The Need for Energy Storage in a Net Zero World

Chris Llewellyn Smith

Oxford Physics

Talk at Virtual Conference on Medium-Duration Energy Storage in the Net-Zero UK, 23 March 2020

Outline

- **Implications of net zero for energy storage**
- **Assessing the storage needed to support the grid**
- **2050 storage needs in a net zero UK**
- **Storage technologies**
- **Concluding remarks**

Background:

I am leading a **Royal Society study of large-scale long-term storage** – what is likely to be needed and whether/how it could be provided. We have set up working groups (on whose work I will draw) studying the Need (led by Tony Roulstone), Hydrogen and Ammonia (led by Nilay Shah), Non-Chemical Storage (led by Phil Eames), Synfuels (led by Matt Davidson) and Novel Chemical Storage (led by Ian Metcalfe). Another group (led by Karen Turner) which is taking a cross-cutting look, and considering market and systems issues/value, cost, safety, public acceptability, readiness, ….is about to start formulating conclusions and drafting a road map for R&D, demonstrators and eventual deployment.

This study will be followed by a study of all energy storage.

Question: Does it make sense to look at long-term storage in isolation?

Yes: long term solutions might also meet intermediate and short-term needs, but short/medium term solutions (batteries, liquid air,..) won't be able to meet the long-term (e.g. months) needs

Studying long-term needs has cast a lot of light on medium and short term needs

Energy Storage in a Net 0 World 1

Storage is needed to power vehicles, ships, and planes (and mobile phones,…) **and buffer variations in demand (for heat, transport, electricity) and supply**

It is currently mostly provided by **fossil fuels**

For example, in the UK in 2018 fossil fuels on average **stored 170 TWh**:

35 TWh - coal (falling)

15 TWh - gas (capacity fell from 50 to 15 TWh after closure of Rough field): only 7 average days' supply!

120 TWh - oil

Supported by

Pumped hydro - 30 GWh capacity (potential to increase by a factor of 3)

Biomass at Drax 200 kt → 1 TWh heat or 400 GWh electricity

Hot water tanks 40 GWh

Grid connected batteries 1.8 GWh

+ Potentially EVs: if 20 million @ 60 KWh **with 10% supporting grid → 120 GWh**

also 1,400 TWh in natural and low enriched uranium, but nuclear not used as a buffer in the UK

For Comparison
UK Annual Total, TWh:
Primary Energy 1,960
Final Energy 1,390
including:
Electricity 330

What will play the role of the UK's 170 TWh stored in fossil fuels after they are phased out?

In a high-renewable net 0 world, need new flexible/dispatachable electricity supply and/or storage

Energy Storage in a Net 0 World 2

- **The need depends critically on**
  - **To what extent can we continue to use Fossil fuels plus CCS?**

    Scope is limited: in a net 0 world, CO2 that escapes capture & upstream methane emissions will have to be offset (in strong competition with other demands for offsetting)
  - **How will heat is provided?**

    How much by hydrogen - from Steam Methane Reforming + CCS (also requires offsetting), or electrolysis (puts up electricity demand)?

- I think that **the Committee on Climate Change has been overoptimistic in assuming that CCS can capture 95% in all cases, and in estimating the effects of methane leakage using GWP100**

  The CCC estimates that 90 Mt of negative CO2 emissions will be needed to achieve net 0 in 2050

  If 95% → 90% and GWP100 → GWP40 this increases to 130 Mt CO2

  = the sum of all the possible contributions considered in the RS-RAE GHGR report - 'very challenging'

Need → understand the realism and cost of high capture better + limit leakage + be careful with GWP

and ask: will CCC's assumption of 148 [226] TWh/year of gas power [SMR hydrogen] generation be acceptable?

See back-up slides for more details

Assessing Storage Needs

- Focus on the need for storing electricity and on flexible low carbon electricity supply - mention storage of heat: could → modest reduction in need for storing electricity
- Needs depend on location. Focus mainly on UK* + methods for assessing needs, universal Likewise, technologies universal, although optimal mix is location dependent
- Mainly* discuss work done for RS study with **Tony Roulstone** and **Paul Cosgrove** in Cambridge

  *although describe results of one US study before getting into details of our modelling
- Builds on a lot of excellent earlier work on storage in the UK, Europe, USA etc.

  Most of these studies are partial in one way or another (only look at a single year; only look at current demand – want to look to future; with one exception, all assumed 100% efficiency; none looked at more than one store). Ours deals with these points but is not (yet) complete.

  Closest is work by Mark Barrett et al at UCL (also done for RS study) – paid more attention to details of demand that we did, but assumed storage 100% efficient

Our conclusions agree with Barrett's & other authors' where comparison is possible

Assessing Storage Needs for with High Levels of Renewables

- Analyse

  Residual Demand = (Wind Energy + Solar Energy) - Energy Demand

  over many years (essential), hour-by-hour using data or model for demand + (scaled up) wind and solar data or model

- **Start with 100% wind + solar**, i.e. initially scale wind + solar so that <residual demand> = 0
  Then add other contributions, demand management,…

- Storage is **not** 100% efficient (as assumed in almost all studies): vital to consider < 100%

  To compensate for inefficiencies, need to increase wind + solar supply

  → *decreases the need for storage (deficits decrease; some deficit periods → surplus periods)*

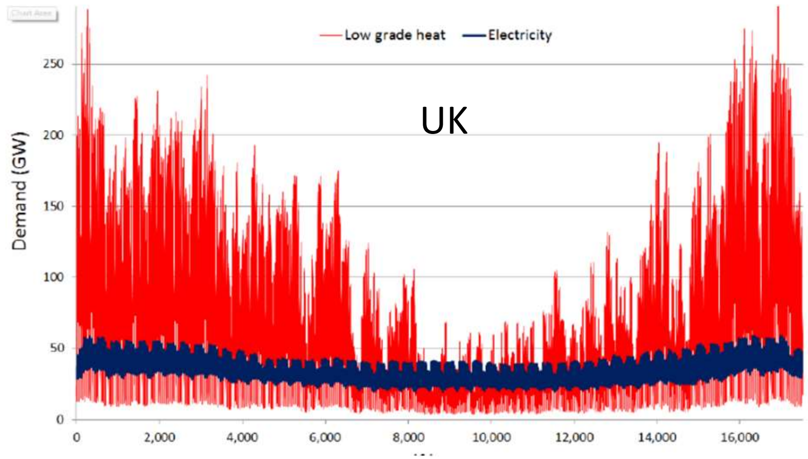
- Will describe study with three stores, with round trip (power → X → power) efficiencies:
  - **Short store** ≤ 6 hours (Li-ion batteries, flywheels, dropping weights,…) **90%**
  - **Medium store** 6 hours to 1 week (Compressed Air, Liquid Air, Pumped heat,…) **70%**
  - **Long store** > 1 week – power to gas with X = hydrogen **40%,** ammonia **25%**

  Return to these and other candidate technologies and their limitations later

Wind and Solar Resource

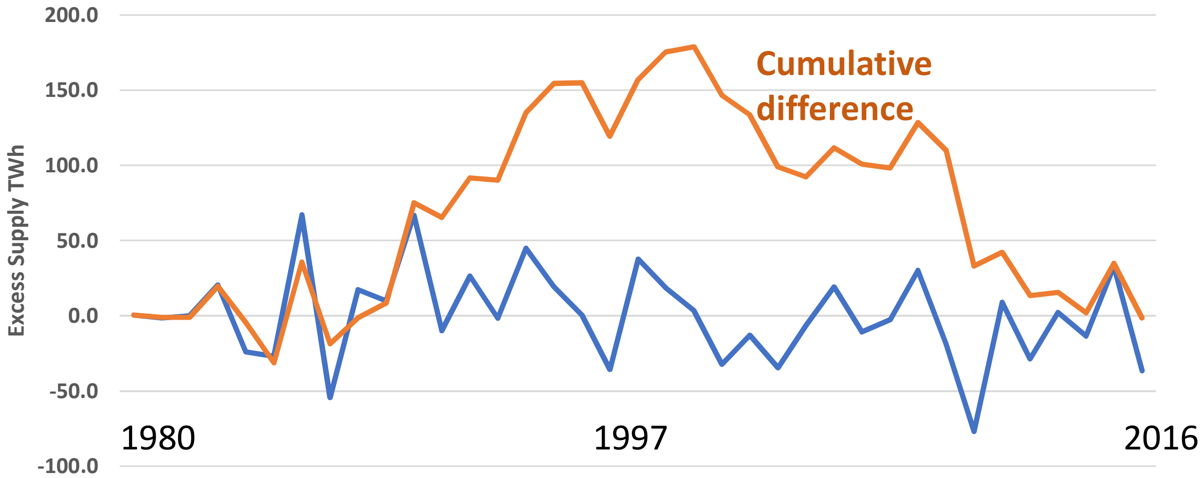
Need many years* of hour-by-hour* (scaled up) wind and solar data or model

* Vital: wind can very by +/- 15% from year to year, there are 'wind' droughts' every few years, demand varies by season and time of day:



UK annual wind + solar* – 600 TWh (approx. 2050 demand)

<wind + solar> = 600 TWh/year



37 years of Ninja renewable data, with 20% solar, 80% wind* (70/30 off/on-shore)

* mix chosen to mimic winter/summer demand

Annual supply varies by +70/-75 TWh
Cumulative excess of 175 TWh 1980-2000 + similar deficit 2000-2016

Extreme Stress Event

Studies of short periods may not only miss year-to-year variations and decadal trends, but may miss some '**E**xtreme **S**tress **E**vents' identified by the Met Office:

Weather Extreme Stress Events	Description	Frequency
Winter wind drought	Up to a week of very low wind speed in winter	Every few years
Summer wind drought – frequent	One full day of very low wind speed in summer	One or two per year
Summer wind drought - infrequent	Up to four weeks of very low wind speed in summer	Once every 10 years

Demand

Use hour-by-hour model (made for the CCC by IC)
of 2050 demand of 600 TWh:

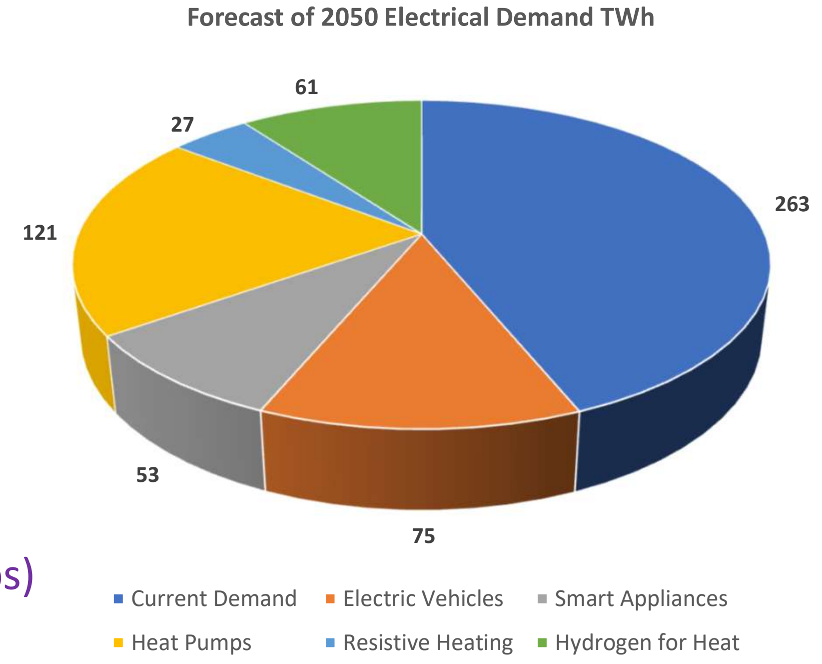
A variety of models are available

Main differences in assumptions about heat and demand for and supply of hydrogen

(if source is electrolysis, no sense using it for space heating

if it's possible to use the electricity supplied → heat pumps
- if not possible, using stored hydrogen → space heat

less efficient than stored hydrogen → electricity → heat pumps)



Then repeat 37 times & combine with 37 years wind + solar 'data' → residual demand

