Energy Storage
Needs and Challenges

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Oxford Physics
Energy Storage

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**, which in the UK in 2018 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 be needed in a world with net-zero emissions?
In a world with net zero emissions we will need

- Alternative fuels to provide and store the energy currently provided by fossil fuels for heat, transport and electricity generation
- Industrial process that do not vent CO2

Can we continue to use fossil fuels with Carbon Capture and Storage?

*Only to a very limited extent because the 10% of CO2 typically not captured + some 10% CO2-equivalent upstream emissions will have to be off-set*

What about electricity?

Moving to net zero will almost certainly require major contributions from wind and solar, which are becoming cheap* in terms of generation cost, but are highly variable and need the support of back-up (currently provided by fossil fuels) or storage in order to play a large role

*very cheap in good condition [IRENA (May 2019) reports on-shore wind and solar as low as $15/MWh, off-shore wind as low as $50/MWh, in some places, with costs still falling]*

Finding candidates that could provide this storage (which will cost money, and lose energy) is a major challenge, on which I will focus in much of this talk
<table>
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<th>Storage to support provision of:</th>
<th>Heat</th>
<th>Transport</th>
<th>Electricity</th>
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**After remarks on aviation and shipping, will focus i) the needs for large-scale long-term storage in support of the grid, ii) power → Fe, Si & synfuels as not covered by other speakers**
Since the 2016 Paris Agreement

Agreements have been reached on International Aviation (2.8% of anthropic CO2) and Shipping (2.7%) - which are not included in the UK’s net zero by 2050 commitment, although the then Minister stated that the government was considering including them (as recommended by the Committee on Climate Change)

International Aviation (2/3 of total emissions; the 1/3 from national aviation is covered by Paris)

2016 CORSIA (Carbon Offsetting & Reduction Scheme for International Aviation) agreement by 103 states (responsible for 90% of current international emissions)

Contrails + a relatively small contribution from NOX, which are not cumulative, may (correct treatment not universally agreed) more than double the global warming effect of CO2 emissions:
International Shipping → 2.7% of fossil fuel CO2 emissions (domestic shipping & fishing: 0.6%)

UN’s International Maritime Organisation:
2016 – emissions from new ships at least 30% less from 2025
April 2018 – meeting of some 170 countries agreed (despite opposition from Brazil, Saudi Arabia, USA..):
• Emissions should peak as soon as possible
• Relative to 2008:
  - Emissions in 2050 at least 50% less
  - Intensity at least – 40% [- 70%] by 2030 [2050]
“Most new ships built in 2030 will have to have zero emissions”
Now Focus on Large-scale Long-term Energy Storage, because –

- Providing affordable such storage will be key to moving to net-zero

- I am leading a Royal Society study of what is likely to be needed and whether it can be done

  In preparing this talk I have drawn on preliminary work by working groups 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), but they have no responsibility for what I will say, and mistakes and opinions are mine. Another group (led by Karen Turner) is about to start work on comparing the options, taking into account system value, cost, safety, public acceptability, readiness, ….

  It will be followed by a study of all energy storage, which will look at the complete needs/means matrix

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

**Yes:** long term solutions could also meet intermediate and short-term needs, but short term solutions (batteries, flywheels,..) won’t be able to meet the long-term need
The Need for Long-term Storage 1

The volume and duration of the storage that will be required when fossil fuels are phased out (apart from very occasional or small scale use of gas + CCS) will be strongly location and scenario dependent - will consider the UK and the USA.

The RS study is mainly focussed on electricity storage, but is also considering whether/how much heat could be stored on the required scale (which would impact the need for electricity storage).

Will consider UK scenarios with very high wind and solar. The UK has the resource:

<table>
<thead>
<tr>
<th>UK Resource</th>
<th>Plausible (conservative?) annual potential</th>
<th>Approx. Need in high renewable UK</th>
<th>Generation in 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>450 TWh - 20% efficient PV on 2% of farmland</td>
<td>150 TWh</td>
<td>13 TWh</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>100 TWh - turbines on 1.5% of all land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore wind (fixed)</td>
<td>300 TWh - turbines on 3/4 of realistic sites + conservative load factor</td>
<td>590 TWh</td>
<td>57 TWh</td>
</tr>
<tr>
<td>Offshore wind (floating)</td>
<td>500 TWh – turbines on 1/3 of realistic sites + conservative (?) load factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,350 TWh</td>
<td>740 TWh</td>
<td>70 TWh</td>
</tr>
</tbody>
</table>

Result of a simple model (next slide but 2) of a net zero UK, with wind/solar mix chosen to roughly mimic difference in winter/summer demand.

