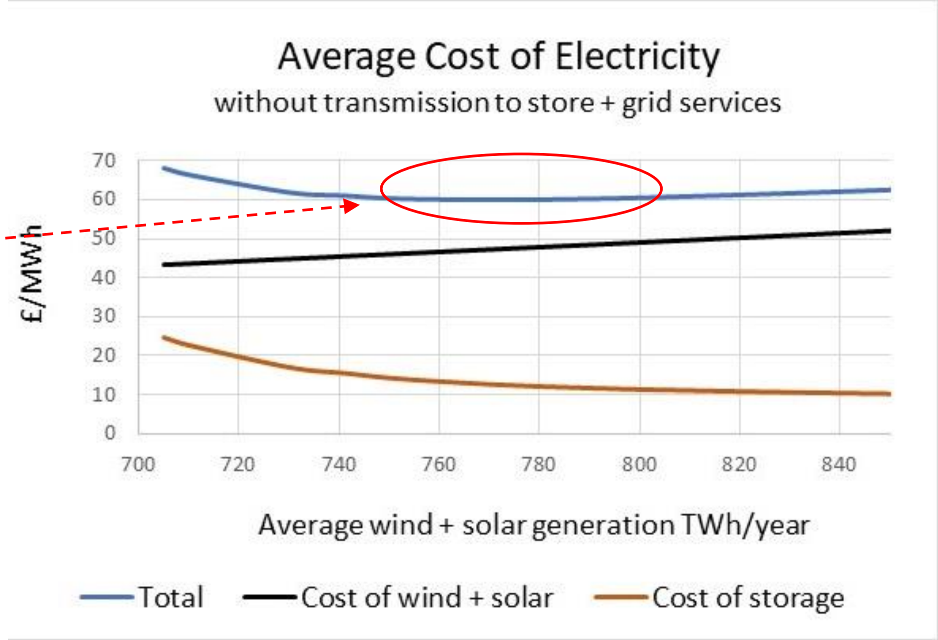
electricity → hydrogen: 74% efficient (2050)

hydrogen → electricity: 55% efficient (2050)

→ need to over-build wind + solar supply (by > 23% in this case) to allow storage to meet demand. *Does not change the need to store 10s of TWh for decades – next slide*.

With central costs described later

Cost minimum



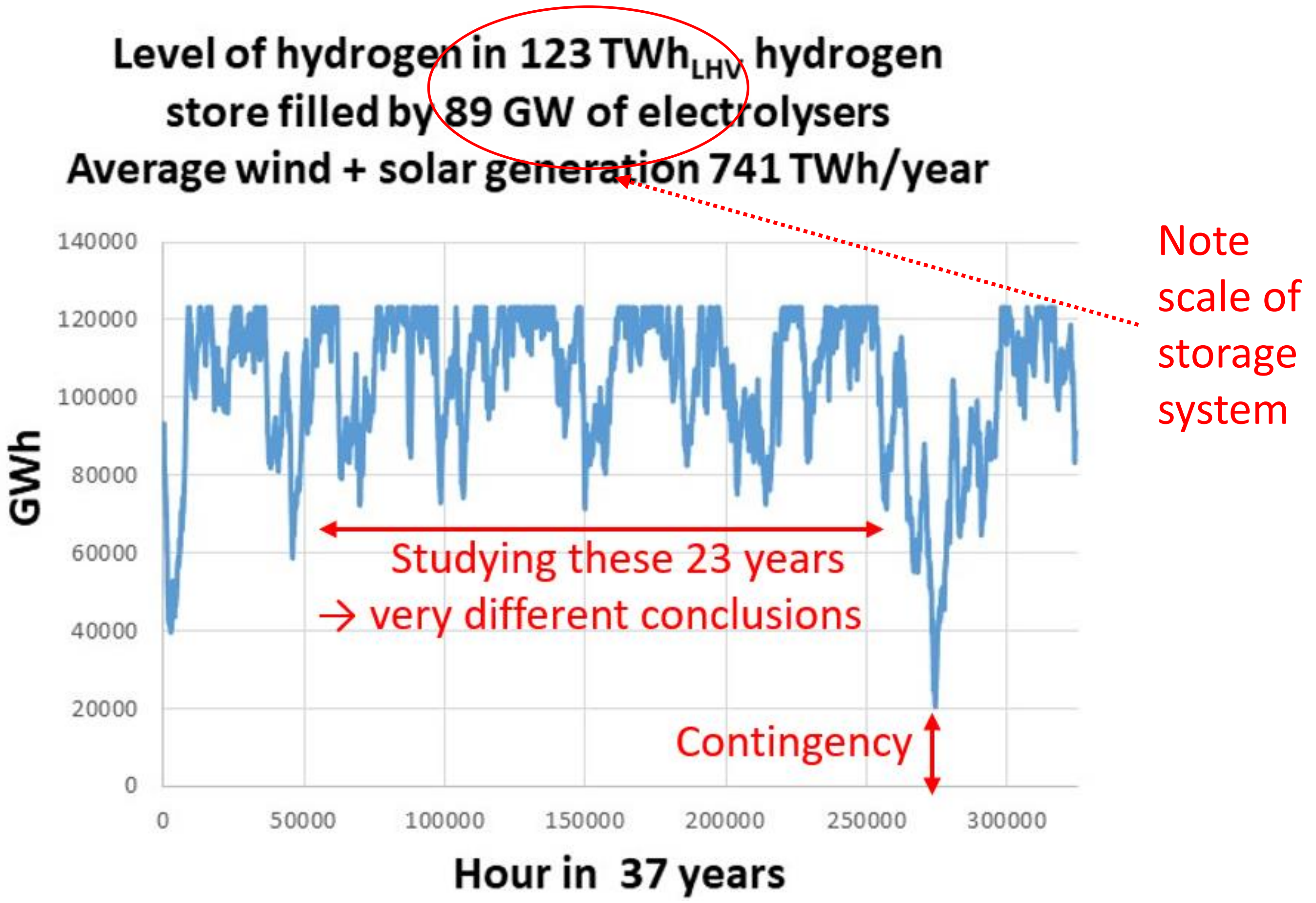
Level of hydrogen in store in **Benchmark Model**

Studies of less than several decades of wind and solar seriously underestimate the need for storage, and overestimate the need for other flexible supply and wind and solar

Issues

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

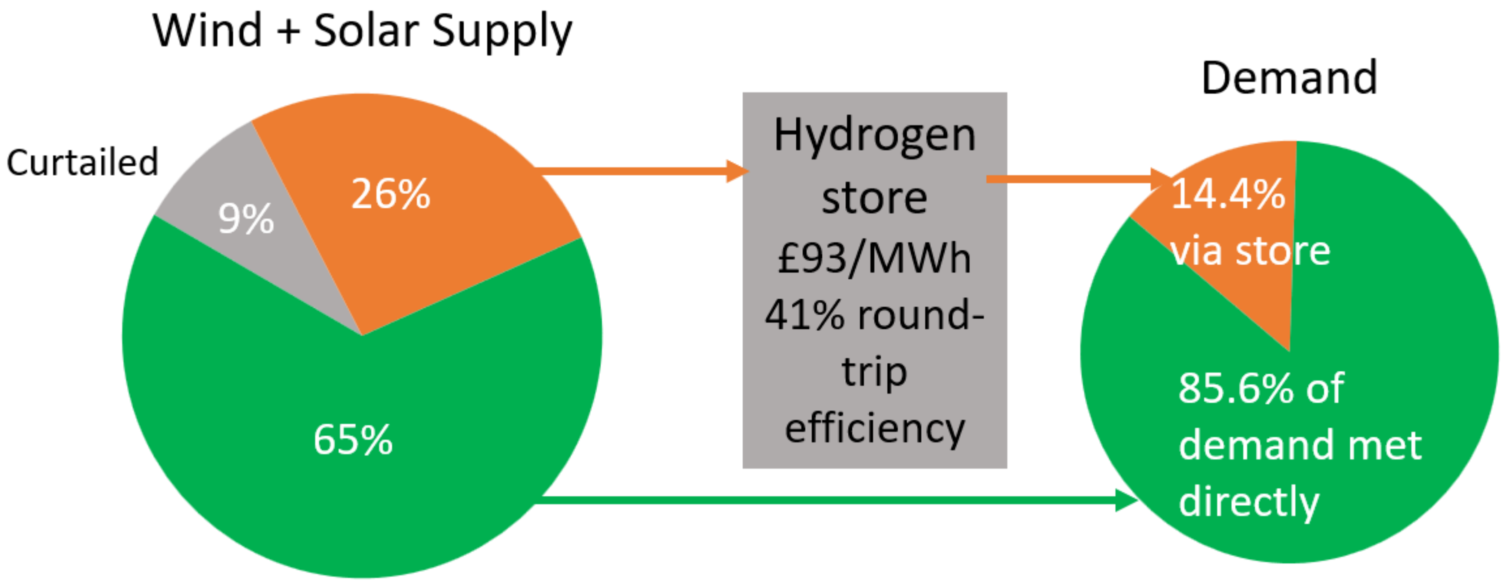
According to the Met Office 'The year-to-year variability of wind is expected to continue at today's level and to have a bigger impact on electricity supply than climate change'