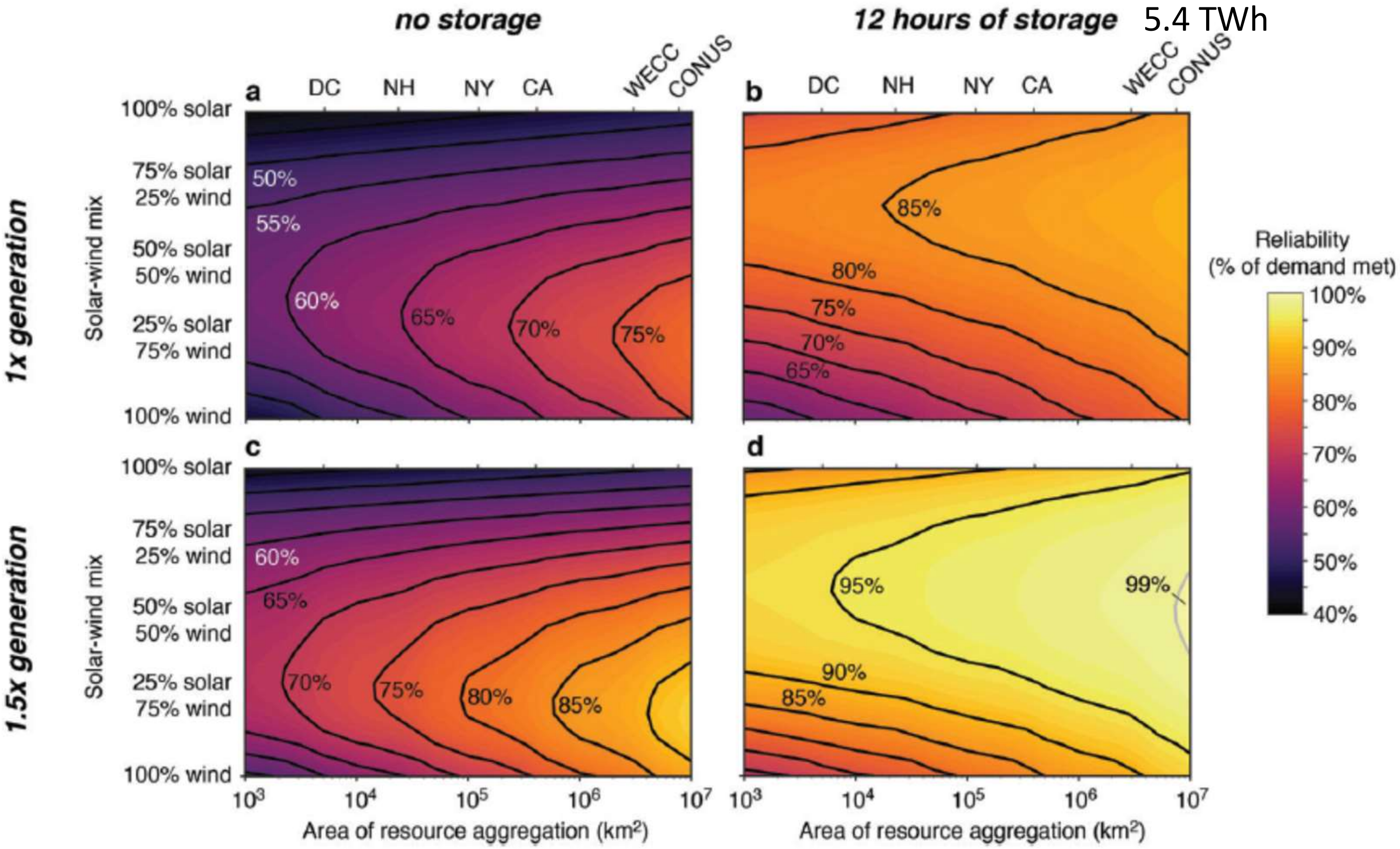
OK as first approximation, although current demand varies by +/- 3% from year-to-year in a way that is correlated with the weather (could try to model at a later stage)

Ignore transmission losses: in reality, if demand is 600 TWh need something like 660 TWh supply

Assuming storage is pre-losses (approx. true - mainly in low voltage distribution network) have to scale up size of stores correspondingly

The US Need assuming storage is 100% efficient

Study (Shaner et al) tried to match US demand (actual 2015-16) with 100% wind + solar supply (based on scaled up 1980-2015 data) aggregated over scales up to 10^7 km^2:



To meet the NERC system reliability **criterion** (loss of load < 0.1 days pa with 99.97% probability), with continental grid:

Need to increase overprovision and/or storage e.g.

With 1.5 x generation, need 400% overprovision

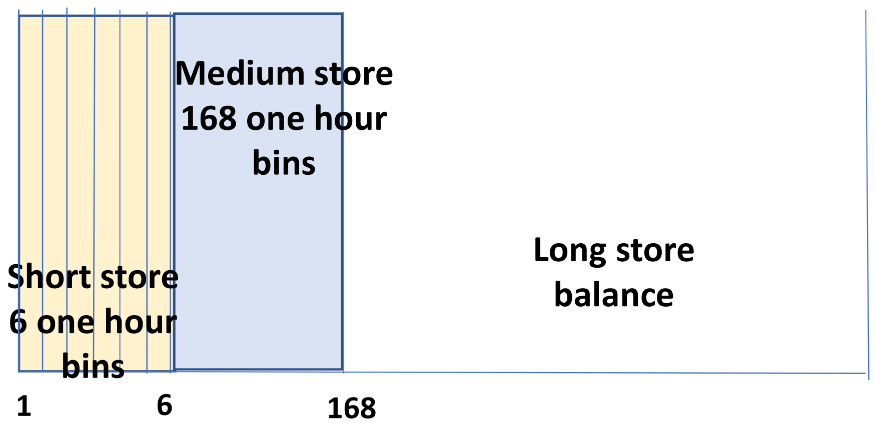
or

With 10% of overprovision, need 32 days of storage (345 TWh)

Also find: the need for curtailment/storage kicks in really seriously at around 70%

Very large grid effective because USA covers different climates and time zones

Energy Storage Studies – Three Tiers of Energy Storage

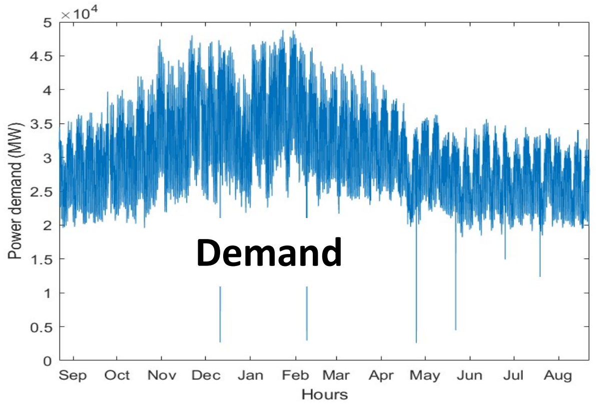


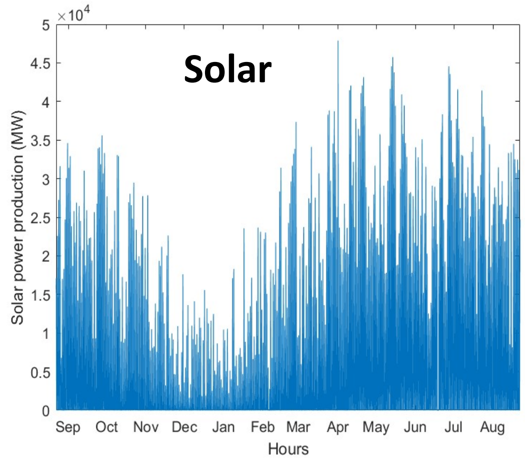
Decisions on despatch and allocation of energy to stores taken hour-by hour on the basis of week-ahead forecasts of weather and demand

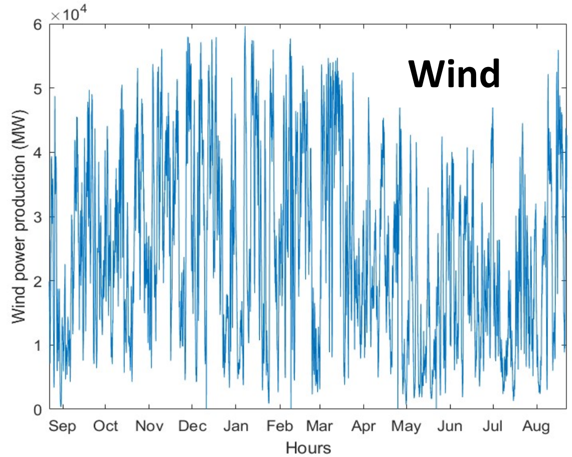
- Multi-level stores reflect different storage needs:
  - Short - balance daily peaks
  - Medium - remove weekly wind & demand fluctuations
  - Long - deal with longer term variations
- Stores constrained in time – one hour bins - not in volume: Short: 6 hours; Medium: 168 hours; Long: else
- Objective is to ensure that forward stored energy is able to meet expected deficits – hour-by-hour starting with Short term store
- At a given point in time, if there is a surplus of energy on the grid, the Short store will store it only but if there is an energy deficit foreseen in the subsequent 6 hours. Subsequently, similar process for Medium store and 168 hours, with the balance into Long store
- Can handle more stores

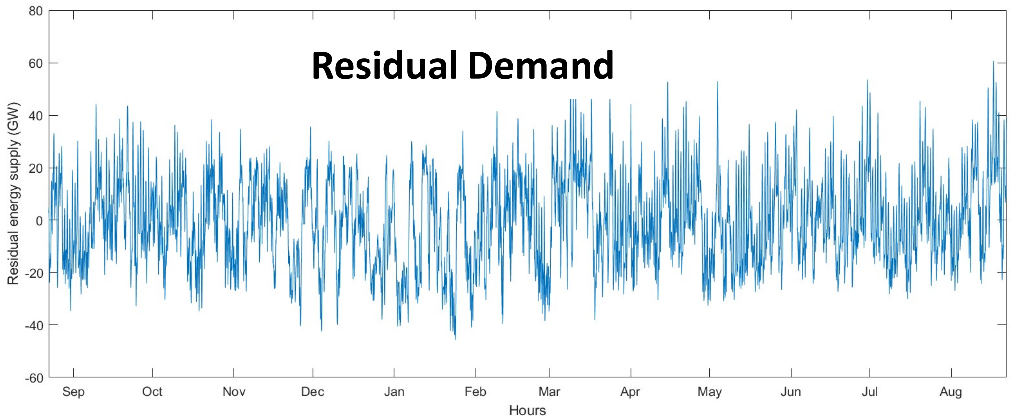
Energy Storage Studies – Start with One Year (simple to explain)

Demand based on current demand 268 TWh with matching supply data based on solar & wind, from GridWatch 2018-19 scaled to provide 100% renewables – **20% solar 80% wind → approximate match of seasonal supply to demand** (15%/85% better)







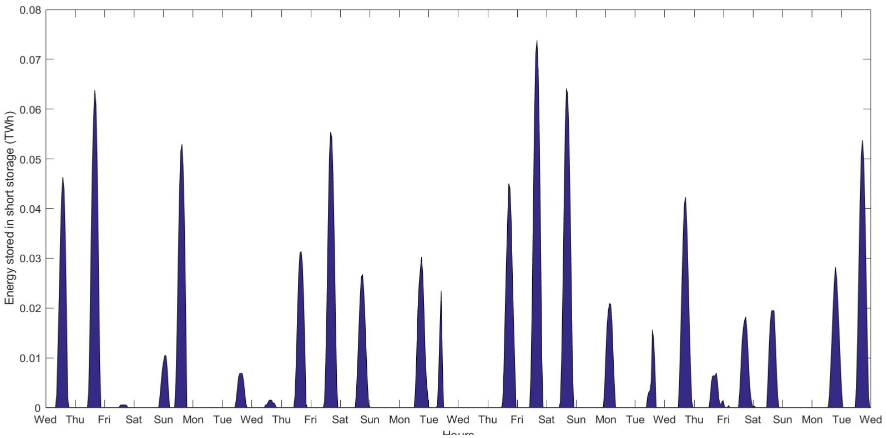


Multi-year studies → if wind/solar mix mimics winter/summer demand (not necessarily → min. cost), major issues are dealing with rare weather events (wind droughts,…) and year to year variations

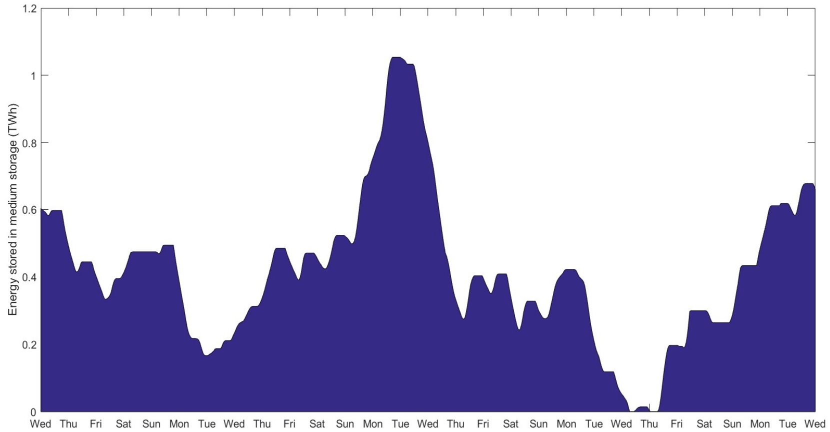
- **not** providing inter-seasonal storage

One Year Data, Three Stores, 100% Efficiency

268 TWh demand (grid watch data) 20/80 solar/wind mix

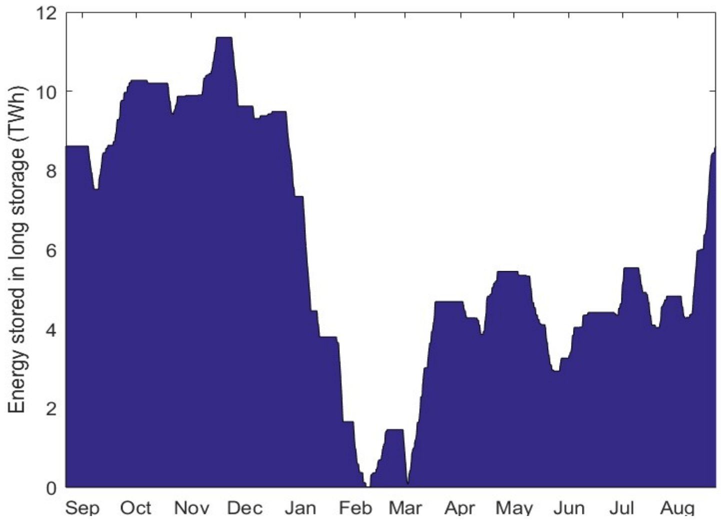


Short: June storage profile (annual on next slide)
Stores up to 100 GWh. Power up to 25 GW.