What about the cost? →
Projected Generating Costs - LCOE for UK projects commissioned in 2030

From a 2018 report by Aurora Energy Research - to whom many thanks for permission to use this figure

<table>
<thead>
<tr>
<th>Technology</th>
<th>2030 LCOE Estimates (£/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore wind</td>
<td>Fixed: 64, Variable: 45, Capex: 146</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>Fixed: 47, Variable: 76, Capex: 97</td>
</tr>
<tr>
<td>Solar (utility &gt;5MW)</td>
<td>Fixed: 45, Variable: 90, Capex: 1243</td>
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<tr>
<td>Solar (resi. &lt;10kW)</td>
<td>Fixed: 89, Variable: 89, Capex: 134</td>
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<tr>
<td>Biomass</td>
<td>Fixed: 134, Variable: 116, Capex: 137</td>
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<tr>
<td>Nuclear</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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<tr>
<td>CCG T (56% eff.)</td>
<td>Fixed: 134, Variable: 116, Capex: 137</td>
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<tr>
<td>CCGT (53.3% eff.)</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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<tr>
<td>Coal with CCS</td>
<td>Fixed: 134, Variable: 116, Capex: 137</td>
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<tr>
<td>Gas with CCS</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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<td>Gas recip</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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<tr>
<td>Diesel recip</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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<tr>
<td>OCGT</td>
<td>Fixed: 146, Variable: 146, Capex: 146</td>
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</table>

- In 2030, solar provide the lowest LCOE, followed by onshore wind.
- Revised gas and carbon price projections see thermal generators being more costly than renewables, on a LCOE basis.

*Latest offshore wind auction → strike price of £(2019) 45/MWh
LCOE estimates assume a 10% hurdle rate: 6-7% more common in bids for CfDs

Integration cost not included
The Need for Long-term Storage 2

The need (magnitude and duration – weeks, months, years?) for storage (centralised + Σdistributed) when fossil fuels are phased out will depend on the magnitude and timing of future demand and supply.

Require hour-by-hour model values of the mismatch between supply* and demand for many years, derived from a mixture of past demand with additions representing electrification of heating and transport etc., and past solar and wind data, scaled up with different wind/solar mixes + additions for possible new locations.

*first without storage and then with additional supply to allow for energy lost in storage

Constructing realistic scenarios* is a complex task

*with supply from a mixture of nuclear, solar, wind, low carbon supply from interconnectors, BECCS, hydro ..., plus some heating from bio-gas/mass and stored hydrogen fed into the gas and new sources of demand

For orientation →

A simple model of UK demand
+

Two extreme scenarios for supply
- 100% nuclear
- 100% wind + solar
The Need for Long-term Storage in the UK

• Simple model of UK Electricity Demand

Actual 2017 demand* + new electricity need** if i) all cars → electric + ii) domestic & non-industrial use of gas → heat pumps*** with average Coefficient of Performance 2.5 →

October – March 470 TWh + April - May 270 TWH = 740 TWh/year

Uncertainties
* Will be reduced by improved efficiency but increased by economic growth
** Many other things may be electrified – industrial processing,…
*** Instead could put hydrogen in the grid (need to store electricity → need to store hydrogen), but
- in a net zero world hydrogen likely to be produced by electrolysis → increased demand for electricity
- £(hydrogen → grid → heat) > £(hydrogen → electricity → heat) with heat pump with COP > 2

• Extreme scenarios for UK supply adjusted to meet this demand

100% wind + solar
Could get approximately the right winter/summer difference in an average year with something like 80% wind/20% solar, but without storage → severe problems in i) non-average years (expect year-to-year fluctuations of order +/- 10%) and ii) periods of day or weeks with little sunshine and/or wind
→ need to store many 10s of TWhs of electricity

100% nuclear
With existing* inflexible UK nuclear fleet, need to store 100 TWh in the summer for use in winter (can reduce by scheduling refuelling – one month every two years - in the summer)
* could replace with modern Light Water Reactors that can be ramped between 50% and 100%, but ramping puts up cost
Now →

• US studies

• UK needs in high renewable scenarios

• The effect of inefficiencies (not included in studies of which I’m aware)

  Typical round trip (power → X → power) efficiencies:
  
  X = Li-ion battery ~ 90% (uneconomic for over a few hours)
  
  X = Liquid or Compressed Air ~ 70% (uneconomic for over ~ week)
  
  X = Ammonia ~ 15- 50% (cost rises very slowly with storage time: leading candidate for long-term storage)

In many cases the cost of power to be stored is small compared to the cost of storage, so the efficiency does not greatly matter. However, in the case of large-scale storage efficiency can have a big influence of the total amount of input energy that has to be generated, especially if it’s as low as 25% - which I will use to illustrate this point.