Costs

Example in benchmark case (central 2050 projection of storage costs - sensitivity on next slide) in 2021 prices

With hydrogen storage only, the average cost of electricity is a minimum with wind + solar supply ≈ 1.33 x demand:



If wind + solar generation costs £35/MWh:

Average cost of electricity
=£(1.33 x 35 + 0.144 x 93) = **£60/MWh**

+ cost of

- Transmitting wind and solar to store (£3/MWh)
- Batteries (£1/MWh) to provide grid services

System average costs not very sensitive to cost of storage

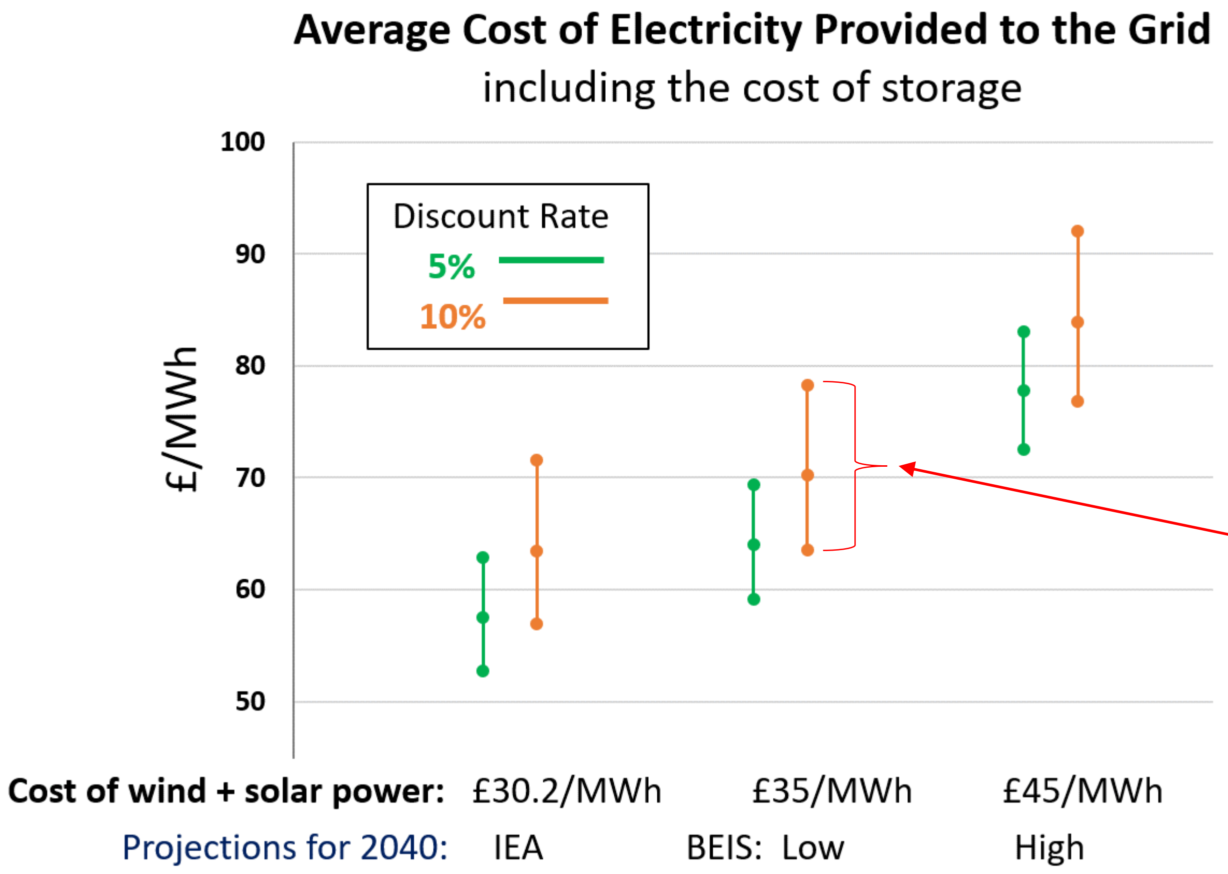
Electricity from store is very expensive:

if solar + wind cost £35/MWh: direct supply costs £38.6/MWh, electricity from storage costs £188/MWh

partly because it must be able to meet full demand when wind + solar ≈ 0 → very low (14%) load factor - this is true of *whatever* complements wind and solar → ***alternatives look more expensive***

Will investors be willing to fund the (essential – but expensive) large-scale storage that will be needed?

H2 (+ battery storage) only – sensitivity to assumptions



2021 prices
Includes:
£1/MWh for batteries → grid services
+ £3/MWh for transmission from wind/solar farms to stores
+ 20% contingency in size of store (contributes ~ £1/MWh)

range of storage costs (low/base/high)

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

Over £200/MWh in most of 2022. Today £92/MWh.

Additional/ alternative storage technologies studied

Looked in most detail at

- **Li-ion batteries**
- **ACAES** as exemplar of technologies in second category
- **Hydrogen**

and their costs

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	≲ 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 ≲ 10 GWh	≲ 70%	Compressors, Expanders, storage caverns and thermal storage TRL 9. Complete systems 7-8.
Carnot battery	GWh	≲ 45%	TRL 7 with resistive heating
Pumped Thermal	< GWh	50%	TRL 4-6
Liquid Air	< GWh	≲ 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	≲ 30%	TRL 7-9 - outclassed by ammonia and hydrogen for electricity storage
Ammonia	Single large tank ~ 250 GWh	≲ 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 in Report

Alternatives and additions to hydrogen storage

- **Alternatives**

  Ammonia could do the whole job and be located anywhere, **but** more than £5/MWh more expensive

- **Additional storage**

  - **Advanced Compressed Air Energy Storage** - more efficient but higher volumetric storage cost

    Cannot provide all storage, but combined with hydrogen would very possibly (but not certainly) lower the cost

    - would reduce the need for large-scale hydrogen storage (by ~ 15% ?) but *would not remove it*

  - **Li-ion batteries** for peak shaving/arbitrage (as well as rapid response to stabilise the grid)?