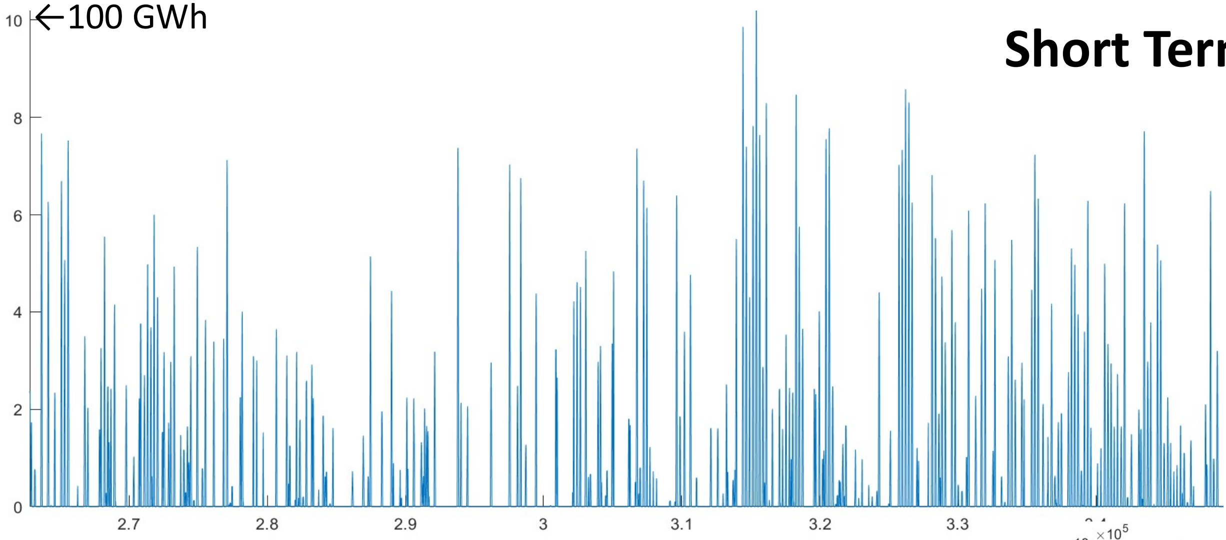


Medium: June storage profile (annual on next slide)
Stores up to 1.8 TWh. Power up to 30 GW.

Long: annual storage profile
Stores up to 11 TWh
Power up to 45 GW.



Annual Profiles - Annual demand 269 TWh, 100% Efficiency

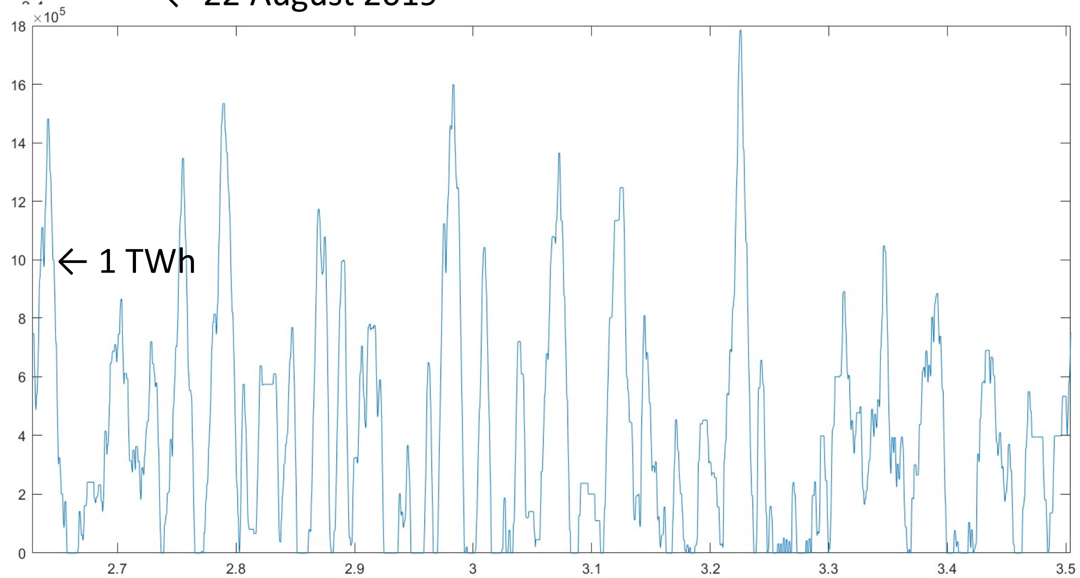


Short Term Store

Only filled if energy can be dispatched within 6 hours

Cycles ~ 100+ times; requires high power capacity 25 GW; delivers 6.7 TWh pa or 2+% of demand, with high discharge ramp rates

Limit capacity to around 60 GWh or less? Depends on how much rapid response storage is needed + relative costs of S and M



Medium Term Store

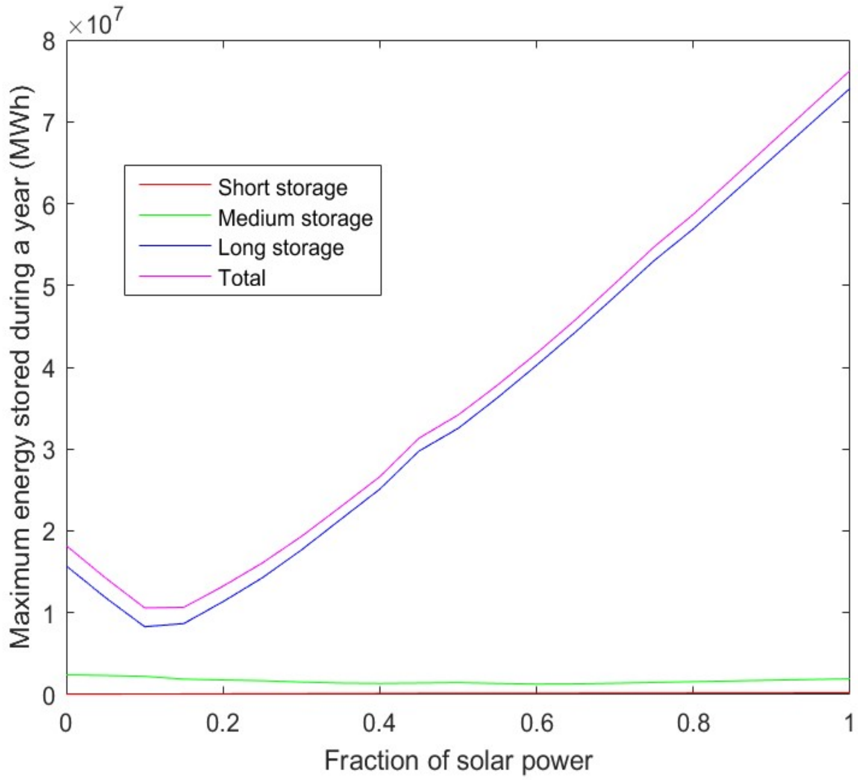
Only filled if energy can be dispatched within 168 hours

30 GW power; delivers 21 TWh pa/8% of demand, with high discharge ramp rates > 3 GW/hr

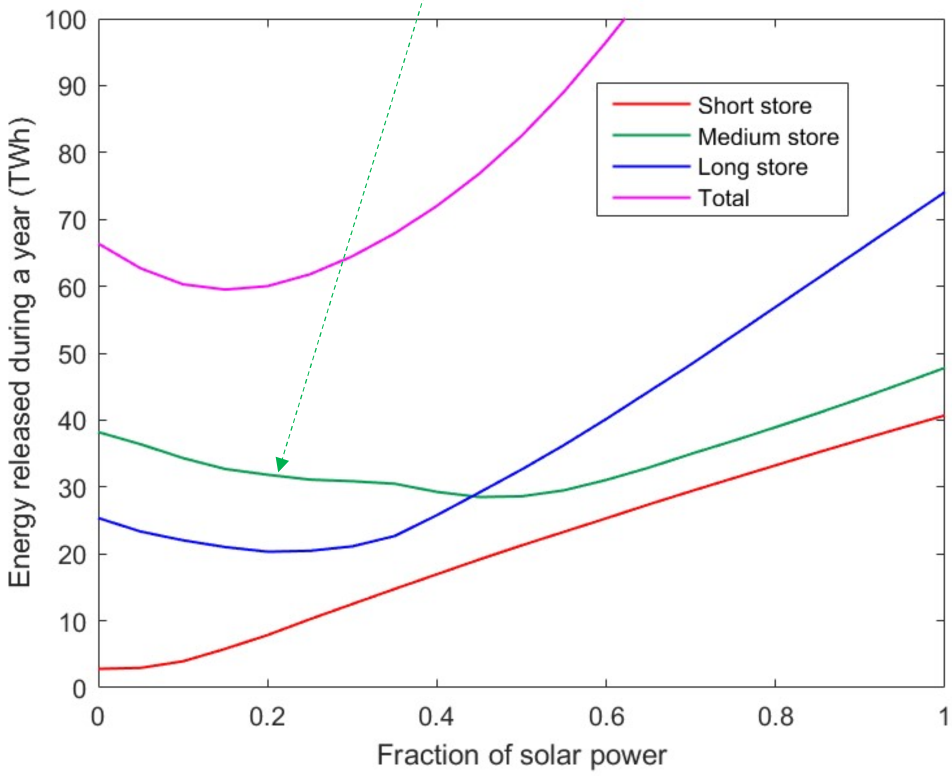
Sensible to limit capacity to 0.8 -1 TWh?

One Year Study – Store Sizes & Energy Released. 100% Efficiency

- Long store dominates sizing. At 10-15% solar: Long ~ 10 TWh, Medium 1.8 TWh, Short ~ 100 GWh
- Energy released is large - 60 TWh (22% demand). At 20% solar: **largest contribution from Medium Store**



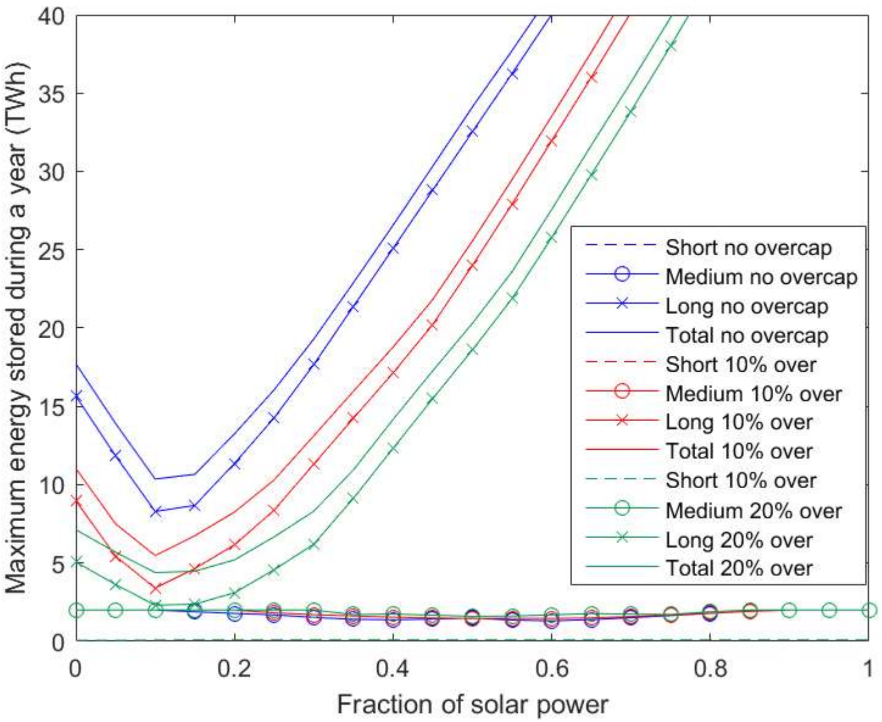
Store size v Mix



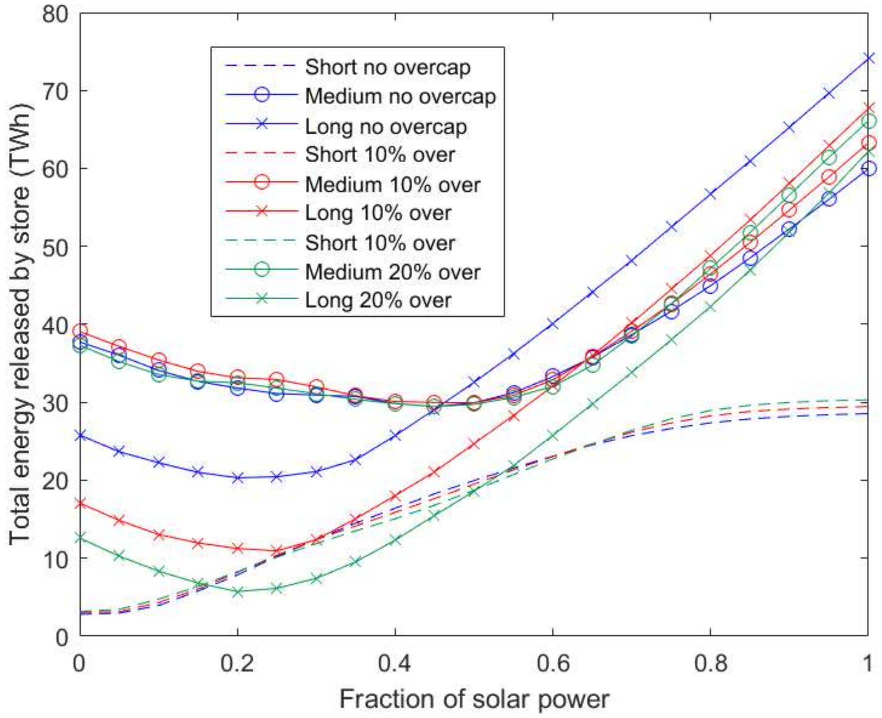
Energy release v Mix

One Year Study – Over-capacity. 100% Efficiency

- Overcapacity reduces size of L and energy it releases - less effect on M and S
- Diminishing benefits of overcapacity and related curtailment above 10%



