Large-scale* Electricity Storage

Chris Llewellyn Smith

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

Contributors include - Tony Roulstone, Paul Cosgrove, Richard Nayak-Luke, Mike Muskett, Seamus Garvey, Nilay Shah, Phil Eames, Paul Shearing, Ian Metcalfe, Keith Bell, Royal Society staff, …

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Approach: identify 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.

- **As fossil fuels are phased out** (in transport, space heating, providing industrial heat...)

  - an increasing share of the world's final energy will be provided by electricity

  and as electricity supply is decarbonised

  - an increasing fraction will be provided by wind and solar

- 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. Therefore 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 but small in GB, ...) *****not zero emissions: fugitive CO_2 + upstream methane leakage

- 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)

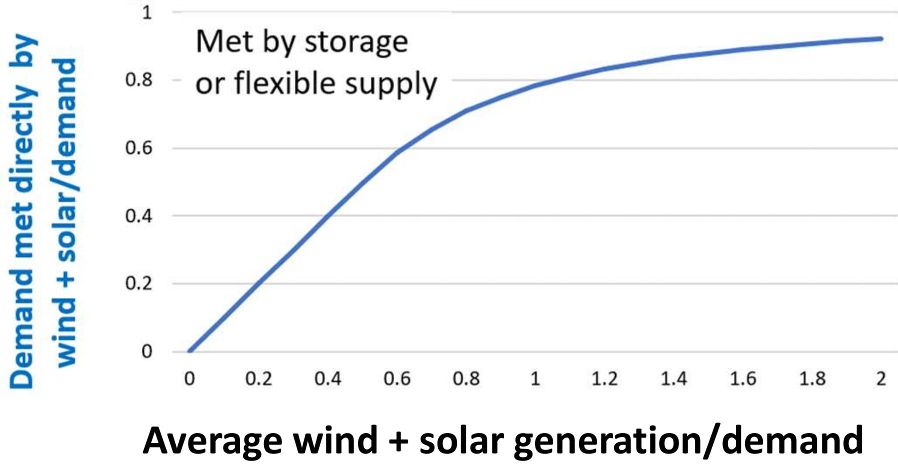
  and

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

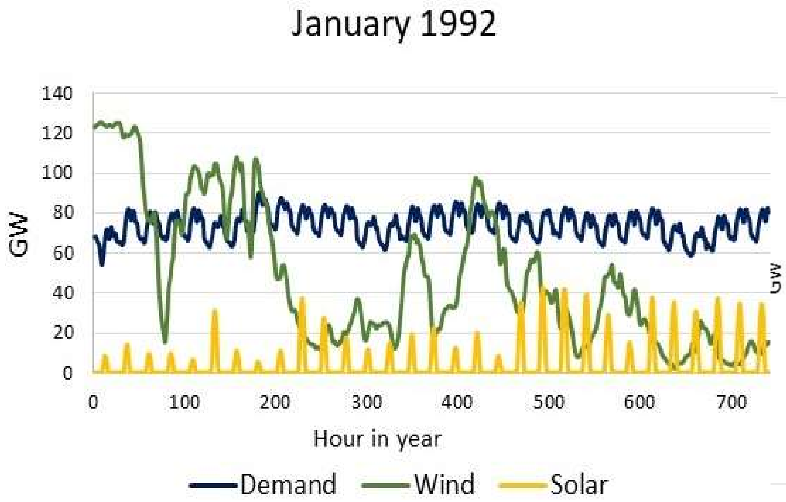
* Studies based on less than several decades of wind and solar supply seriously underestimate the need for storage *and* overestimate the need for wind and solar and other flexible supply

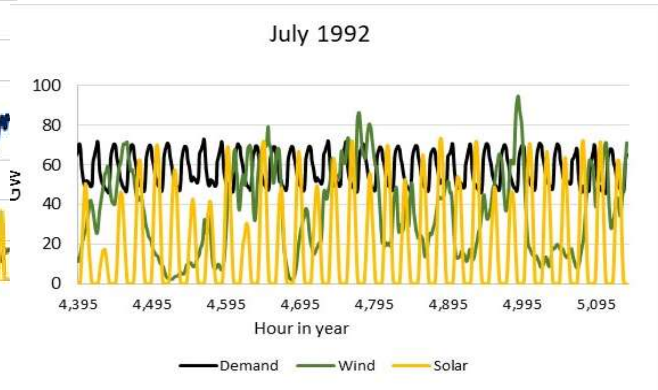
The Need for Storage

However much wind and solar are installed they can never meet all demand directly. In UK with the NR model of wind (80%) and solar(20%) + AFRY model of demand:



In the **short/medium term (focus of most studies)**:





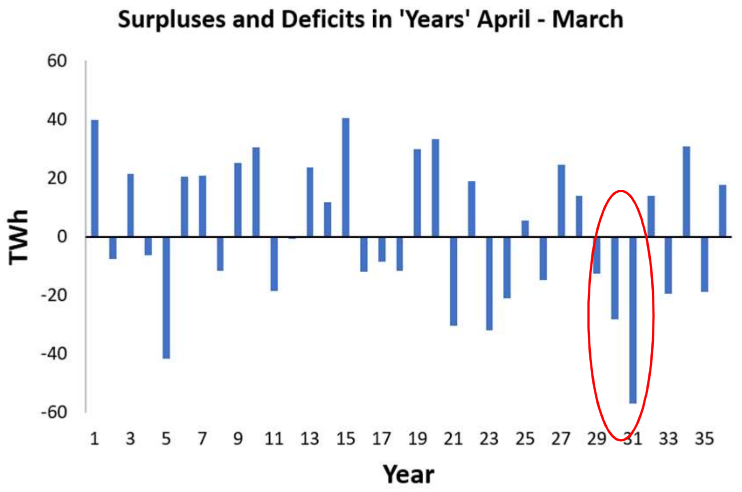
This is relatively easy to deal with

Long-term variations are the real problem

Note: volatility is the issue, not seasonality

Here and on next slide 37 year annual average of wind and solar generation = 570 TWh/year = demand

The Need for Long-term Storage



In N Europe 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

'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)

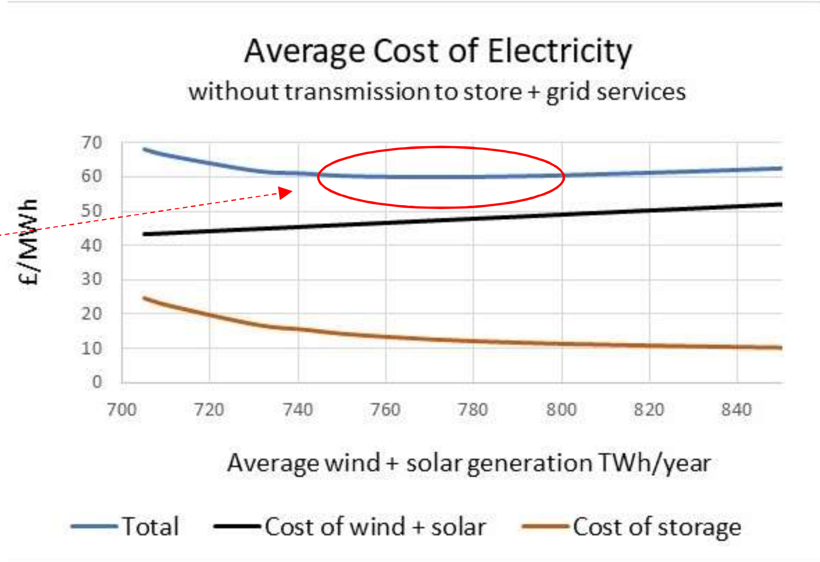
  hydrogen → electricity: 55% efficient (2050)

→ 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.*

In ‘**Benchmark Model**’

With central costs

Cost minimum



Note scale of storage system

Level of hydrogen in store in

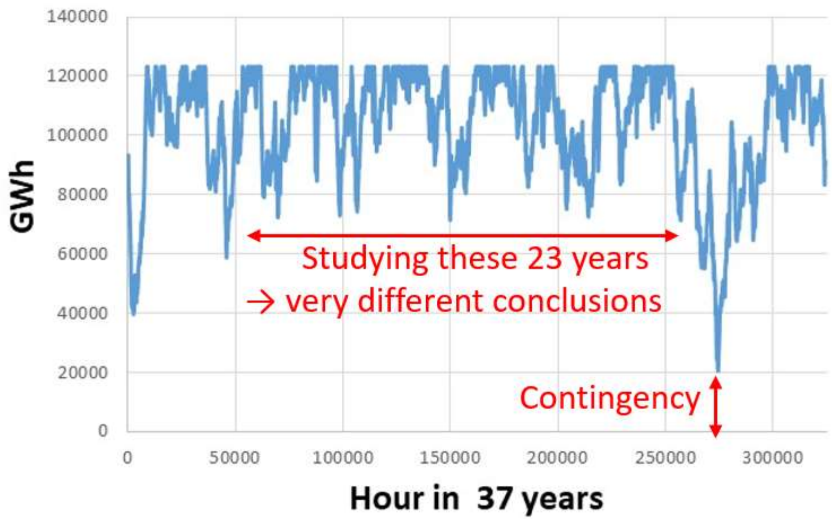
Studies of less than several decades of wind and solar seriously underestimate the need for storage, and overestimate the need for other flexible supply and wind and solar