    - find that once hydrogen and ACAES are available, it will be cheaper to use them, rather than Li-ion

Note:

With several types of store, need a protocol for scheduling their use that minimises the cost: implementation will require an unprecedented level of collaboration between generators and operators of storage

Additional Supply

- **Interconnectors –** should help manage system, **but** there are pan-European wind droughts, accompanied by cold periods: should not design a system that cannot meet demand when imports not available

- **Nuclear baseload** - increases the average cost of electricity ***unless** nuclear costs less per MWh than the average cost per MWh without it* - only advantageous if hydrogen storage costs high and nuclear costs low

  Lowers storage requirements, e.g. in central H2 case, 200 TWh/year reduces electrolyser power/storage capacity by 40%/27%

  Nuclear cogeneration of hydrogen only helps if nuclear cost is low: e.g. below £60/MWh with 10 GW nuclear and central storage costs

- **Flexibly operated gas + CCS**

  Cannot replace storage – high emissions + higher costs

  Combined with hydrogen - *could* lower costs* without leading to very large emissions

  e.g. model of 20 GW_e → 2 Mt CO_2/year + 5 Mt/year CO_2 equivalent from methane leakage

  *depending on the costs of storage, wind and solar power, and gas plus CCS, and the price of gas and the carbon price. Have not explored the sensitivities in detail (multiple unknowns) + prefer to aim for a net-zero

  Would **not** remove the need for large-scale long-term storage - but would reduce the required scales of storage (by 30%?) and of wind plus solar supply

  Would provide diversity, but expose GB's electricity costs to fluctuations in the price of gas, and increasing reliance on imports as GB's gas reserves decline

Further steps

- **Whole-system modelling that takes 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 & ensure 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
  - cost estimates: need underpinning by detailed engineering estimates
- **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**

  Large scale demonstrations of many storage technologies still needed, but **hydrogen is ready now**

Conclusions of Royal Society Study

- **Studies of storage that look at wind and solar over less than several decades seriously *underestimate* the need for storage, and *overestimate* the need for other flexible supply and wind + solar supply***
- GB's 2050 electricity demand could be met by wind and solar supported by large-scale storage, at a cost that compares 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)
- **Hydrogen benchmark case → upper bound on costs.** Adding other types of store quite likely → lower cost, as will coproduction of hydrogen for all purposes
- **Caveat – all costs in 2021 prices;** sensitive to increases in commodity prices, projections of wind + solar costs, general inflation, market conditions, etc ....
- The need for large-scale storage should be evaluated periodically using whole systems models and the latest projections of costs and demand
- It is already clear that GB will need 10s of TWh of hydrogen storage in the net-zero era
  - **should start building it now,** and
  - **develop/deploy appropriate business models,** with the incentives/guarantees required to ensure the investment that will be needed

THE ROYAL SOCIETY

*e.g. study used by the Climate Change Committee which looked at individual years and did not allow storage to transfer energy between years

More on Methodology

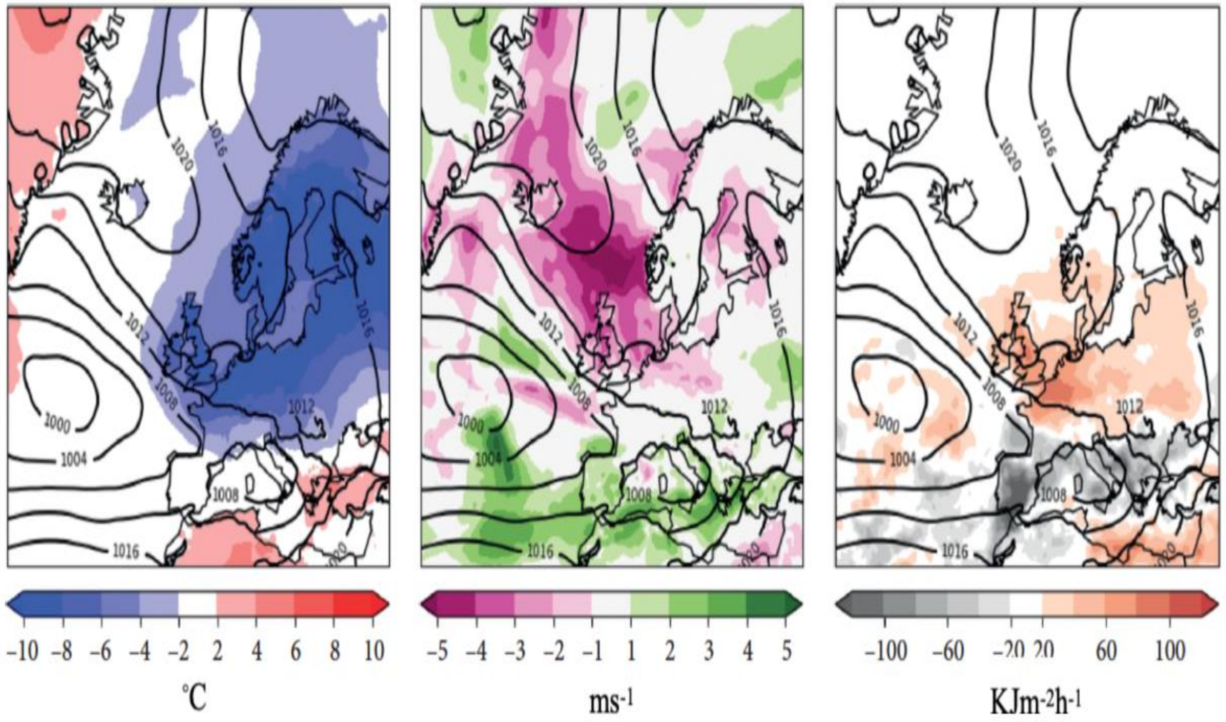
- **Weather**
  - correlations with demand, how many years should be studied?
- **Demand side measures**
- **Modelling with a single type of store**
- **Modelling with several types of store**

Low wind periods cover much of Northern Europe and coincide with cold periods → high demand

→ should **not** design a system that cannot meet demand when imports are not available

Wind/demand correlations are not included in our modelling which uses a model of 2050 demand based on 2018 weather repeated 37 times

Iain Stafell recently manged to approximately remove 2018 weather and put in weather in years 1980-2016 → increases store size by 10%



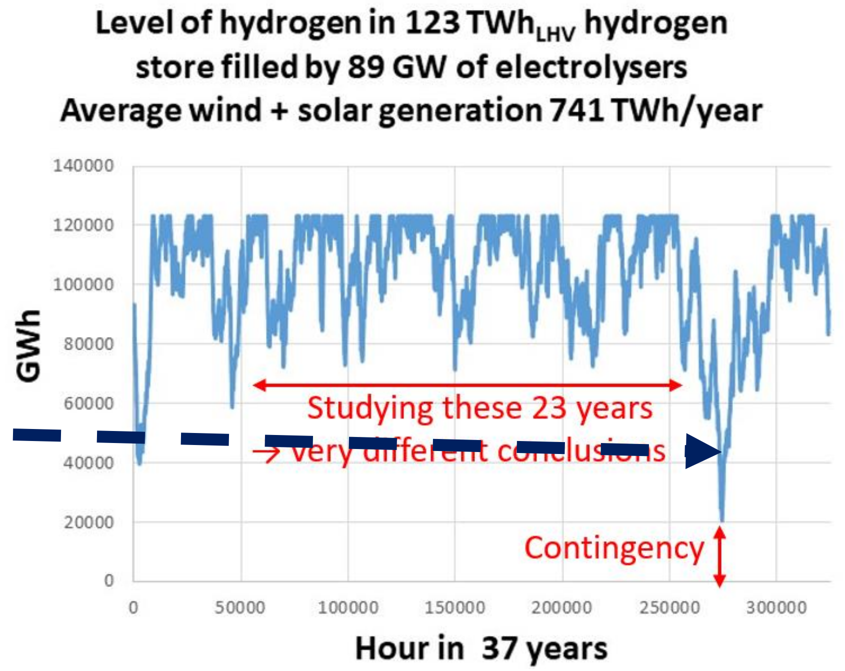
Average, over top ten periods of (demand - wind and solar supply) in 1980-2019, of the deviation from the mean (for the days on which each event occurred - all were between 10 December and 21 February) of: temperature at 2 m, wind speed at 100m, and solar irradiance.

What length of weather sequence must be studied?

German studies (Ruhnau & Qvist) also show need to study many years, as do US studies

- *and studies of 'low rain years' in New Zealand*

Demand-side Measures



- Traditional demand-side measures (which involve peak shifting/flattening) could not deal with long term variability

  Suppose store 20% too small: can meet demand in all but 322 hours in 37 years (0.1% of the time)

  but missing power averages 35 GW – over half the average

- What about 'pre-emptive demand management'?

  UK Met office publishes forecasts of the levels of wind in the coming three months

  Suppose that when wind is forecast to be less that 80% of the average in three consecutive months*, demand is reduced by 2.5%

  → reduce size of store by 10%, electrolyser power by 3%.