Store size v Mix



Energy release v Mix

One year study with inefficiencies: hydrogen vs ammonia

- see (not very enlightening) slides in back-up material for details

Efficiencies: Short 90%, Medium 70%

Long 40% (typical of NH_3)

- Need at least 18% overcapacity to ensure supply always meets demand, because of losses
- Inefficiencies increase store sizes - factor of order 3 for the Long Store for 20% overcapacity, 15-20% solar
- With fixed overcapacity, the amount to be supplied by store does not depend on the efficiency – but inefficiencies decrease the safety factor
- To restore the safety factor, have to invest in more overcapacity

Long 25% (typical of H2)

- Need at least 14% overcapacity to ensure supply always meets demand, because of losses
- With fixed overcapacity, the amounts to be put into L are bigger by a factor 40/25 = 1.6 for NH3, and its size is bigger by the ratio of the input efficiencies - but storage losses decrease the safety margin
- To get the same margin, need a bigger overcapacity with NH3 → more investment in generating capacity + bigger store than for H2 (not by quite as much as with equal overcapacities as increased overcapacity decreases the need for storage)

H2 (40%) vs NH3 (25%) Efficiency

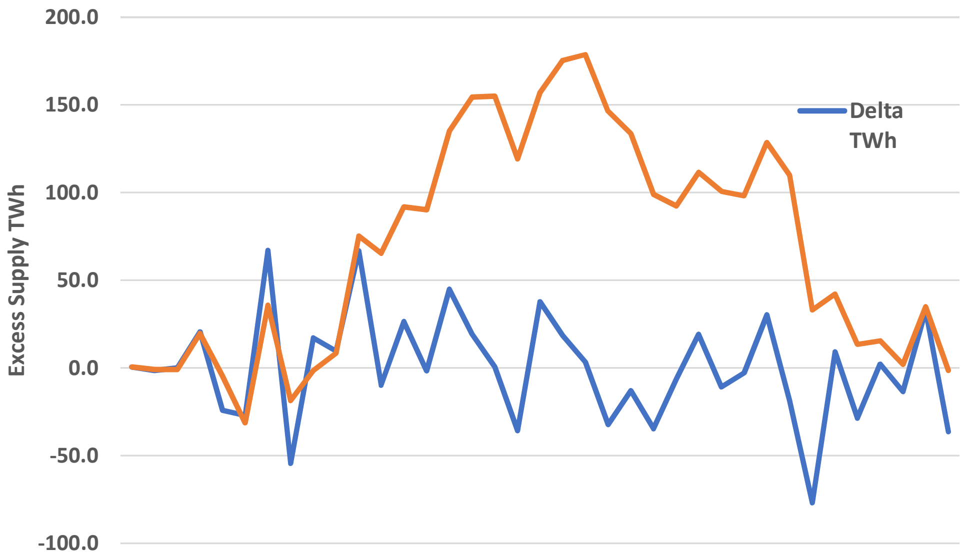
- **Hydrogen is obviously cheaper to produce** (for a given cost of energy) **and less is needed, but it is more expensive to store unless in salt caverns**
  Is the UK capacity sufficient?
  Yes. BGS due to publish new estimates, including 250 - 300 TWh for the maximum theoretical for Cheshire – roughly an order of magnitude higher than previous estimates
  What about power?
  Extraction may be limited to 10%/day (to respect integrity of caverns) - **not a problem**

- **Ammonia may be much than cheaper UK-made H2 when made using very low cost solar power in (e.g.) Morocco → could be best bet for** powering ships, providing industrial heat,…(see back up slides for more on the ammonia and hydrogen)
  - **but** for providing electricity to **buffer renewables** it makes no sense, more ammonia than hydrogen is needed, and the whole idea is to use excess UK renewable power to make it

Focus on hydrogen from now on

Multiyear – Annual Variations in Wind Dominate

Return to 37 years of wind + solar – constant 600 TWh/year:



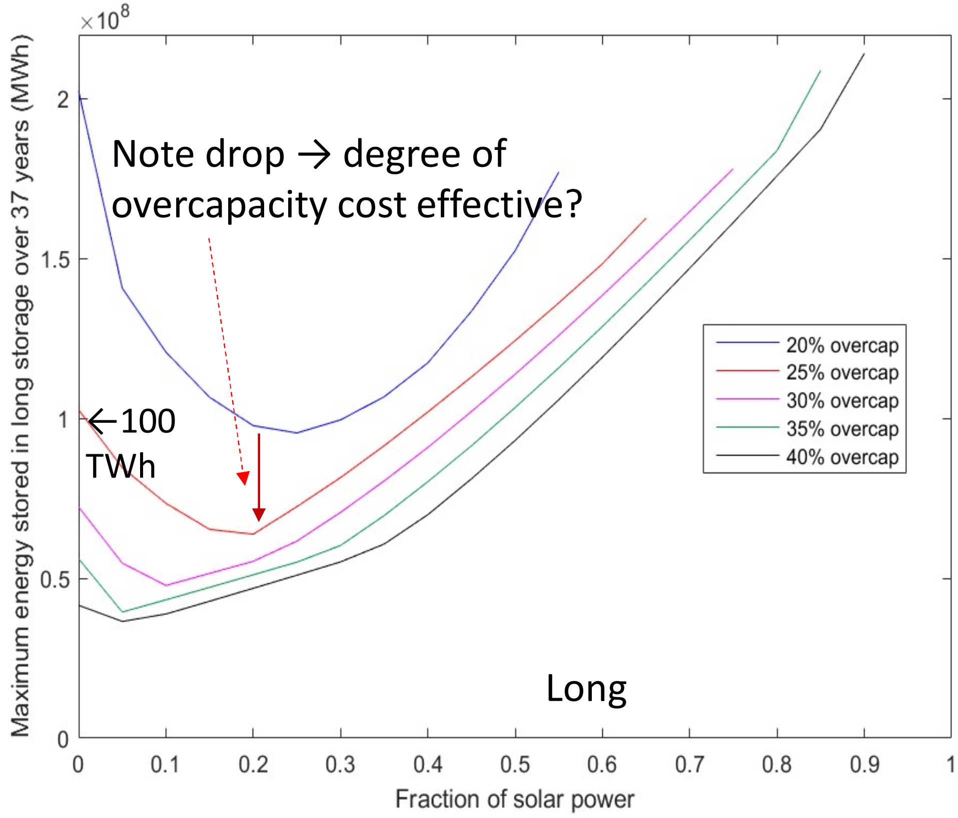
Need to shift energy from 1980-2000 →2000-2016

To understand, added a hypothetical (not realisable) **V**ery **L**ong **S**tore (>180 days, or 1 year)

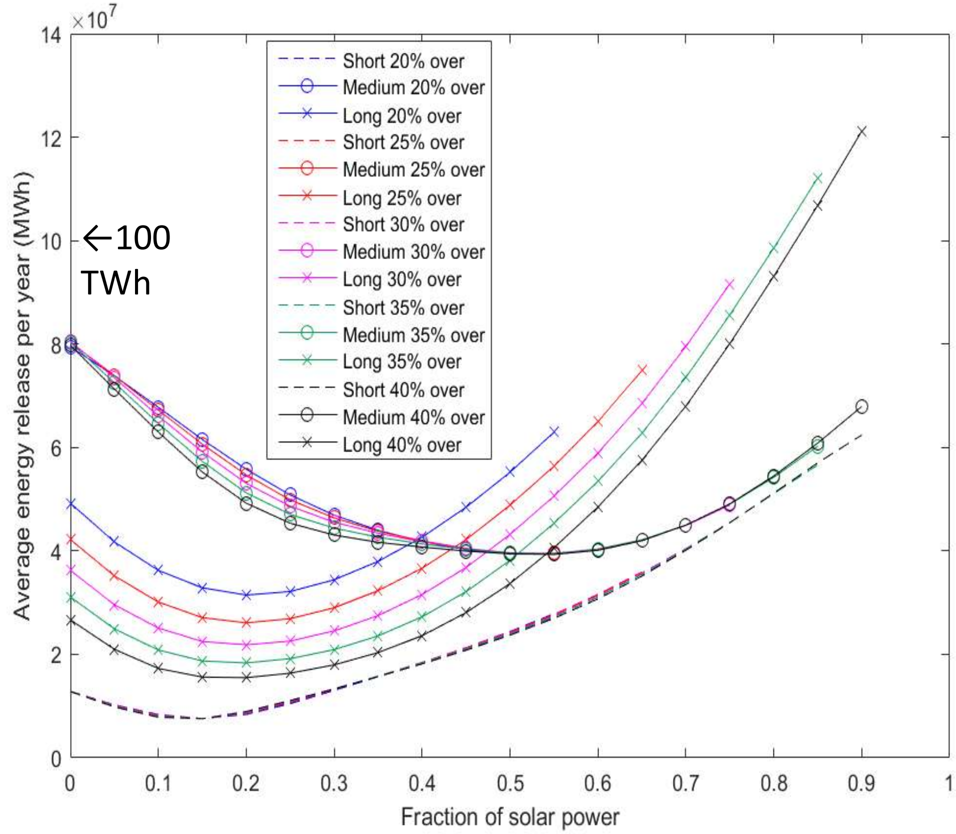
Overcapacity:	0	6%	10%
Stored in **VLS**:	~ 200 TWh	40 TWh	10 TW

In practice (some overcapacity needed as a safety factor & cost effective?) very long term storage minor: no need to distinguish VLS and LS.

Multi-Year, Efficiency ≠ 100%, L – 40% (H2)



Maximum Stored



Average Energy Released

With 20% overcapacity at 20% solar:
Maximum in M = 0.074 x 10^8 MWh = 7.4 TWh
Maximum is S = 0.0024 x 10^8 MWh = 240 GWh

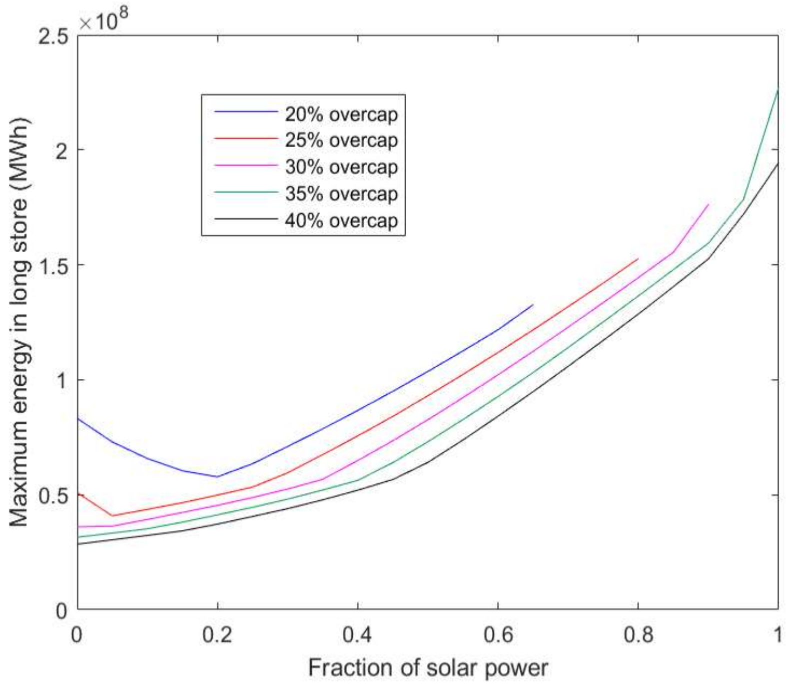
Multi-Year, Efficiency ≠ 100%, L – 40% (H2)
With 25% Baseload

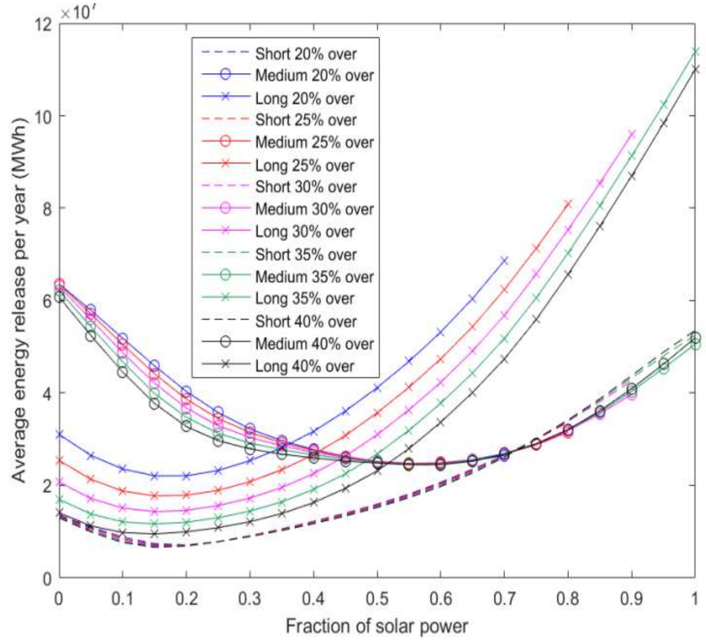
i.e. baseload = 25% of demand = 150TWh/year. Overcapacity of (e.g.) 20% means renewables + baseload = 1.2 x demand

Reduces range of renewable variations → large reduction in storage e.g. at 20 % solar