Issues

- Is 37 years enough? No → 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’

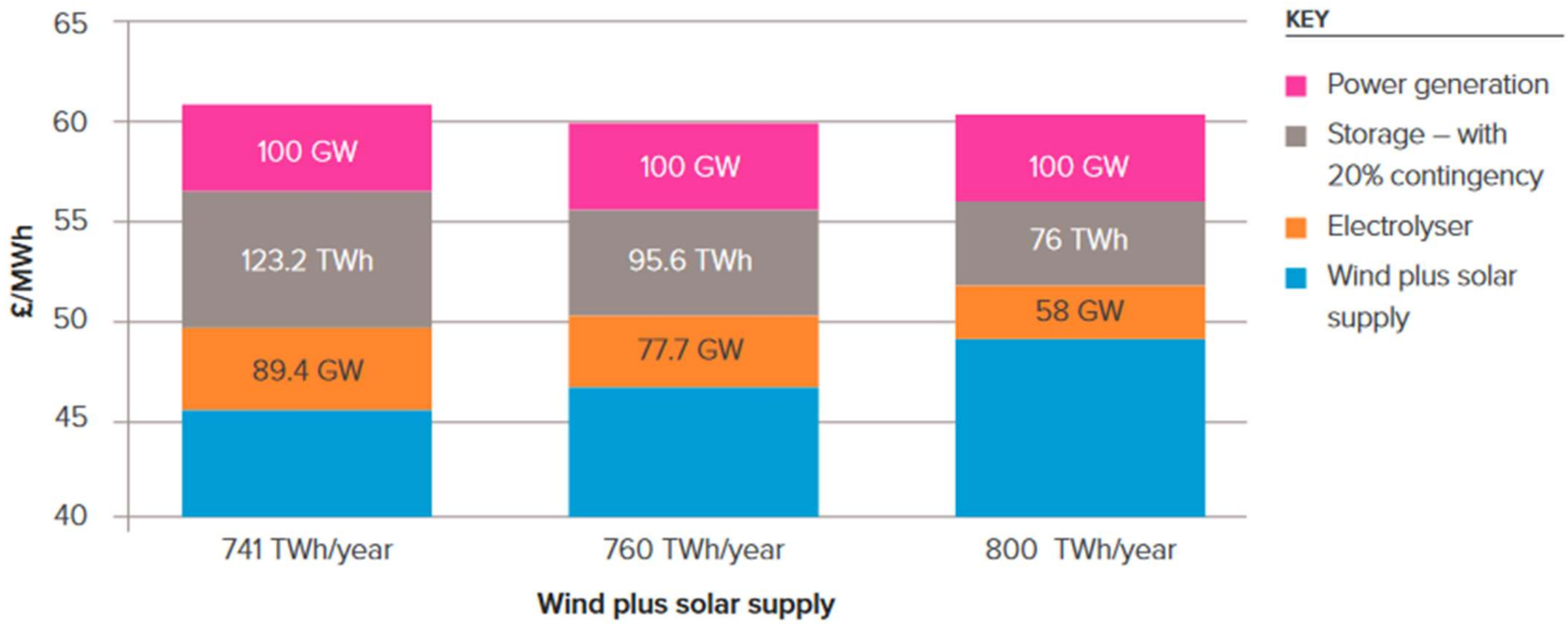
Level of hydrogen in 123 TWh_{LHV} hydrogen store filled by 89 GW of electrolysers
Average wind + solar generation 741 TWh/year



Size of storage system is sensitive to the level of wind and solar:

Breakdown of average cost of electricity.