  Not much impact on average cost of electricity, but easier to build storage by 2050

*18 out of 444 months in 37 years

Modelling with a single type to store

Hydrogen with 74% electrolyser efficiency, 55% generation efficiency

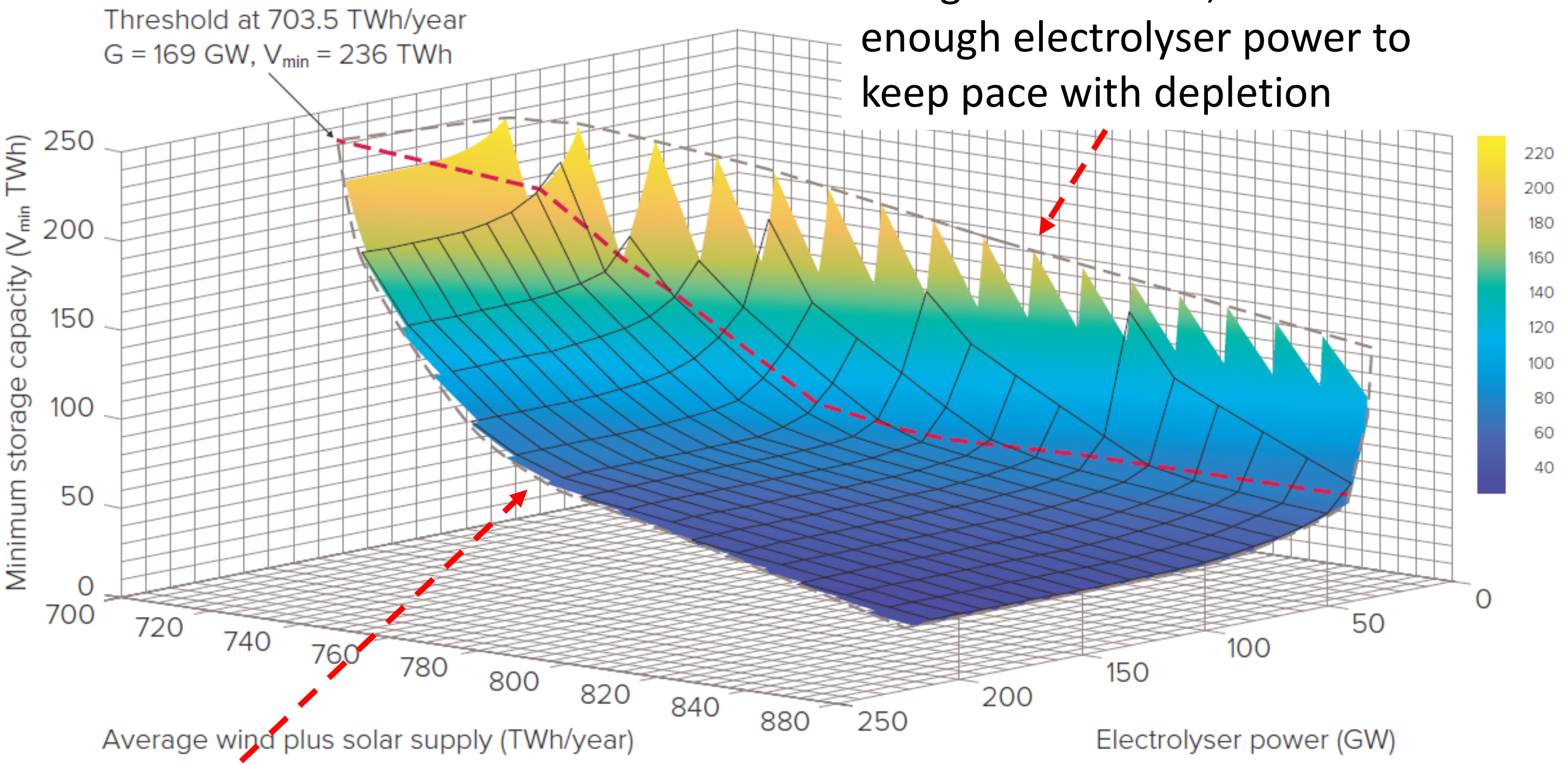
Variables – electrolyser power, storage volume, level of wind + solar generation

– power generation capacity fixed by need to meet demand

Minimum cost depends on **relative** cost of electrolysers and storage
- smallest possible store not the cheapest

Interrogators only seem interested in volume

To right of this line, not enough electrolyser power to keep pace with depletion



Enough electrolyser power to store all surpluses – no point building more

Modelling with several types of store

N stores → 3N + 1 (level and cost of wind plus solar generation) variables:

N charging powers, N storage powers, N generation powers (able together to meet demand – so fixed if N = 1)

With costs for each component, seek lowest cost combination which can meet demand as a function of these variables

First need an algorithm for scheduling the use of stores:

Following a proposal by Stan Zachary*, assign a marginal value to the energy in store (related to round trip efficiency and level in store) that depends on the round trip efficiency and the level of energy in the store

Energy is preferentially put into the stores with highest marginal value and energy is preferentially withdrawn from stores with lowest marginal value

Example of results with hydrogen and ACAES later

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

More on Technologies

- **Hydrogen**
  - cost assumptions (electrolysers, storage, power generation)
  - water needs
  - storage in depleted gas fields or aquifers

- **Advanced Compressed Air Storage**
  - often misleadingly called Adiabatic Compressed Air Energy Storage

- **Large thermal ‘Carnot’ batteries**
  - won’t discuss ‘pumped thermal’ which is another form of Carnot battery

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** $/kW$_e$ Today	500 - 1000	500 -1400	700-1400	1100 – 1800	> 2000	2800 -5600
2050/Future $/kW$_e$	< 200	200-700	< 200	200-900	< 300	500 - 1000
** In their simulations, IEA assume a future cost $450/kW$_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 (Solid Oxide)

Limited by availability of iridium (Polymer Electrolyte Membrane)

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

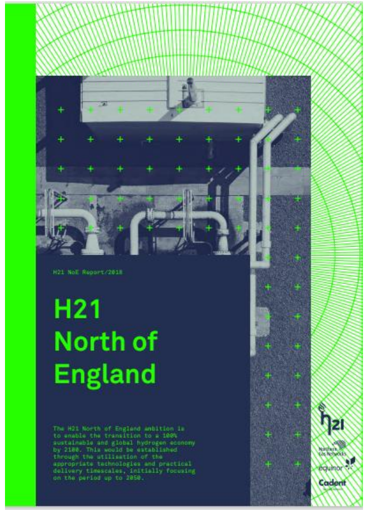
Assume 74% (results not v sensitive)

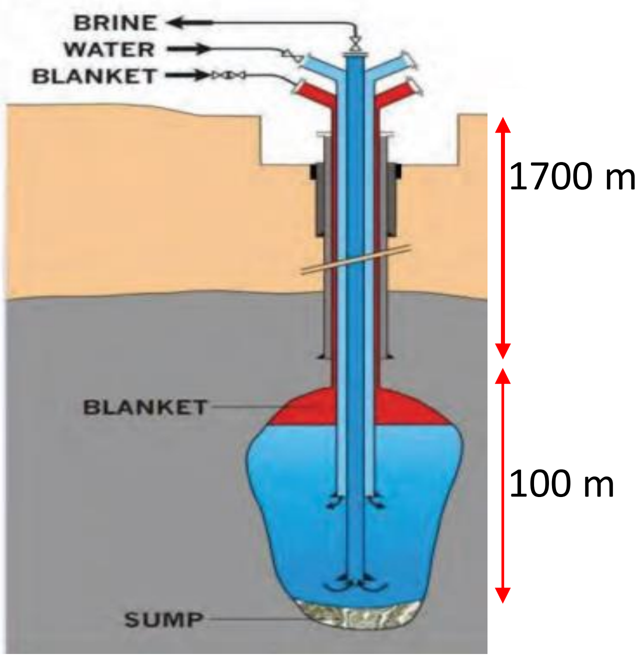
Full system costs: v dependent on module size + scale of manufacture
Assume $450/kW +/-50%