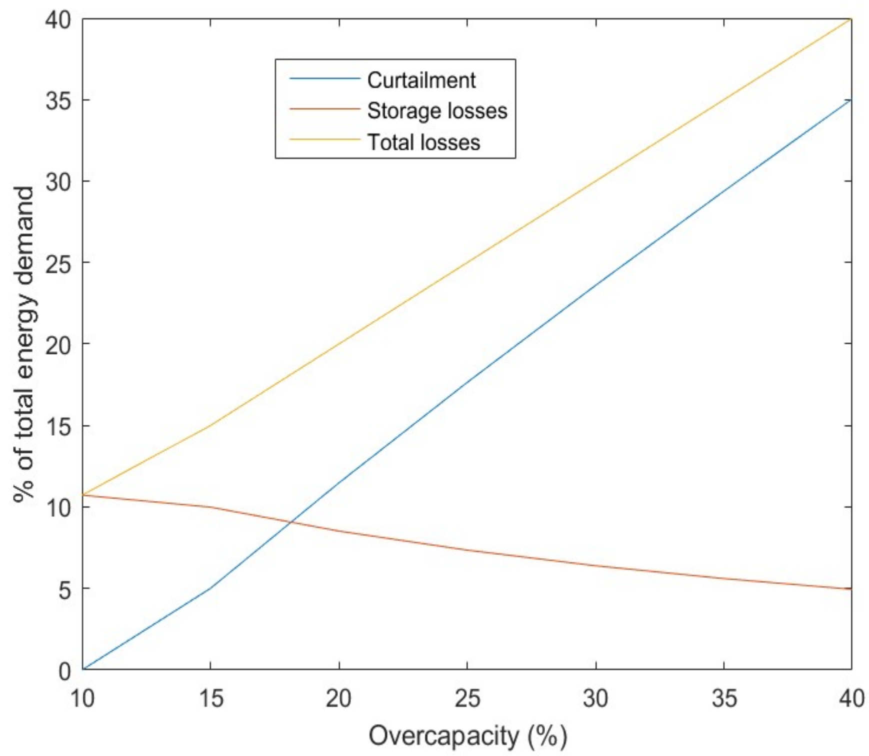
Maximum energy in L reduced from 100 TWh to 55TWh

Annual energy released by M recued from 50 TWh to 40 TWh





Losses and Curtailment vs. Overcapacity, with 25% Baseload Efficiency ≠ 100%.   L= 40% Hydrogen



Some excess overcapacity (above that need to compensate inefficiencies) could be cost effective - being studied, together with varying baseload size (see one back-up slide), **adding dispatchable low-C power,…**

37 Year Study with 100% Wind + Solar →

- Multi-year study essential
- Minimise storage with 15-20% solar/wind mix: might want more depending on costs
- Inefficiencies matter. Need capacity above that needed to compensate for them – safety margin, reduces long-term storage - could lower cost
- Medium term store does much of the heavy lifting
- Significant baseload (not surprisingly) → large reduction in storage need

Now consider adding

- Demand shifting (demand reduction from efficiencies taken into account in 2050 model) – will ignore:

  Potential to shift expected to increase (to 5-11 GW), but only for a few hours

  Some shift will be automatic. In periods of surplus supply, prices will drop: will this shift demand, or create new demand ? Need ideas for use that can happen at any time (drying biomass,…)?

  In extremis – very rare events – could → '3 day week': politics?

- Baseload + flexible backup

  Gas + CCS, BECCS + CCS or Nuclear - like to run in steady state, but can vary

  Methane fuel cells + CCS – looks as if it could be flexible, capture relatively easy

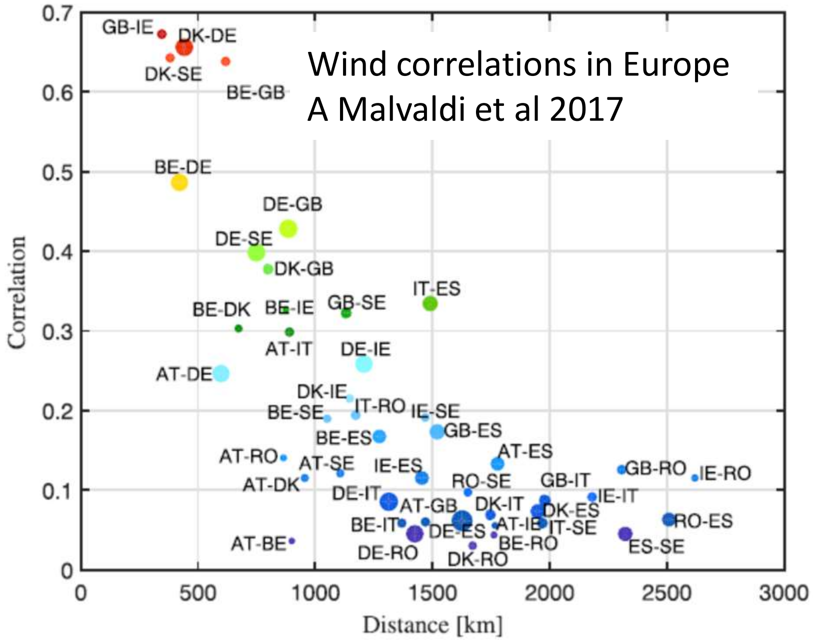
  } So far treated as baseload – will study flexibility

- Large grid/interconnectors →

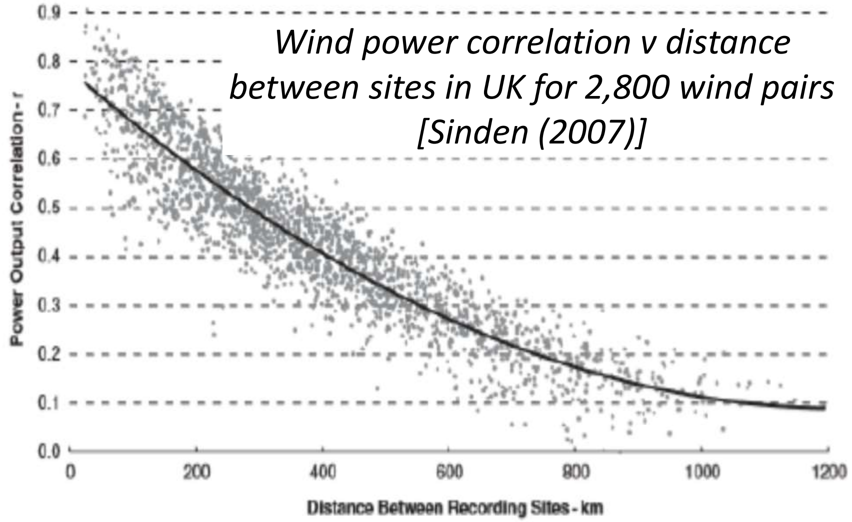
Large Grid/Interconnectors

- Beneficial effects of a hypothetical continental grid in the USA shown earlier – would average across different climates and weather systems + aggregating different time zones smooths out peaks in demand
- Potential benefits for Europe are not as big as area much smaller

Not a panacea – there can be wind droughts across Europe – but geographical spread helps with solar & wind:



while minimising correlations should be a criterion for siting wind farms in the UK:

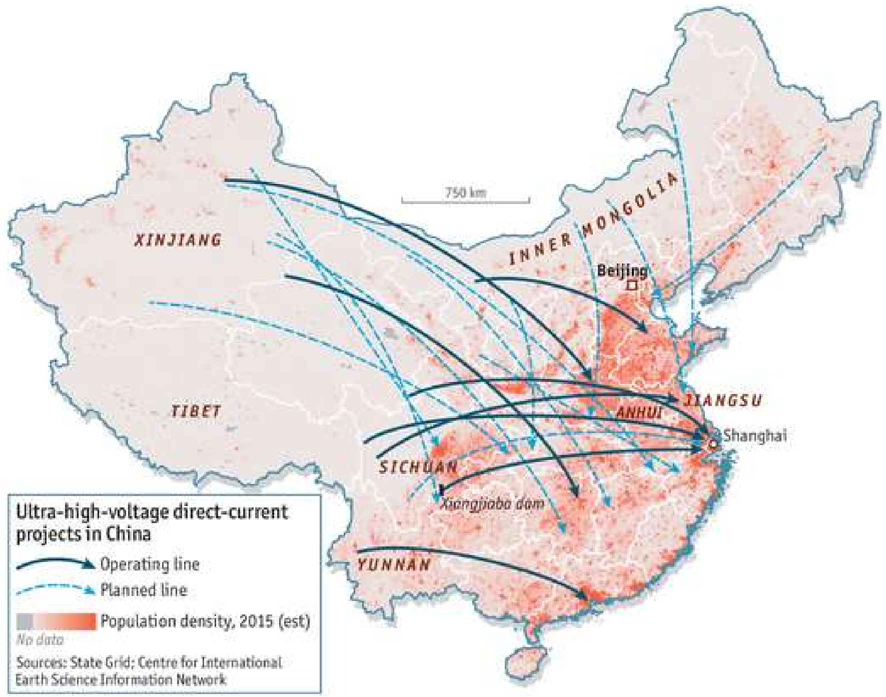


Politics a barrier →

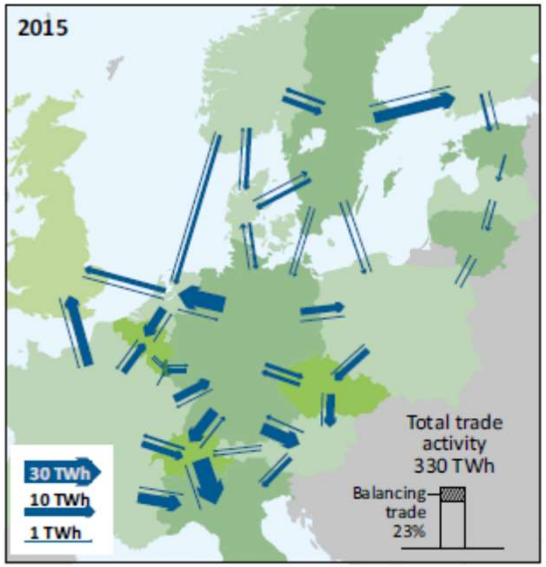
Supergrid. Happening in China:

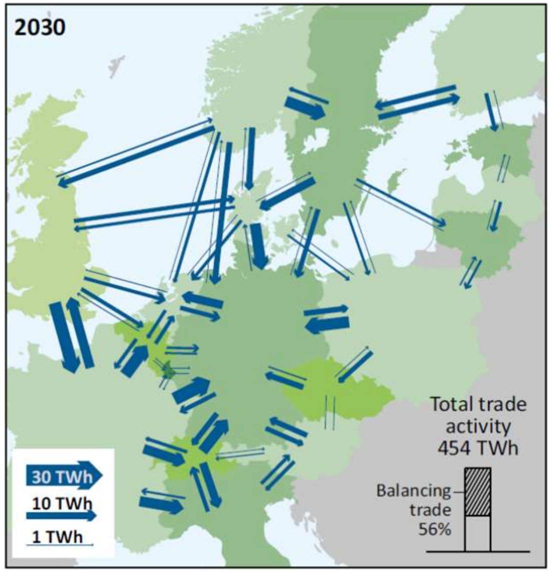
lines under construction in India, Brazil, USA,…

Singapore considering3,800 km link to Australia



But not in Europe where it could lower cost of solar/wind in Germany by bringing power from the south/west of the continent, link to storage capacity in Scandinavia….





Costs

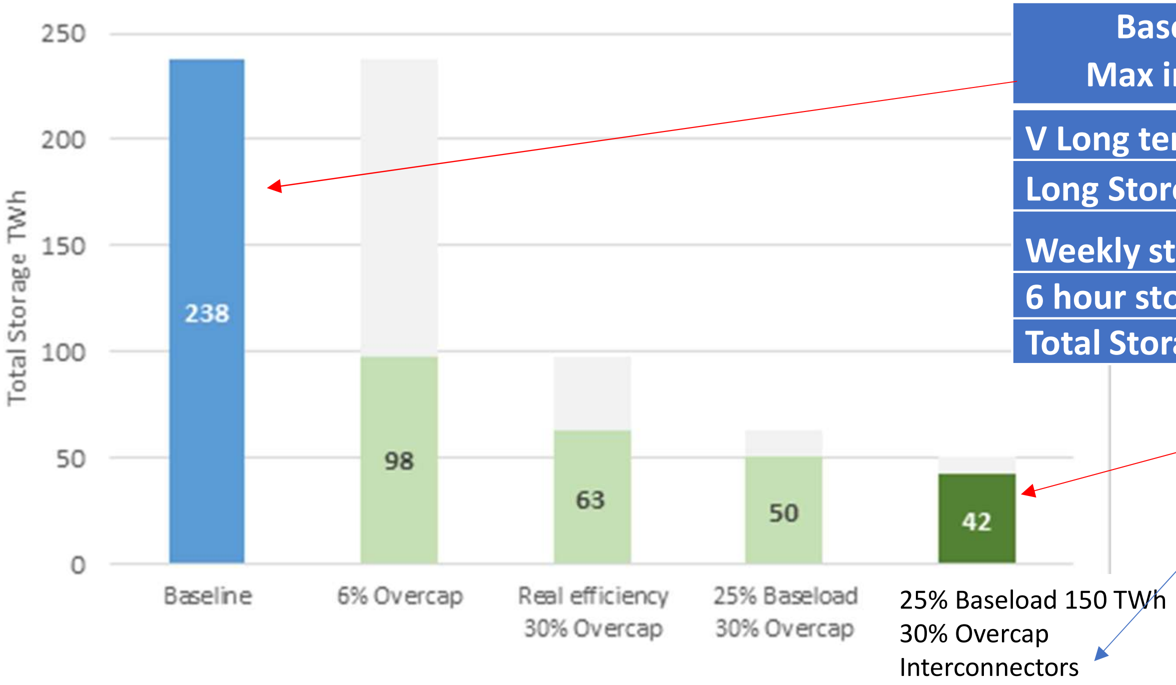
On land $1m/GW/km – 3-4 times more undersea?