• Given storage is expensive, is overprovision (beyond that needed to compensate storage inefficiencies) economic (cost of energy ↑, cost of storage ↓)?

• Questions about candidate technologies

• Candidate technologies
The Need for Long-term Storage – the USA

Study (Shaner et al) that tries 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$^2$:

Rapid improvement as scale of aggregation is increased and storage and overprovision are included, *but with 12 hours of storage (assumed capacity of 5.4 TWh) the NERC system reliability criterion* (loss of load < 0.1 days pa with 99.97% probability) *can only be met if the assumed 50% overcapacity is increased to 400%*

Varying the assumptions:

- Excess capacity and/or storage required increases sharply as renewable share increases above 70%
- 32 days of storage (345 TWh) with a solar/wind mix between 25-75%, would provide high levels of system reliability, with 10% of overprovision
The Need for Long-term Storage in the UK 2

- On the basis of studies of the US, Europe and the UK (none fully satisfactory) it seems that a 100% wind and solar UK would need of order 100 TWh long-term storage

- The Royal Society Needs Group is converging on numbers in the 100% renewable case, and considering how to include the effects of overprovision + adding supply from interconnectors + (flexible) BECCS and (semi-flexible) nuclear

- The conclusion is expected to be that a net-zero UK will (depending on what is assumed) need something like 50 TWh of long-term storage unless
  - Keep large amounts of gas + CCS and/or hydrogen provided by steam methane reforming gas + CCS and offset the CO2 that is not captured + methane that inevitably leaks, in competition with other strong demand for offsetting and/or
  - Add a lot of Bio Energy + CCS (BECCS) – where will the biomass come from?

Further studies* are required of more complex cases to establish the ultimate need for energy storage reduction in a complex renewables-heavy energy system

* including of offshore wind: needed more results from Hywind, updated cost projections for floating wind farms, more analysis of correlations of the wind resource in different places, and discussion of ‘floating hydrogen factories’
Effect of Inefficiency - 100% Steady Nuclear UK

With 100% Efficient Storage

Winter Demand

Generation

Storage

With 25% Efficient Storage

Winter Demand

Generation

Storage
Effect of Inefficiency - 100% Wind + Solar UK

With 100% Efficient Storage

Adding generating capacity to compensate inefficiency:

- Everything in surplus periods ↑
- but only the blue contribution to deficit periods ↑
- Some deficit periods → surplus periods, in others the deficit decreases, but the deficit never → 0
- if there are periods with no wind and solar

If (e.g.) efficiency = 25%: need to add capacity until

\[ \text{Surplus} = 4 \times \text{Deficit} \]

Needs detailed modelling, but with a 10% initial deficit and 25% efficiency, adding something like 15% to capacity might do the job, and reduce the deficit to perhaps 5%

Demand shown constant for simplicity
Is Overprovision Economic?

Cost = Cost of energy $S + X$ - call unit cost 1 
+ Cost of storing (conversion + transmission + storage + regeneration) - call cost per unit of power provided $x$

Overprovision by $X$ reduces the amount stored by $\Delta(X)$

$\Delta(X) < X$ (probably a lot less), as adding generating capacity increases supply surpluses more than it decreases deficits

$\rightarrow$ changes the cost by $\delta \epsilon = X - x \Delta(X)$

Not obvious whether $\delta \epsilon < 0$ - overprovision economic
or $\delta \epsilon > 0$ - $\delta \epsilon$ overprovision not economic

Need proper modelling of $\Delta(X)$ & an estimate of what value of $x$ might be reasonable for whatever storage might be used

The economics of overprovision would obviously improve if there were users willing to buy curtailed energy at unpredictable times (drying biomass?...?)

Holy grail: find an industry that could switch between energy light and energy heavy activities depending on the weather
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?
Candidate Technologies for **Large-scale Long-term Storage**

- **Ammonia and hydrogen** (listed first as it is most promising)
  - £(green ammonia) > £(green hydrogen) but NH3 cheaper to transmit & store
  - If use is close in time & space to production, use H2 otherwise NH3
  - Already on large scale (for fertiliser): world's annual supply of NH3 if converted to electrify with 50% efficiency would → 400 TWh - all world’s electricity for 6 days!