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

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

Hydrogen 2 Underground Storage





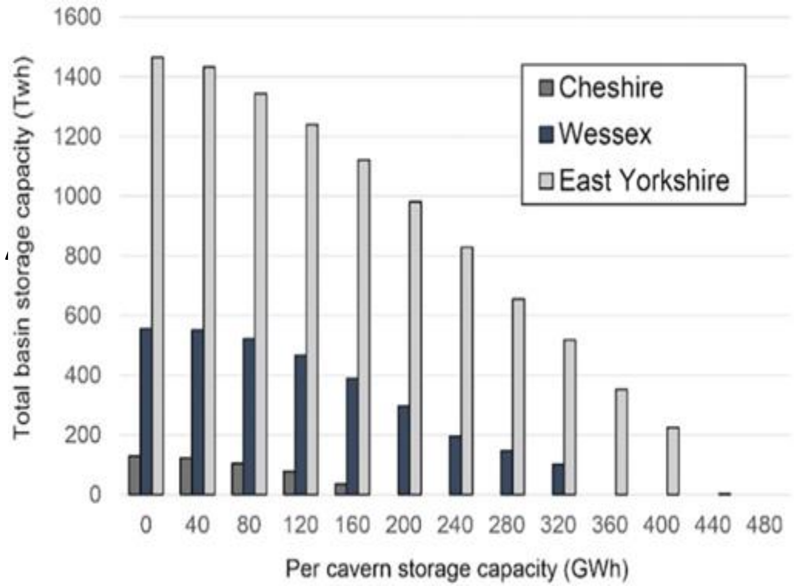
Costs from H21 NE study of clusters of 10 x 300,000 m^3 of solution-mined salt caverns in E Yorkshire (sharing common surface facilities)

→ 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:



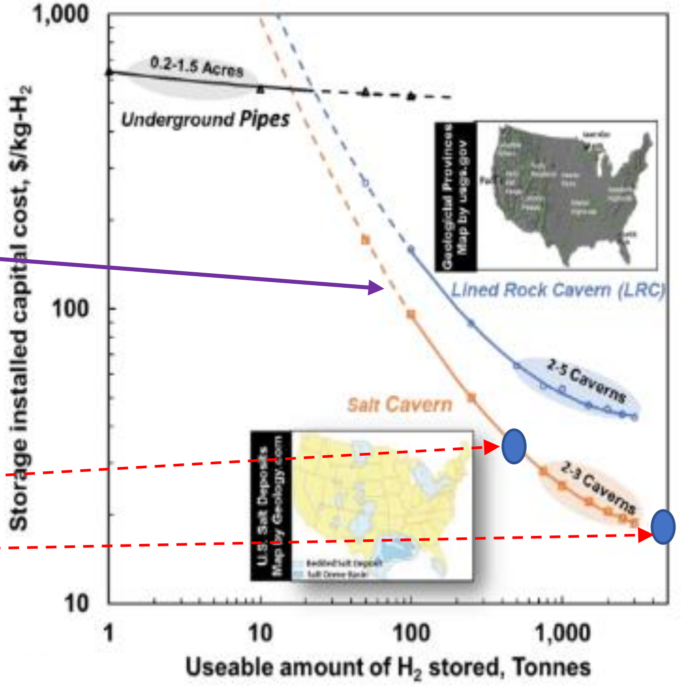
Comparison with other estimates difficult - cost depends on geology, geography (distance to brine disposal), and **size:**

£/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

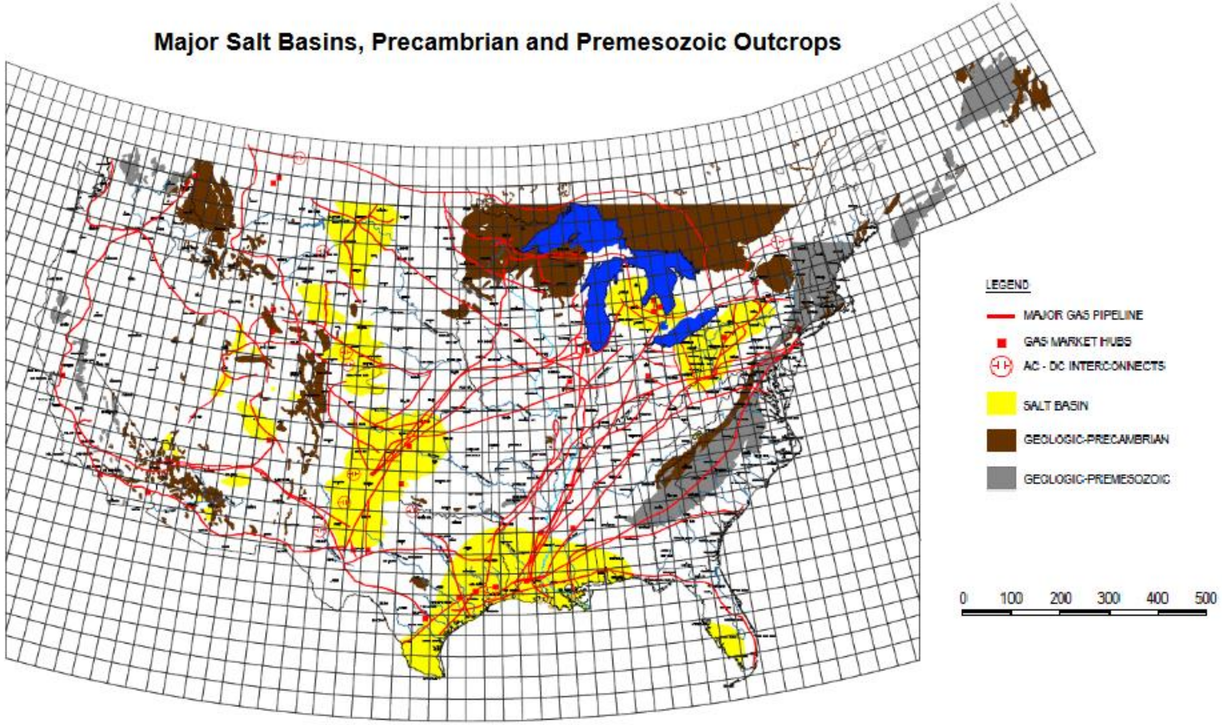
- H21 NE

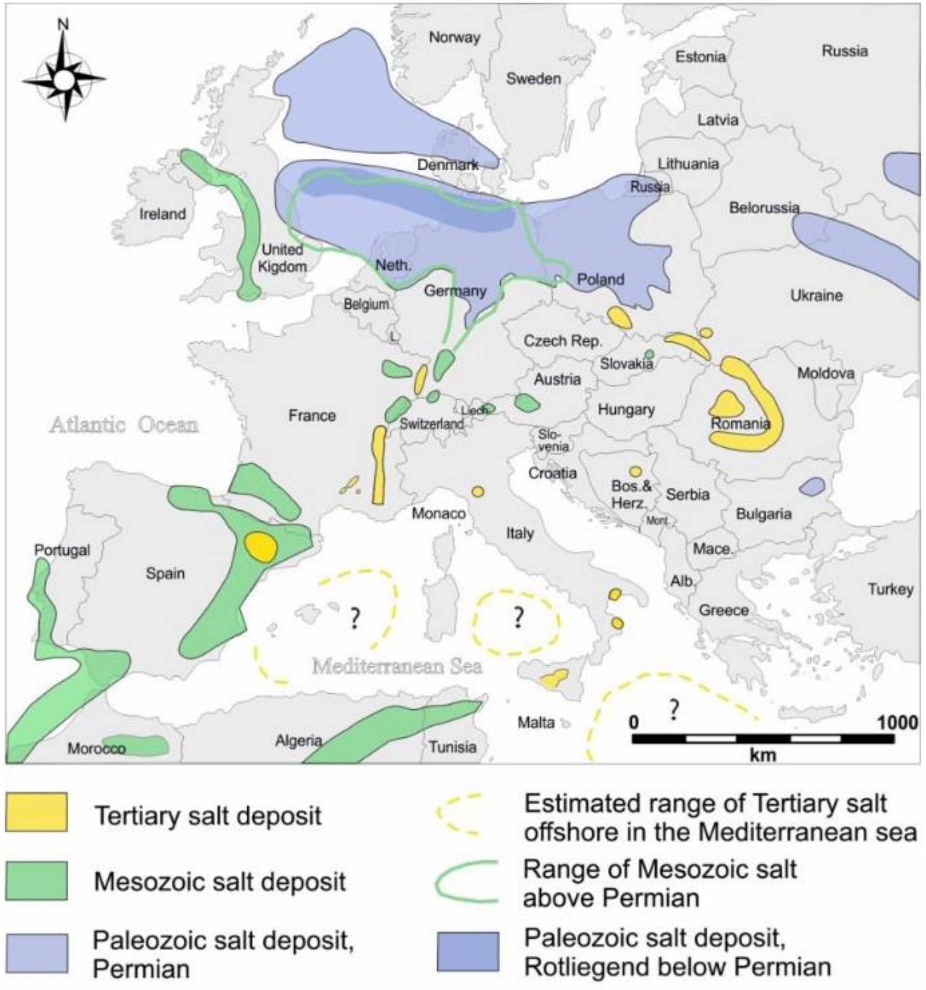


Salt Cavern issues

1. Where could they be located?

Possible alternatives → next slide





2. Brine disposal?

We assumed in sea - environmental impact? If remote from sea, in saline aquifers

Water for electrolysis?