Losses

Transmission 0.3% per 100 km

Conversion Ac/DC 1-2%

Magnitude of UK Long-Term Storage Need



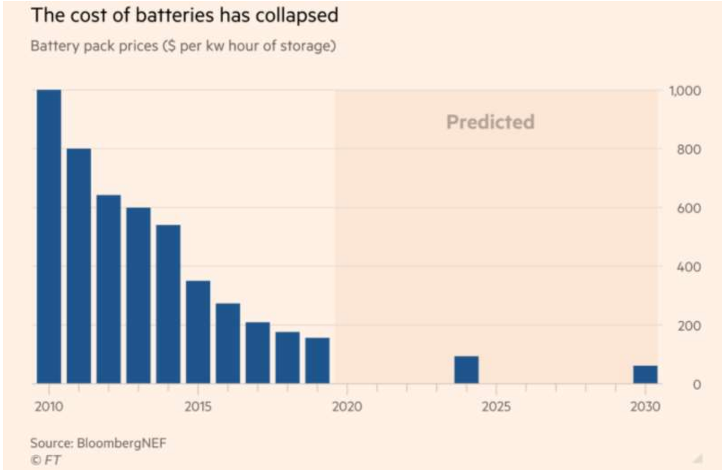
Baseline Max in 37 Years	Power GW	Stored Energy TWh	Av .Energy from Store TWh p.a.
V Long term Store	40*	180	11.6
Long Store ≤ 1 year	15	50	45
Weekly store	80*	7.5	62
6 hour store	120	0.33	8
Total Storage TWh	* ESE need	238	127

Estimate – Tiziano & Barrett of effect of 20 GW of flex. interon. supply – in& out	Max Power GW	Max Stored TWh
Very long term store	30*	10
Long Store ≤ 1 year	10	27
Weekly store	60*	5
6 hour store	90	0.17
Total Storage		42

Multi-year Storage Waterfall - where we are today, **but more work needed on incorporation of flexible low C power and costs* -** ideally should optimise for costs, but given uncertainties in demand, supply and storage technologies this would probably be premature

*Caution with costs in recent NIC power paper, which is bullish on hydrogen. The costs of storing and transmitting hydrogen are not included. At one point it suggests burning SMR + CCS-derived hydrogen in turbines to make power (methane + CCS surely cheaper). Discussion of weather effects is left pending. Seems to omit aspects that our model includes. The treatment of nuclear is cavalier – in my opinion.

Candidate Storage Technologies



Short term (frequency, voltage regulation,...) **– hours**

- Batteries – not economic unless cycled frequently
  - flow batteries could be used up to a day or so
- Flywheels
- Dropping weights

Medium term – up to a week

- Pumped Hydro – UK expansion limited
  Norway could provide Europe with 123 TWh by linking existing reservoirs + constructing new ones linked to them
- Compressed Air - optimum charge/discharge in 1-5 days: cost-effectiveness decreases with time
- Liquid Air - *could provide TWh storage for the UK*, **but** economics and cycle efficiency require storing heat of compression and cold from evaporation
- Pumped Heat - cost probably prohibitive unless cycled frequently

Long-term – weeks, months….

- Ammonia and hydrogen
- Thermochemical – need large heat input (concentred solar, nuclear). Viability ~ cost + temperature + energy density (low in cases I've looked at) + … claimed there are possible candidates: *need more work*
- Synthetic fuels – fuels made from captured CO2 look unattractive (best to bury it); Liquid Oxygen Hydrogen Carriers could provide local heat and power on a TWh scale

Storing heat could help with winter/summer demand difference: Solar heat → store in summer → district heating in winter - significant numbers in Germany, … 80 GWh system proposed in Austria. *Could contribute on TWh scale in UK*

Questions about Candidate Storage Technologies include:

- System value: what need would it fill, and what value does it provide for the whole system?
- Suitable for large (TWh) scale (aggregated central or/and distributed) storage? Limits on scale (technical/financial)?
- Suitable for storing for weeks, months, years? Technical (self-discharge rate) and/or financial limits?
- Limits on rate of charge/discharge (power)?
- Other technical characteristics: safety (can dangers be mitigated?), technical limits on location, environmental impacts (any residual greenhouse gas emissions,…), efficiency,…?
- Likely future cost (CAPEX, OPEX, Levelised Cost of Electricity when used in different ways)? Sensitivity to discount rate?
- Potential Synergies, e.g. use of Nitrogen from LAES to make NH3, oxygen from electrolysis for oxy-combustion to facilitate CCS,…?
- Social acceptability?
- Readiness (how soon could it be deployed)?
  - Technical Readiness Level?
  - Need for more R&D and/or demonstrators?
  - Could it benefit from existing infrastructure?
  - Potential supply chain issues?
  - Limits on speed of installation?
- Will market reforms (if so what?) and/or changes in regulations be needed to encourage timely deployment?
- Does it store energy in a form that could be imported from places where renewable energy is very cheap?

Concluding Remarks

- To assess the need for storing electricity in a high renewable world must look at many years of supply and use efficiencies ≠ 100% + different stores
- Big questions on UK demand: How will heat be provided? How much hydrogen electrolysis/SMR + CCS? Need to re-examine pre net 0 views on using hydrogen (from SMR) for space heating
- Big questions on supply: How much gas and BECCS + CCS will be tolerable? How much can CCS capture, at what cost? How much can we limit methane leakage & how she we account for the effects? Availability of biomass. Future of supergrids/interconnectors?
- Likely UK will need 10s of TWhs of electricity storage – most for 6 hours-1 week, but short term essential (grid services), amount of long-term critically dependant on answers to above questions about demand and supply
- RS study still work in progress – needed more on incorporation of flexible supply, minimisation of cost (so far focussed in minimising storage)
- Improved electrolysers and hydrogen and ammonia fuel cells/engines would enable low carbon solutions in many domains

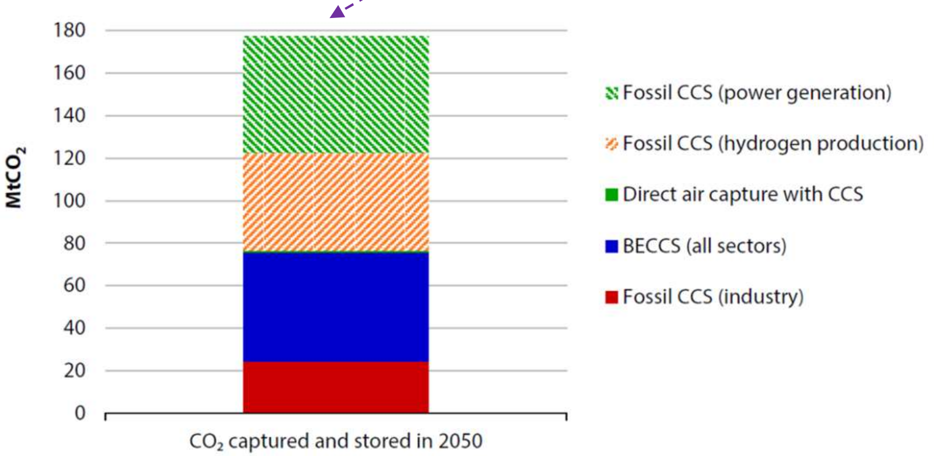
Final remark: there is currently no market for medium or long term storage. Need to understand who benefits from storage and design a market that requires them to pay their share to the providers – *before it's needed*: otherwise we may get stuck with a suboptimal system

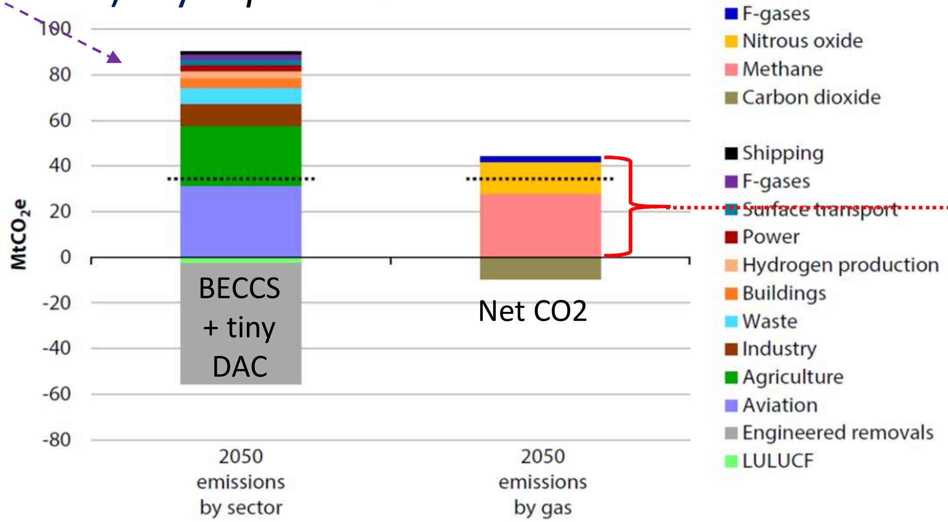
Back Up

With 40 % efficiency (NB – CCS lowers efficiency) **100 TWh of gas power → 50 Mt CO2**

The **CCC assumes CCS captured 95% in all cases** – reference says 'going from 90% capture to 99% in a NGCC plant would only increases the LCOE by 7%' - **but** *it is essential that these findings are now demonstrated in practice*

The Carbon Capture and Storage Association (and others) says *up to 90%*





Based on GWP100. Effects bigger for < 100 years

Upstream methane leakage. Using GWP100*, 1% leakage** of CH4 is 'equivalent' to failing to capture 10% of CO2

*means integrated climate forcing would be the same after 100 years - **but** in 100 years we may have passed a tipping point: meanwhile the temperature effect of CH4 is *much* bigger

**Oil and Gas Initiative - target 0.25% leakage in 2025 (longer term ambition of 0.2%): say 2012 baseline was 0.32% - *very small* compared to the numbers usually quoted (which include Russia, LNG imports,…)

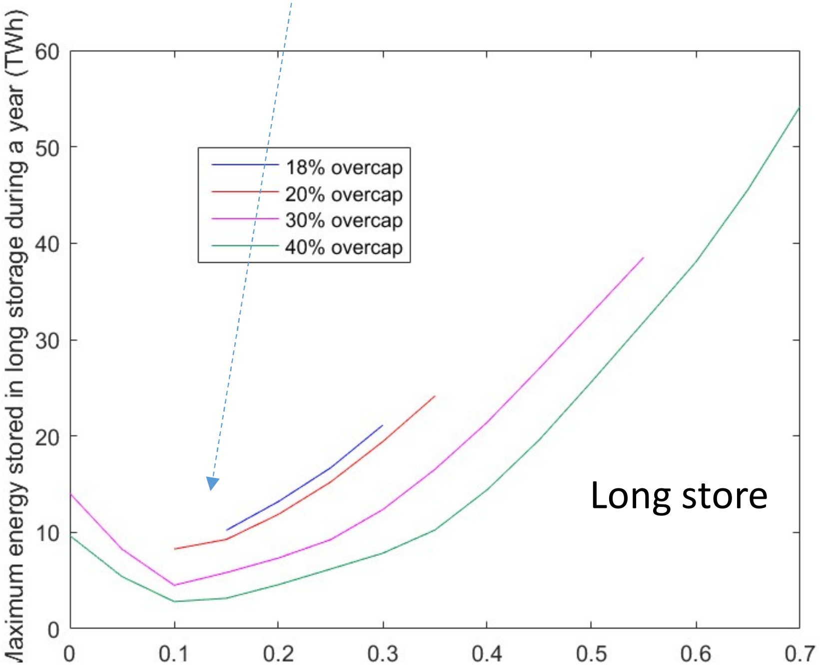
→ dangerous to assume uncaptured CO2 + effects of leakage amount to less than 20%

Same in SMR (→ 0.25 Mt CO2/$TWh_{thermal}$ hydrogen), although CCS easier than in power - CO2 relatively concentrated

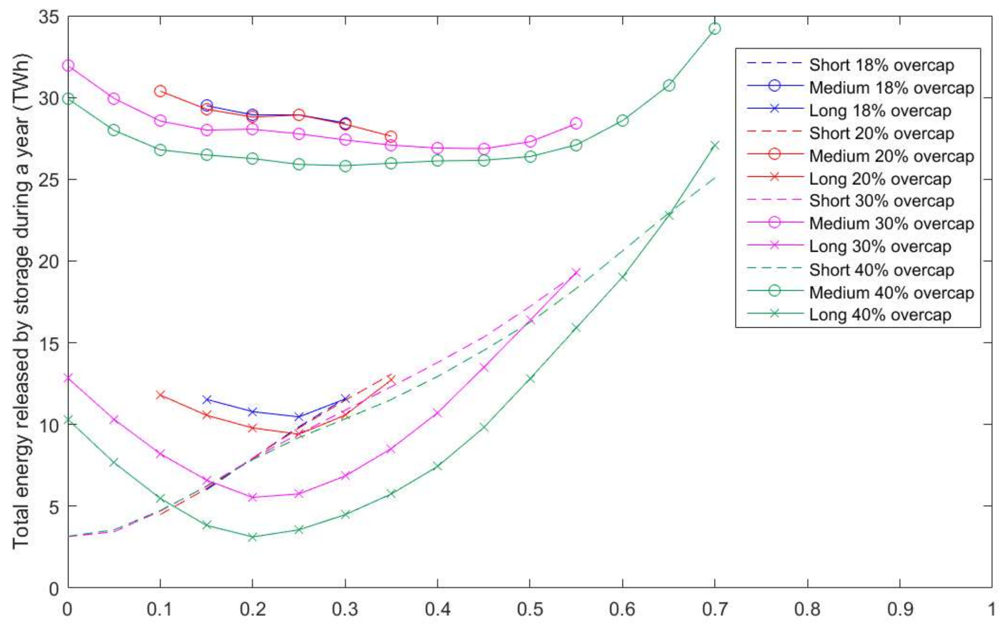
One Year – Over-capacity with Efficiency ≠ 100%