- **Batteries** - flow batteries? Not suited for weeks or months of storage

- **Non-chemical**
  - 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*
  - 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
  - Thermochemical – need large heat input (concentrated solar, nuclear). Viability - cost + temperature + energy density (low in cases I’ve looked at) + ... claimed there are possible candidates: *need more work*
  - Pumped Hydro – UK expansion potential limited, but Norway could provide Europe with 123 TWh by linking existing reservoirs + constructing new ones linked to them

- **Synfuels + Novel Chemical** → following slides
**Synthetic Fuels** - note recent RS report on synfuels & transport

- **e-fuels** (made from captured CO2 + green hydrogen) methane, methanol,.. Hard to justify utilisation (rather than storage) of captured CO\(_2\) *unless* there is no low or zero carbon* alternative**

  * Burning synthetic fuels made from captured CO2 is a low but not zero carbon cycle
  ** Powering flight is often cited as an example with few alternatives but instead of using captured CO2 to make synfuels, it could be buried to off-set using fossil jet fuels (which might be cheaper)

- **Synthetic biofuels** (from bio-derived syngas +hydrogen) – need more work on whether good storage candidates; other calls on biomass

- **Liquid Organic Hydrogen carriers** (hydrogen + ethylcarbazole, or...) Reversible energy carriers with energy densities similar NH\(_3\) can be stored under ambient conditions using existing infrastructure: could provide Storage/Combined Heat and Power in buildings:
  Grid power → electrolyser → hydrogen → hydrogenation → LOHC → domestic heat
  Storage → dehydrogenation → hydrogen → fuel cell → domestic power or grid
  Many such systems *could provide a TWh contribution* (1.8 m domestic oil tanks in Bavaria could jointly store 5.8 TWh)
**Novel Chemical Storage**

**Process:** Oxide $\overset{\text{reduce}}{\longrightarrow}$ element $\overset{\text{oxidise}}{\longrightarrow}$ oxide + hydrogen or heat

1) **Oxides that can be reduced using a common fuels**
   - e.g. iron oxide (reduce: conventional + CCS, or with hydrogen or syngas) $\rightarrow$ iron:
     - iron + water $\rightarrow$ hydrogen
     - iron + air $\rightarrow$ heat (oxygen depleted air stream $\rightarrow$ turbine)

   **Issues:** cost, safety, (re)sizing iron particles (which sinter when reduced) for efficient oxidation,...
   
   Study on-going – watch this space

   Other candidates – Cu, Co, Ni: much less favourable thermodynamically (much less hydrogen per mole)

2) **Oxides that can that can only be reduced electrochemically** *(by Fray-Farthing-Chen process)*
   - e.g. boron, or silicon:
     - Silicon dioxide $\rightarrow$ silicon; silicon + water $\rightarrow$ silicon dioxide + hydrogen
     - Oxidation proceeds at an acceptable rate with small silicon pellets mixed with KOH (produces heat as dissolved) and sugar

   **Issues** include: making Si without CO2 (FFC); cost – not favoured thermodynamically, so need very cheap input energy and/or niche application

   Being promoted by Siliconfuel as a portable source of hydrogen to power drones, fuel cars (hydrogen produced at pressure), or ships
**Concluding Remarks**

- Approaching/reaching net-zero emissions will be extremely difficult.

- Unless **Direct Air Capture of CO2** becomes cheap, fossil fuels will have to go, *except* if they are fitted with **CCS** and the residual emissions can be offset (NB: neither DAC nor CCS would get rid of the debilitating air pollution caused by burning fossil fuels).

- Storage is needed to support heat, transport, and electricity supply. Large-scale storage is currently provided by fossil fuels - replacements will be needed.

- Major contributions to energy supply will almost certainly be needed from wind and solar, plus nuclear, **BECCS**, large scale grids (interconnectors),...

- Large-scale long-term storage will be needed to enable major contributions from wind and solar, with a wind/solar mix designed to mimic the winter/summer demand, unless there are substantial contributions from **BECCS** (whence the biomass?) and/or gas (directly or in steam methane reforming → hydrogen) with **CCS** and the residual emissions are offset.

- The volume and duration of the storage that will be required are strongly location and scenario dependent, but with large contributions from wind and solar the UK will need tens of TWh.

- Ammonia is probably the leading candidate technology, but others can play contributing (perhaps large) roles.