All hydrogen case would use 0.5% of ground water extracted in England. Alternative – de-salinated sea water or water from saline aquifers

Impact on cost ≈ 0

Alternatives to salt caverns

According to a comprehensive IEA technology Monitoring report

storing hydrogen in - aquifers is at TRL 2-3

- depleted gas fields is at TRL 3 (27/4/23 Underground Sun Storage opened the world's first facility that stores pure hydrogen in a depleted gas field Gampern, Upper Austria)

Won't save costs (more complex/expensive surface facilities) **but**

Using aquifers and/or depleted gas fields would enable large-scale hydrogen storage in regions that are remote from salt deposits, which would provide important system benefits. There is therefore a compelling case for carrying out the additional work and trials that are needed to see if this is a real option.

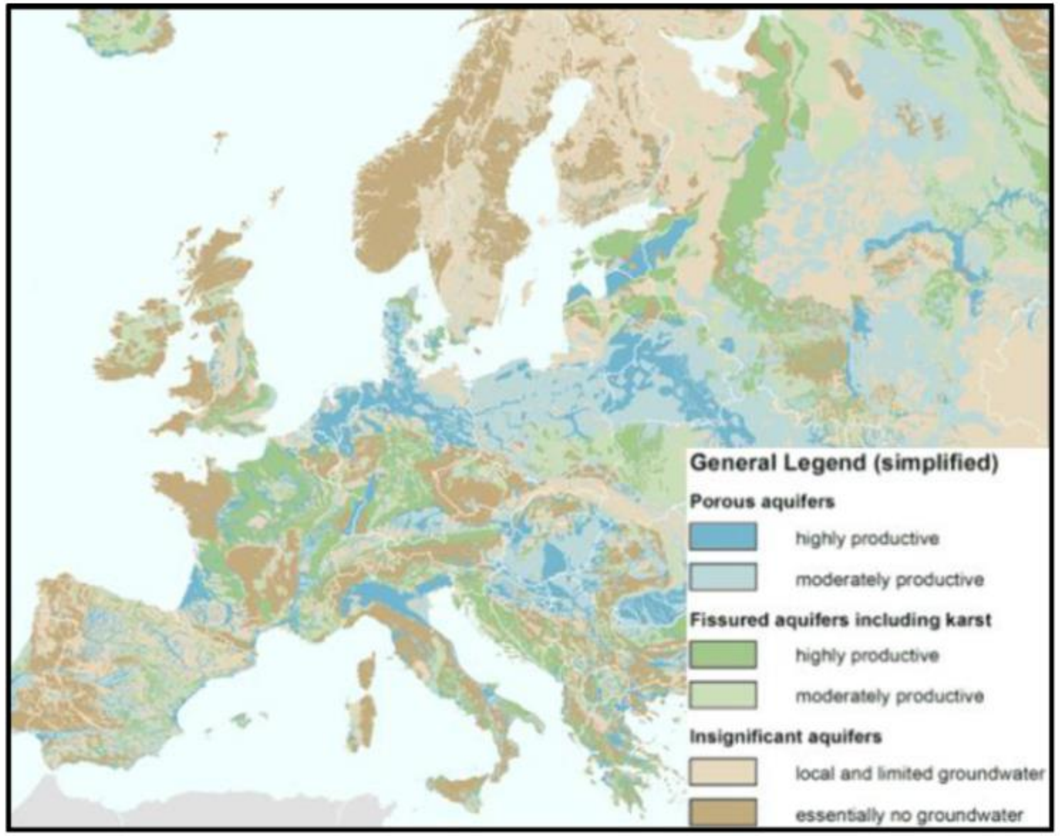


Fig. 9 – Map of the aquifer in Europe (Source: EGDI, "Hydrogeological Map of Europe," 2021).

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**

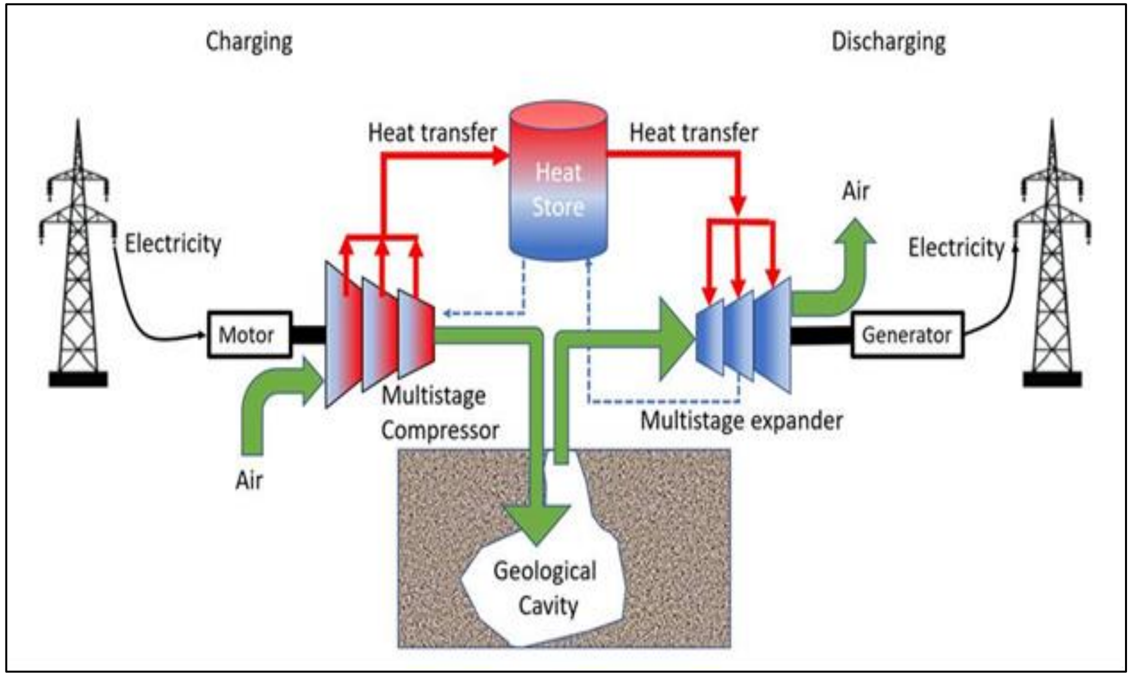
  Could be cheaper that PEM (input from expert at BP + discussions with JCB)

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

Advanced Compressed Air Energy Storage

Three grid-connected ACAES plants now in operation in China, e.g.