Storage round-trip efficiencies - Short 90%; Medium 70%; **Long 25% (typical of NH_3)**

- Need at least 18% overcapacity to ensure supply always meets demand, because of losses
- Inefficiencies increase the store sizes, by a factor of order 3 for the Long Store for 20% overcapacity, 15-20% solar
- For fixed overcapacity, the amount to be supplied by store does not depend on the efficiency – but inefficiencies decrease the safety factor
- To restore the safety factor, have to invest in more overcapacity



Store size v Mix

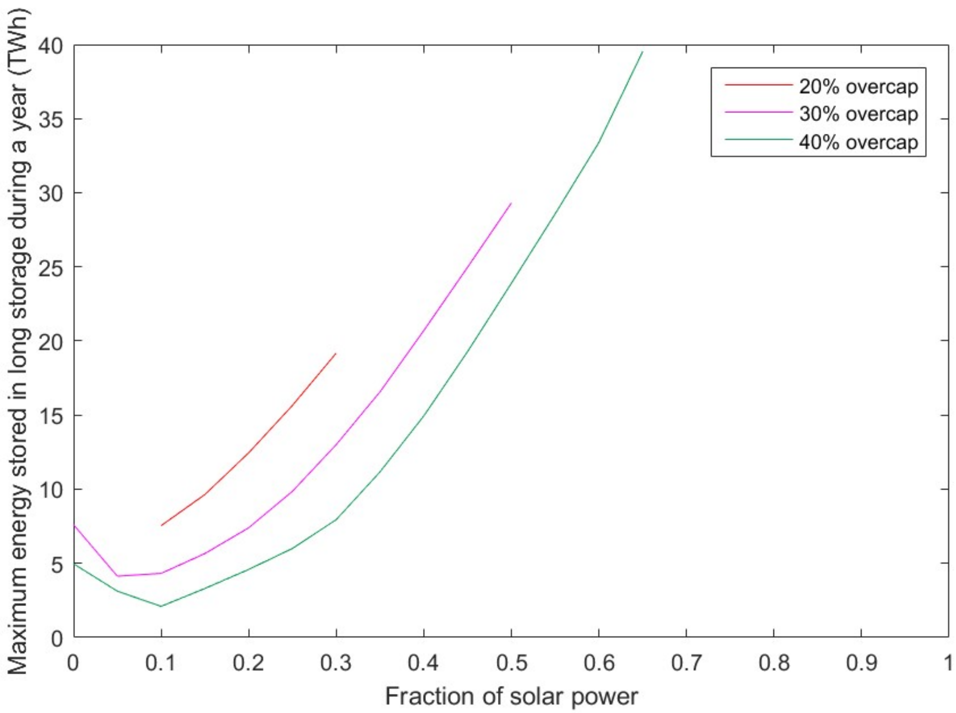


Energy release v Mix

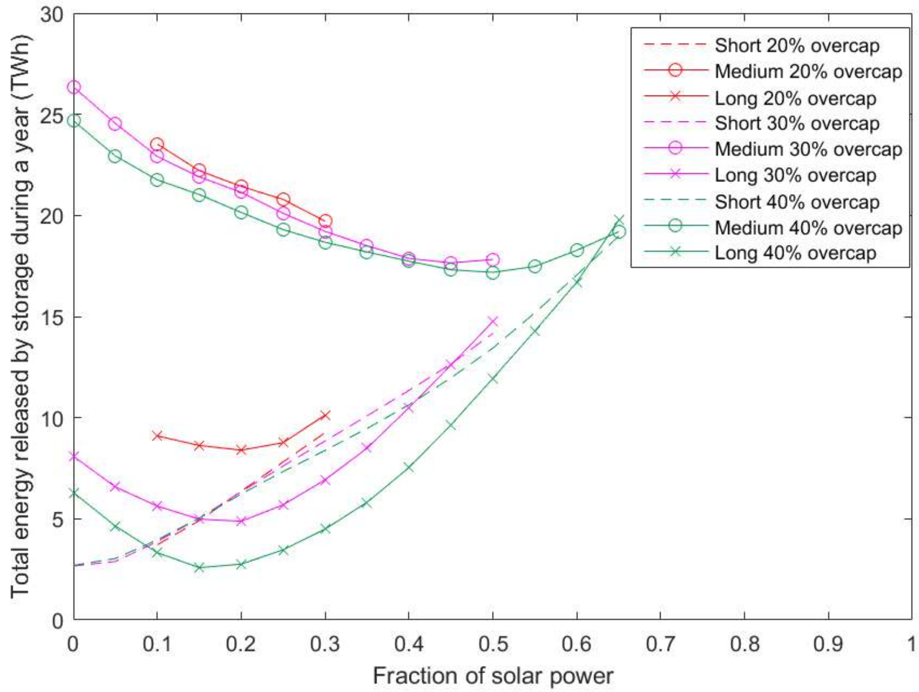
One Year Study with 25% Baseload. L = NH3 (25%)

i.e. baseload = 25% of demand (268) = 67 TWh/year. Overcapacity of (e.g.) 20% means renewables + baseload = 1.2 x demand

- Baseload– nuclear &/or Bio-mass - reduces range of renewable fluctuations
- Reduced Long store size - 5 TWh for 30% over-capacity
- Reduced energy released ~ 30 TWh at 20% solar, 30% overcapacity



Store size v Mix

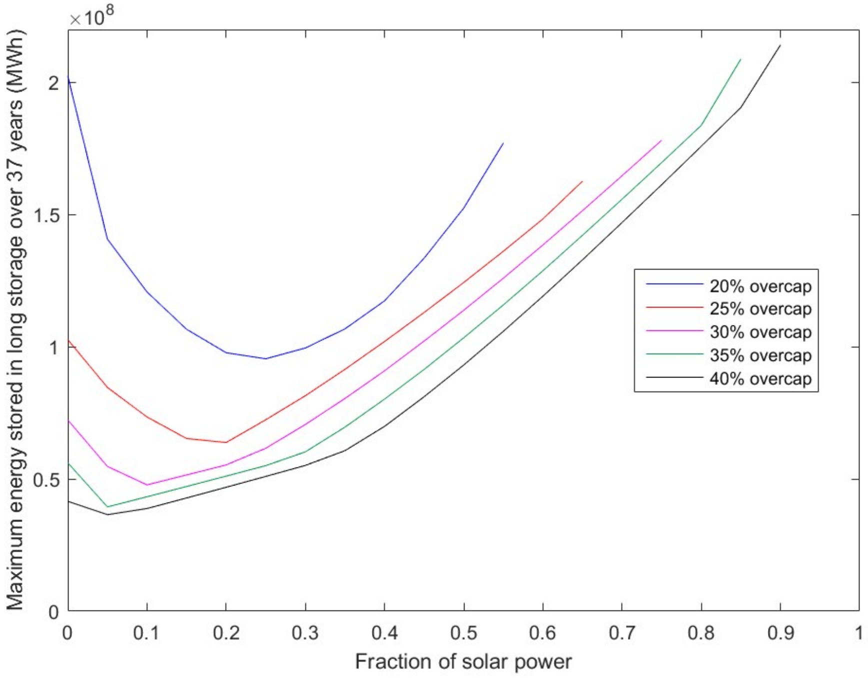


Energy release v Mix

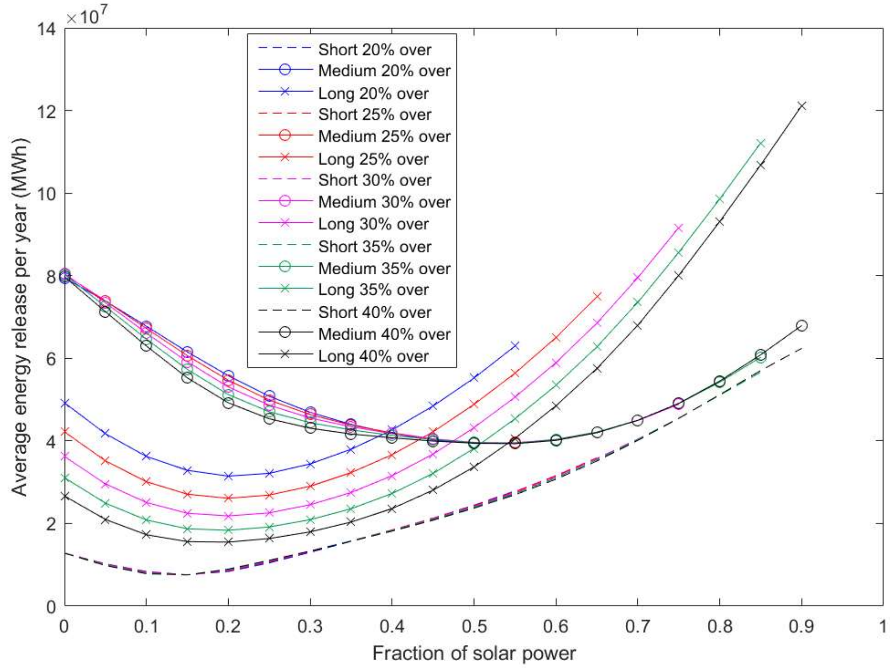
One Year Study with 25% Baseload. L = H2 (40%)

i.e. baseload = 25% of demand (268) = 67 TWh/year. Overcapacity of (e.g.) 20% means renewables + baseload = 1.2 x demand

- Baseload – nuclear &/or Bio-mass - reduces range of renewable fluctuations
- Reduced Long store size - 5 TWh for 30% over-capacity
- Reduced energy released ~ 30 TWh at 20% solar, 30% overcapacity

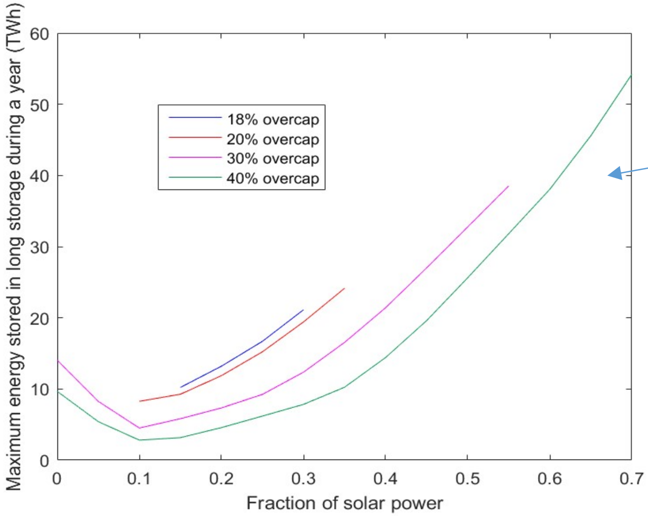


Store size v Mix



Energy release v Mix

One Year Study – H2 (40%) vs NH3 (25%) Efficiency



Efficiencies

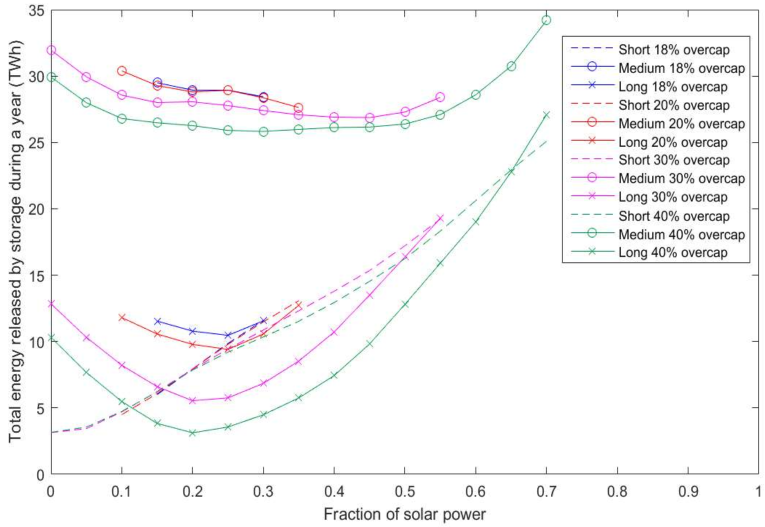
As before

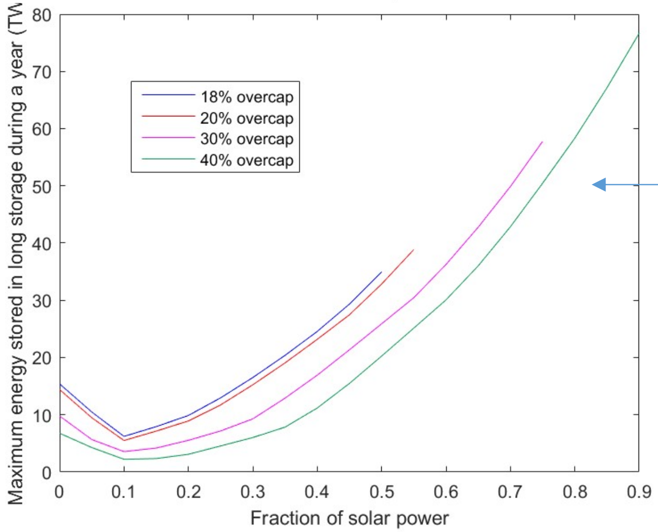
S = 90%

M = 70%

L = 25 % (NH3)