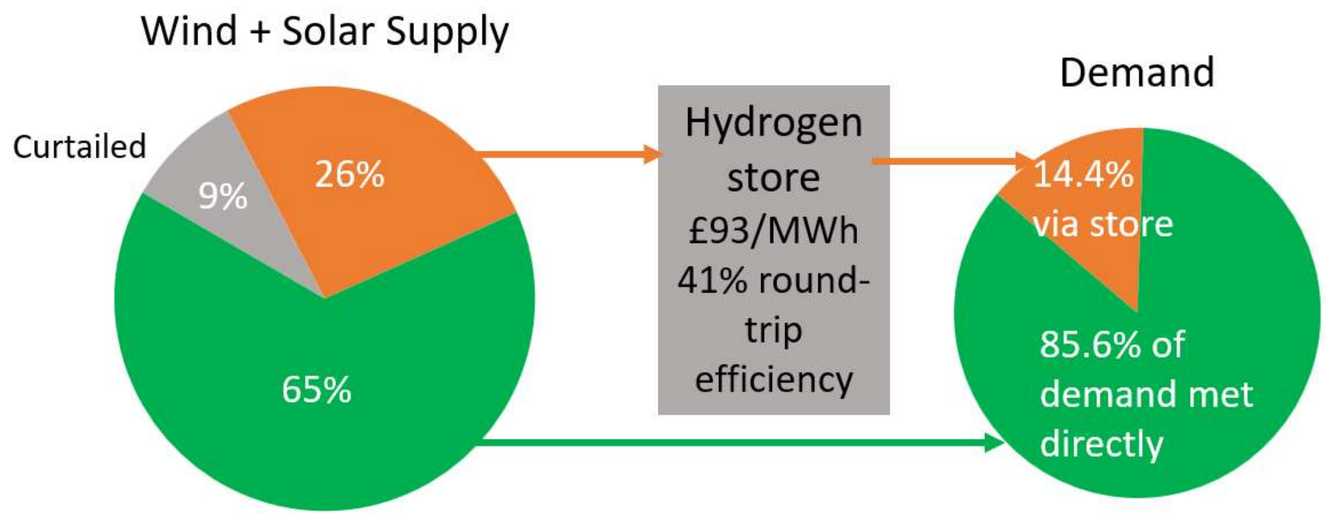
Breakdown of the average cost of electricity for different levels of wind and solar supply, with the base costs for hydrogen storage and a 5% discount rate. The cost of wind and solar supply dominates the total (note the suppressed zero).



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

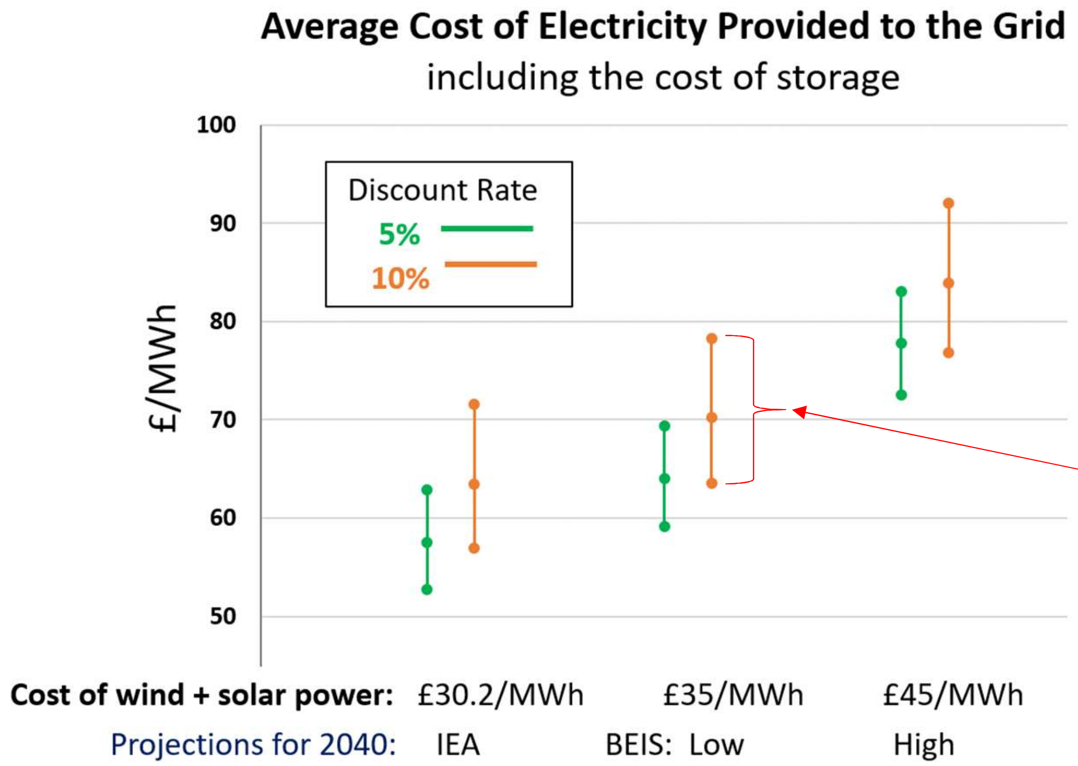
Electricity from store is very expensive:

if solar + wind cost £35/MWh: direct supply costs £39.8/MWh, electricity from storage costs £179/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. £92/MWh on 3/10/23.

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

I have back-up slides with details on hydrogen, ACAES and large Carnot batteries

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 -much more expensive than hydrogen even without allowing for heat losses 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 see next slide but 1

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 - *see next slide but 1*

  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
- **Caveats on next + further comments on next slide**
- 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

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

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Caveats and Further remarks

- **All costs in 2021 prices;** sensitive to increases in commodity prices, general inflation, market conditions, etc .... *and*
  particularly: cost of wind + solar – if it is higher than assumed, nuclear would become more attractive, optimum storage configuration would change

- Storing hydrogen in aquifers (TRL 2-3 according to a comprehensive IEA technology Monitoring report) or depleted gas fields (TRL 3) - would enable large-scale hydrogen storage in regions that are remote from salt deposits → important system benefits → *a compelling case for carrying out the additional work and trials that are needed to see if this is a real option, although **it would not lower costs***

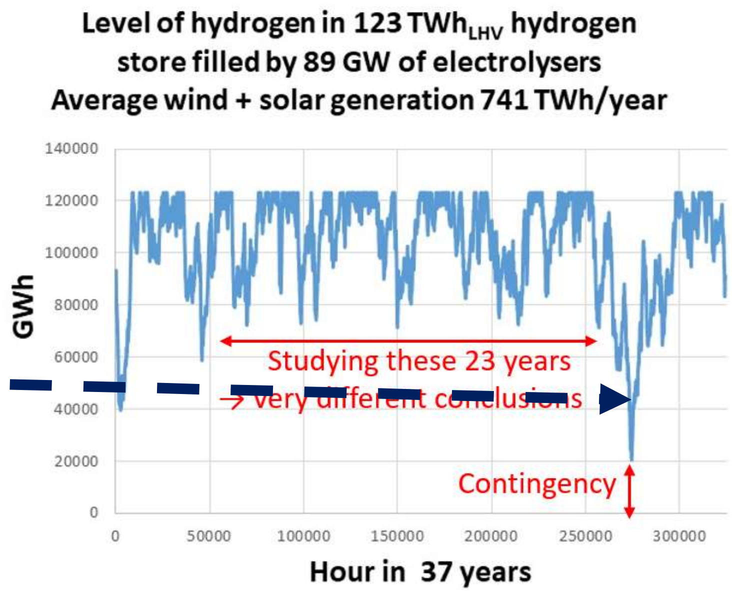
- **Demand side measures:** traditional measures can't fix GB's years 29-31 problem work (next slide), but 'pre-emptive demand management' – reduction when prolonged periods of low wind forecast – could mitigate it

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 much easier to build storage by 2050

*18 out of 444 months in 37 years

Conclusions

- **GB:** 2050 electricity demand could be met by wind and solar supported by large-scale storage, at a reasonable cost– need to get on with it
- **What about other countries? Interdecadal wind variation especially large in N Europe**

  Study of Germany → similar needs relative to demand

  But the available evidence suggests N Europe is not an extreme outlier

  + clear that the many studies that looked at single years are misleading

  What if no suitable salt deposits?

  May be possible to store in aquifers (TRL-3) or depleted gas fields (TRL 3)

  - but it won't lower the cost

  Could use ammonia, or e-fuels (e-methanol)

  [Similar problem in New Zealand with low rain years]
- **Everywhere need:** multi-decadal modelling → core 2050 storage need

  large scale demonstrators + large-scale deployment once core needs are clear

  market structures that incentivise the required investment will be a pre-requisite

GET ON WITH IT