- 50 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)$^{0.6}$

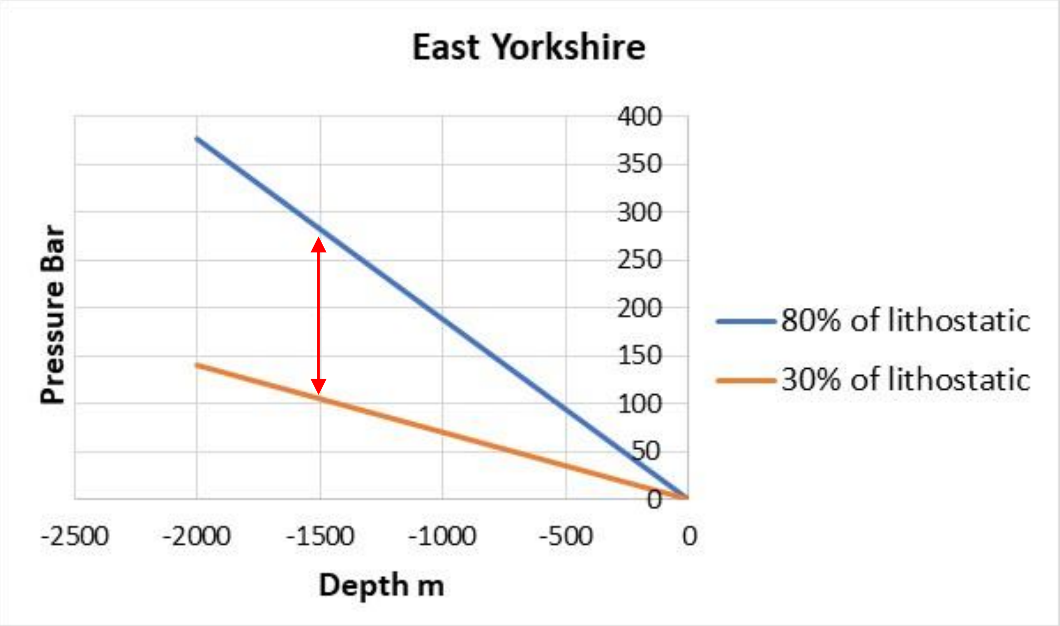
Underground capacity in GB

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 m³ (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,...

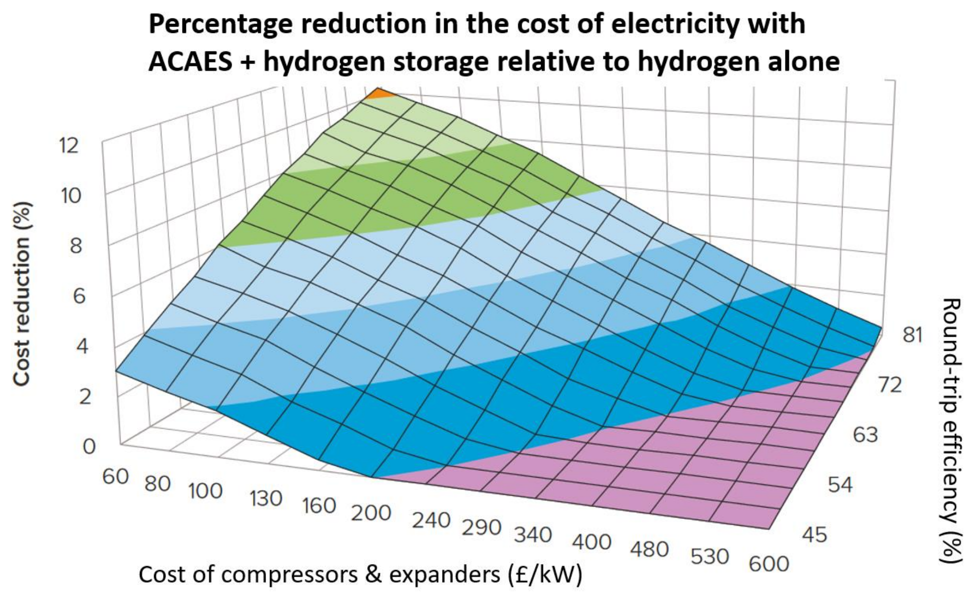
- **Assume £(100-500*)/kW for ~ 60 MW**

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

+ 4%/year O&M

Combining ACAES with hydrogen can lead to a cost reduction of several percent if efficiency is relatively high and the power cost is relatively low:

e.g. with 68% efficiency (found in modelling) ACAES lowers cost *provided* compressors and expanders each cost less than £450/kW - not assured, but may well be the case in 2050 for large compressors and expanders manufactured in significant numbers



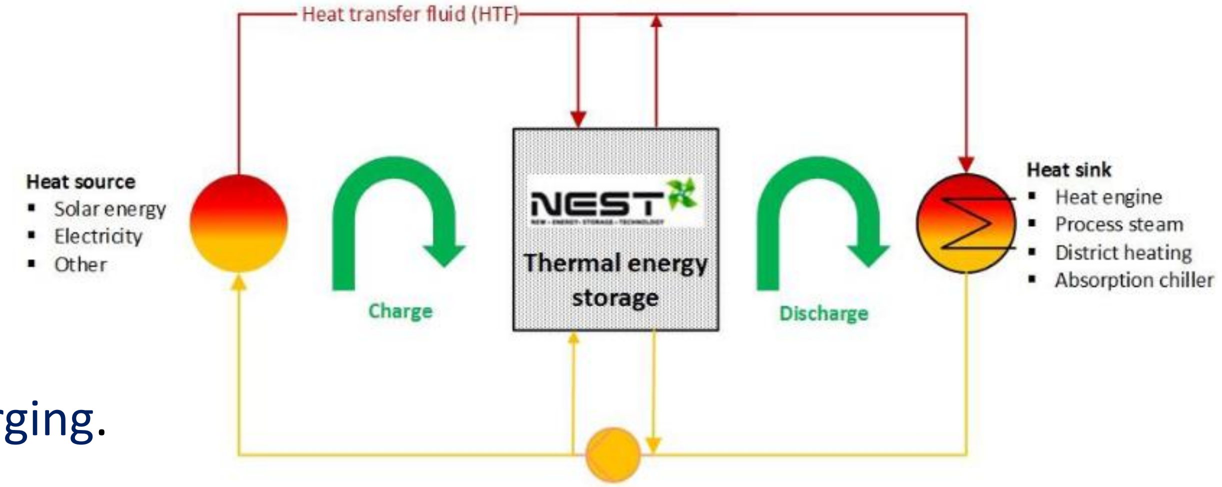
Although the capacity of ACAES is much smaller than that of the hydrogen store, it delivers more energy/year, because it is cycled much more frequently:

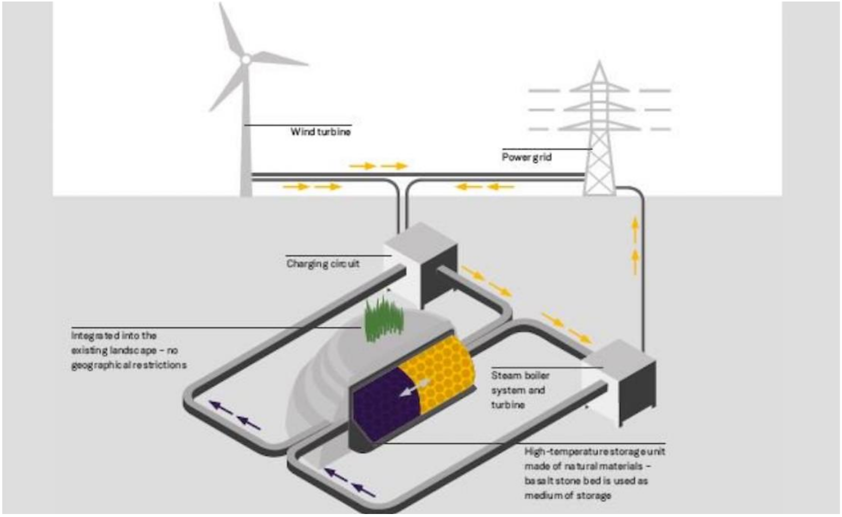
Example with power costs £350/kW, 66% round-trip efficeiency + H2 base costs	H2 only	Hydrogen + ACAES	
		H2	ACAES
Capacity to deliver per cycle TWh_e	44	37	2.4 [6.8 GWhe/cavern]
Electrolyser/Compressor power GW_e	77	40	29 [82 MW_e/cavern]
Generation/Expander power GW_e	88	65	23 [65 MW_e/cavern]
Annual delivery TWhe	85	36	52