Min Overcapacity 18%



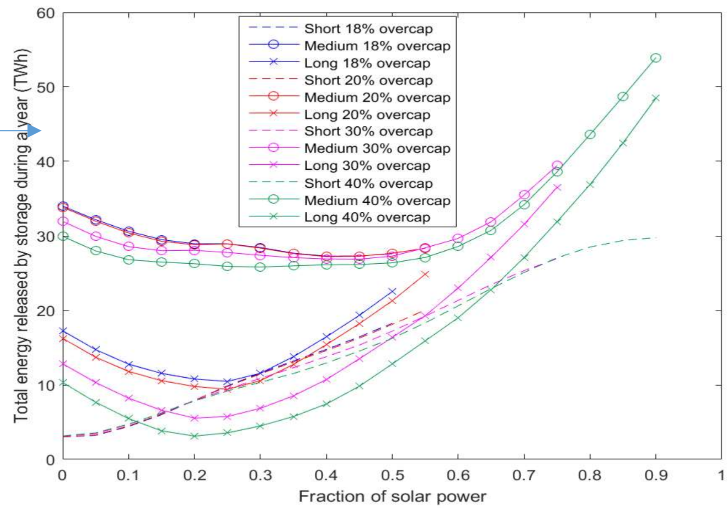


Keeping S, M fixed put

L = 40 % (H2)

Significant effect on effect on size of L

Min Overcapacity 14%



Varying Baseload Size

With supply fixed @ 120% of 600 TWh demand + 20% solar, and inefficiencies (40% for L):

720 TWh supply		Store size TWh				Energy Release TWh			
Renewables	Baseload	Short	Medium	Long	Total	Short	Medium	Long	Total
480	240	0.19	5.4	49	54	7.0	33	20	59
600	120	0.20	6.4	65	72	7.2	43	24	75
720	0	0.24	7.5	98	105	8.3	56	31	95

As the baseload increases/renewables decrease:
Store sizes decrease - most for L
Energy released decreases – most for M, but a lot for L also

More on Hydrogen & Ammonia→ other talks for other technologies

Many potential roles in low carbon world

– transport (HGVs, Shipping, Aviation), industrial heat, reducing iron ore to iron, storage

- **Ammonia more expensive to make but cheaper to store and transport than hydrogen***

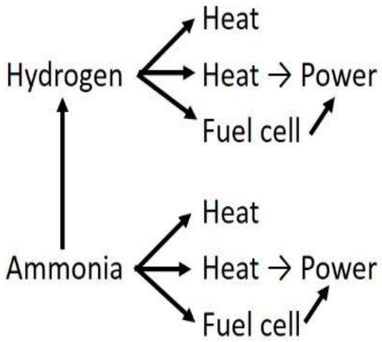
  → if choice, hydrogen best if used close (in time and space) to point of production, unless large scale underground storage available – ammonia if distant

- **Production**

  Electrolysis* (or SMR + CCS, but…) → hydrogen + nitrogen via Haber Bosch → ammonia (or direct synthesis?)

  * could be done, with costs savings, at offshore wind turbines

- **Use**



Hydrogen turbines being developed, also ammonia but much less advanced

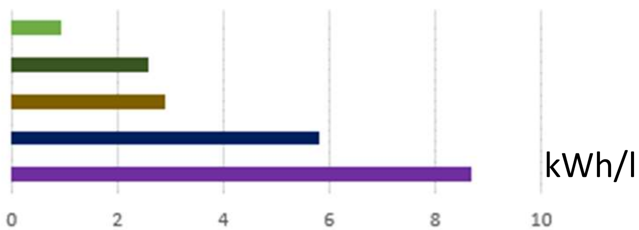
Hydrogen fuel cells well developed. Ammonia less so (need solid oxide: PEM cells get poisoned): can dehydrogenate NH3 → hydrogen fuel cell

Keys to H2/NH3 Economy

Cheaper electrolysis, turbines/engines, fuel cells

* **Hydrogen - very small energy/volume except under extreme conditions:**

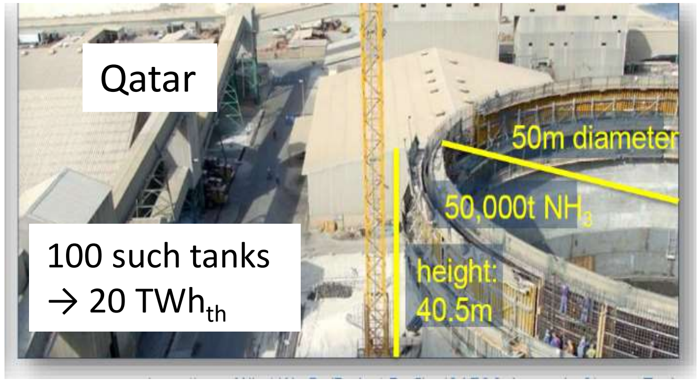
- gas @ 350 bar = gasoline/9.1 = liquid methane/6.1
- liquid (- 259 C) = gasoline/3.3 = liquid methane/2.2

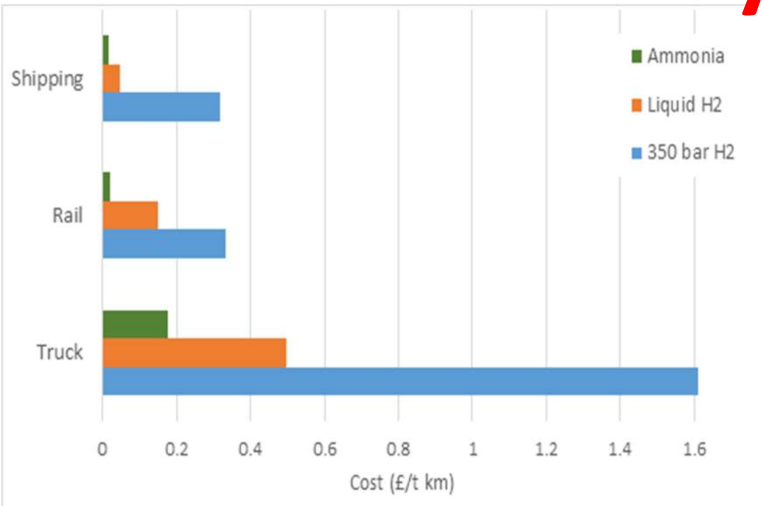


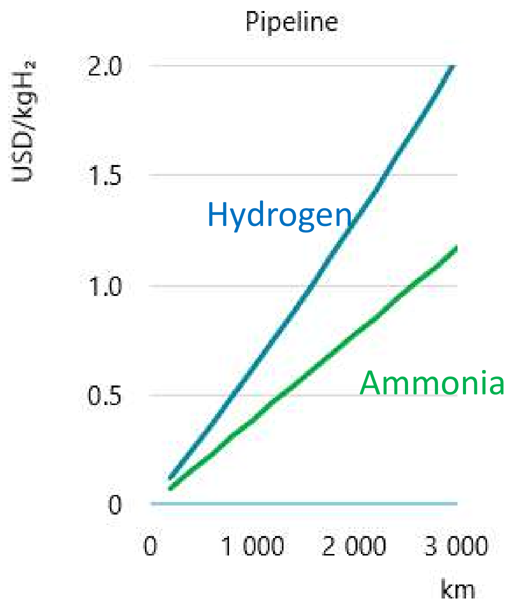
Ammonia is better: liquid (at -33 C, or 10-15 bar) = gasoline/3.0 → cheaper to store and transport

Ammonia Economy

Storage and transport easy:







Costs expected to fall:

Estimates, M Mason
with 5% discount rate
– see backup slides for details

$\$/MWh_{th}$	H2		NH3	
	2020	2040	2020	2040
Solar Morocco	78	48	109	72
Wind N Sea	102	61	136	85

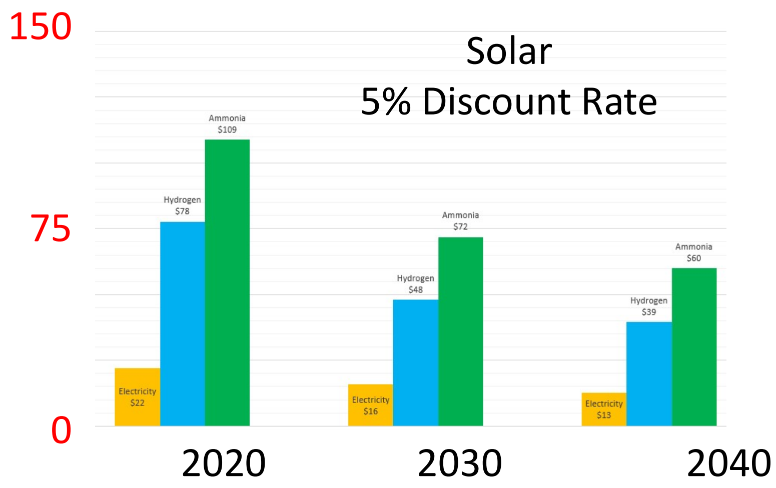
The world's annual supply of ammonia is 800 TWh_{th} (not advocating for electricity storage, but if burned in a turbine at 50% efficiency this would → 400 TWh_e = all the world's power for 6 days!)

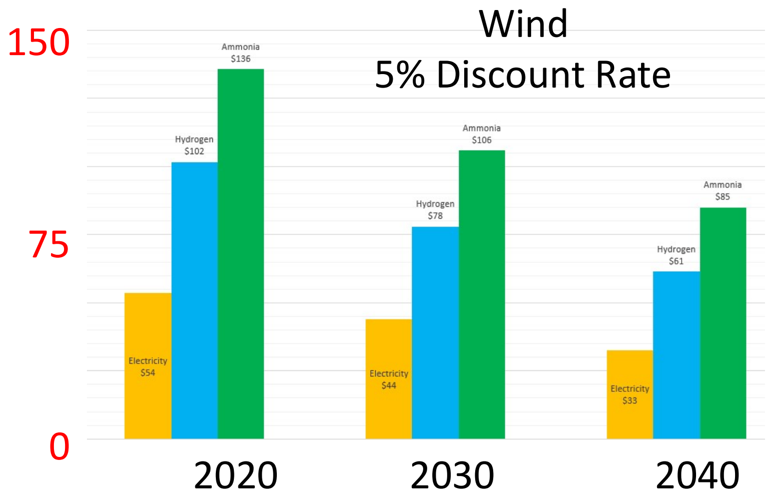
Possibility of making ammonia in Saudi Arabia and N W Australia for export to Japan has been studied. UK could be supplied by N Africa.

Model of Hydrogen & Ammonia Costs (M Mason) – Solar in Morocco, Wind in N Sea

$/MWh thermal (LHV)

Cost approx. x 2 if → electricity



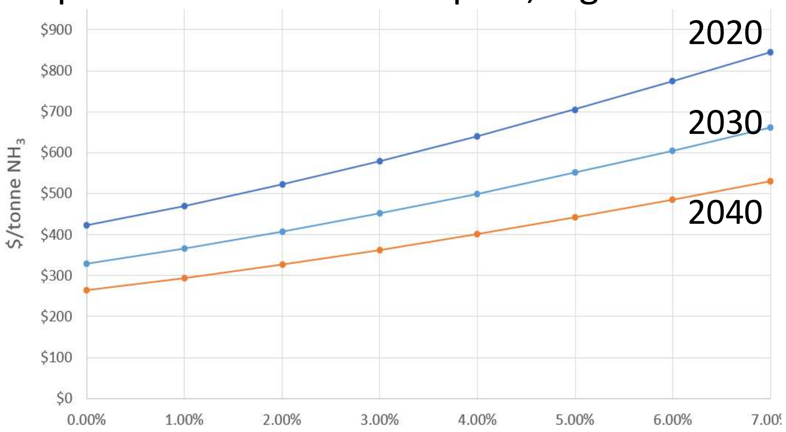


Electricity

Hydrogen

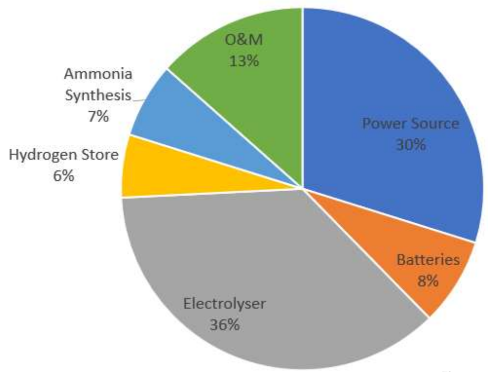
Ammonia

Dependence on cost of capital, e.g. wind:

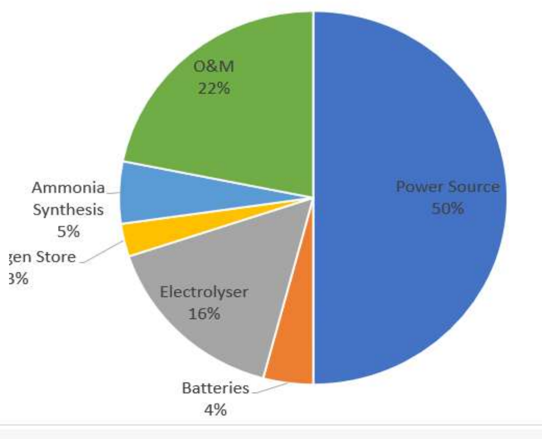


2020 breakdown, NH3 (@ 5%DR):

Solar



Wind



Hydrogen (@5% DR)

Power @ $54/MWh

Electrolyser 18%

Power 59%