Adding ACAES lowers the required level of wind and solar supply because it is more efficient than hydrogen. Correspondingly, it increases the amount of energy that has to be provided by storage

Packed bed thermal energy storage- large Carnot battery

- Low-cost materials, igneous rock with stable properties at temperature of operation (600°C +)
- Storage capacity increases with store volume, heat losses increase with store surface area. Favours large stores.
- High conversion efficiency of electricity to heat for charging.
- Heat to electrical conversion efficiency 45% + possible.
- If low temperature heat can also be used for other applications, district heating, higher energy efficiency can be achieved.
- Large stores with capacities of 10s of GWh_e can potentially achieve low costs per MWh_e
- Higher cost/MWh_e than hydrogen but higher round-trip efficiency and lower cost charging





Siemens Gamesa: built a demonstrator but abandoned plans for a commercial plant

Market and Governance Issue

- Current arrangements in the UK (and other countries with liberalised energy markets) do not provide incentives
  - to build long-term storage (short-term storage can recover costs through arbitrage)
  - for the collaboration that will be required between operators of wind and solar farms and operators of storage

  Need mechanisms that take account of systems costs and operation of the system as a whole

- A possibility (put forward to provoke discussion):

  Enhanced 'central buyer' model: agency charged with procuring generation, storage, grid upgrades... and buying and selling electricity

  - similar to public ownership in many respects, but without removing competition or requiring tax payers to bear all risks

Conclusions

- GB's 2050 electricity demand could be met by wind and solar supported by large-scale storage, at a cost that compares favourably with cost of using the only large-scale low-carbon alternatives

- More generally, large-scale storage will be needed in many countries that will rely on variable supply (wind, or e.g. in New Zealand to scope with low rain years).

- In evaluating the need for storage, essential to look at long sequence of years.

- Need to adopt road maps to net-zero, and start implementing them now (in knowledge that details of the route will change in time)

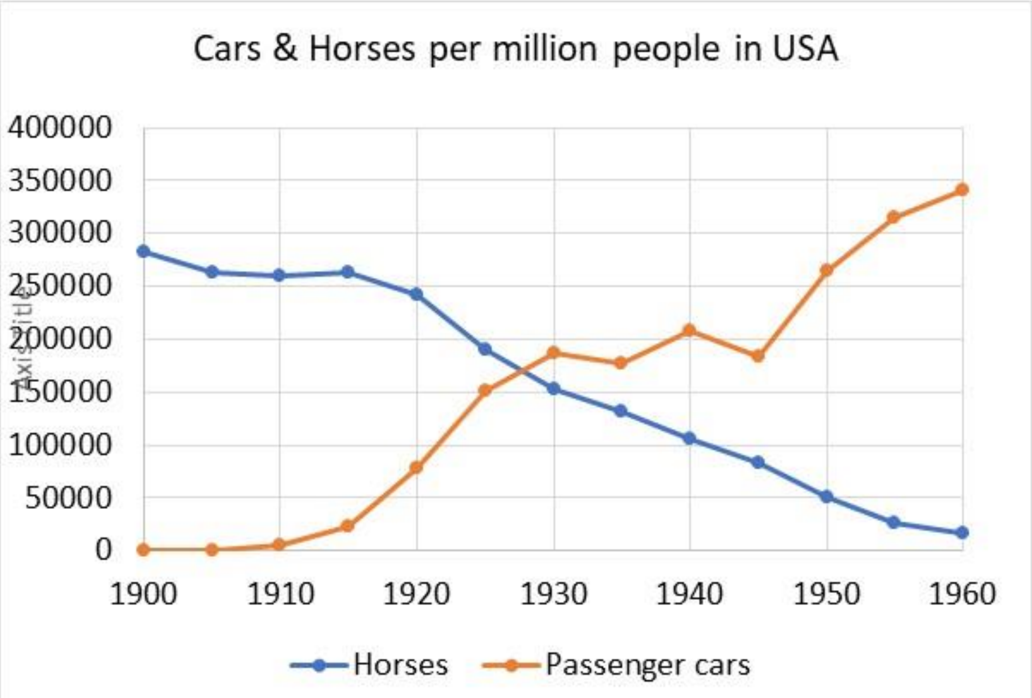
  - moving to a zero-carbon energy system will take time

Counter example?

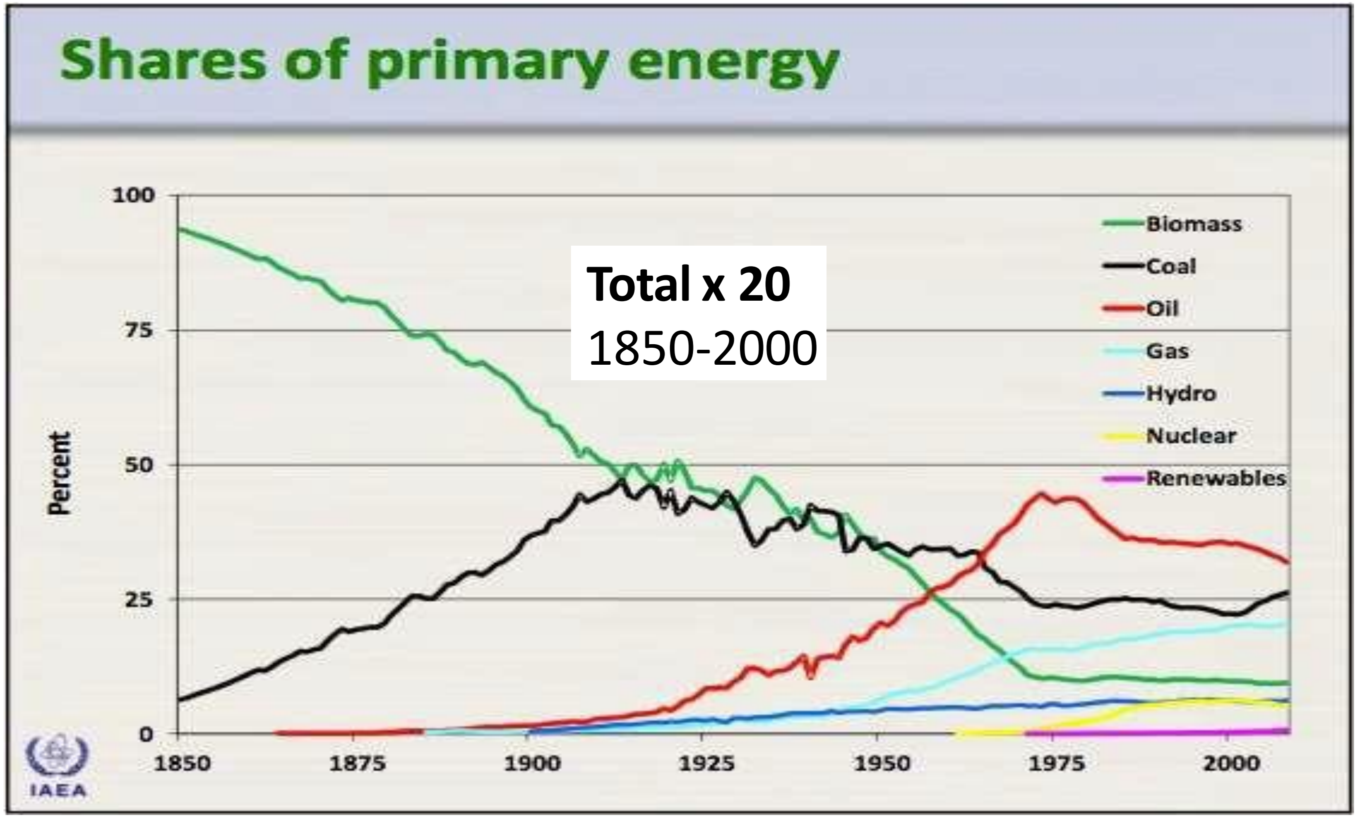
New York 1900

New York 1913

- misleading: cars have obvious advtanges over horses, not much new infrastructure needed, New York is not typical, and the transition took much longer:



The energy mix has changed enormously in the past - but slowly:



In order to move from today (fossil fuels still provide over 75% of primary energy) to net-zero in 2050, the world must

Get on with it