High-temporal-resolution analysis of UK power system used to determine the optimal amount and mix of energy storage technologies

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High-Temporal-Resolution Analysis of UK Power System Used to Determine the Optimal Amount and Mix of Energy Storage Technologies

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Analysis of UK Power System & Energy Storage

- Electricity System Modelling
- FESA Time-step model (my model)
- Electricity System Economics
- DECC 2050 Calculator and Example Scenarios
- Energy Storage Modelling Method
- Optimum Power / Energy Ratio
- Energy Storage Technologies
- Optimal Size and Technology Mix of Storage
- Conclusions
The Old System
Power stations generate whatever the loads demand
Power only flows one way

High Voltage → Low Voltage
New System – More complicated
Power flows in all directions
Supply is much more variable
Electricity demand has a predictable, repeating pattern. Depends on weather, time of year, in a predictable way.

[Graph showing electricity demand patterns across the days of January 2001]
Wind power varies randomly, with greater min-max variation. A bit more wind in winter than summer.
Solar PV is fairly predictable, but no contribution to peak demand, and much more in summer than winter.
Wave power varies randomly, like wind power, but is a bit less variable. Bigger waves in winter than summer.
Tidal power is predictable but still very variable
Overview of FESA, “Future Energy Scenario Analysis”

Electricity Demand
- Electric Vehicles
- Heat Pumps, Appliances etc.
- Domestic, Commercial and Industrial

Uncontrolled Generation
- Wind
- Wave
- Tidal
- Solar PV
- CHP

\[ \sum = \text{net demand} \]

Balancing:
- Storage
- Interconnector
- Time shifting
- Curtailment

Merit Order Of Generators

Dispatchable generation

\[ \sum = \text{National fuel demand} \]

Non-electric fuel use

Total UK CO₂ Emissions
This is why net demand gets more variable
Merit Order of Generation

- Electricity companies first choose or ‘despatch’ the power stations with cheapest running costs = ‘baseload’.
  - E.g. nuclear likes to run all the time.
- Then ‘mid-merit’ generation.
  - Cheaper to build vs. more expensive to run
  - Typically coal or combined-cycle gas (CCGT)
- Finally ‘peaking’ plant
  - Cheap to build or very old power stations
  - Most expensive to run
  - Open cycle gas turbines (OOGT) or oil fired
Net Demand in 2010 (Approximate Generation Mix)

Net Demand, GW

- Peaking
- Mid-merit
- Baseload

Legend:
- Peak Plant
- Low Carbon
- Curtailed RE
- Higher Carbon
- Baseload
DECC 2050 Calculator (Higher Renewables Scenario in 2050)

Net Demand, GW
The Future Need for Energy Storage: Steeper Load-Duration Curves

- Year 2010
- Year 2050
‘Thousand Flowers’ Low-Carbon Pathway in 2050
12 days of surplus, 10 days of deficit, 2 days surplus

1500GWh of shortfall

2500GWh of surplus

Storage needed

Example Weather, 23rd Feb to 18th March

- Interconnectors
- Surplus
- Low Carbon Gen.
- High Carbon Gen.
Demand – Price Graph, 2010

- Low capital cost, high fuel cost, but has to cover capital cost in a few hours
- High capital cost, low fuel cost

Traded Price (Balancing Market) Steeper & Non-linear!

Price, £/MWh vs Net Demand, GW
Demand – Market Market Price Graph, 2050

- High capital cost, low fuel cost, but has to cover capital cost in a few hours.

- The highest value of storage is in avoiding peak prices, **Not** absorbing excess renewable electricity.

- Wind power shuts down, Price goes negative.
Modelled Costs of Electricity Generation in 2050

- Baseload and renewables: High capital cost but ‘free’ running costs
- Fuel costs:
  - £16/MWh_e for CCS,
  - £23/MWh_e for peak gas-fired plant
- Carbon price: £76/tonne of CO_2 equivalent
  - Peak gas plant 460kg/MWh_e
  - CCS plant 50kg/MWh_e
- Value of Lost Load (DECC & Ofgem) £16,940/MWh_e!
Marginal Costs of Generation (1)
Value of lost load (VOLL) is not really helpful in determining economic optimum despatch of energy storage.

We cannot use a look-ahead average as the reference price, because the look-ahead average is too high.
3 Thresholds of Storage

Use peak generation to avoid loss of load.

Use low carbon to displace high carbon.

Lost Load (Storage Replaces Peak Generation)

Peak Plant Fossil Fuel (CCGT)

Low Carbon Fossil Fuel (CCS)

Baseload (Renewables And Nuclear)

Use baseload to displace low carbon.
Priority 1 – Meet peak demand, avoid power cuts

Demand, GW vs Time, hours

Minimum energy calculated by looking ahead

Minimum Energy, GWh
Priority 2 – Stay full enough to avoid high carbon generation

But only if spare low carbon generation is available

Minimum energy calculated by looking ahead
Priority 3 – Stay full enough to avoid low carbon generation

But only if excess base-load or renewable electricity is available to fill the store, and when there is room in the store.
Three Thresholds of Storage

- Perfect forecasting
- Economically optimum
- Reference levels of demand are at thresholds. Jumps up or down as required.
- Minimum generation to avoid the next more expensive generation
Ideally, Energy Store is Always in One of Three States…
(Inspired by Energy Economists at Warwick)

   - Fills when demand / price is below the level.
   - Discharges when demand is above that level.

2. Store is full and reference price is rising.

3. Store is empty and reference price is falling.
   - With an infinite number of possible reference levels, this might be possible.
   - My model has discrete levels.
   - My model is always empty as price falls but not full as price rises.
Choosing the size of the energy store (energy / power ratio)

Move the ceiling down.

- Increasing power, $P =$ peak generation saved
- Calculate the energy capacity, $E =$ store capacity
Optimum Ratio of energy Capacity to Power (GWh/GW) (High Renewables Scenario)

- Large Energy Capacity
  - But Usefulness is Limited
  - By Power Rating
  - Of Store

- Large Power Rating
  - But Store Spends Too Much Time
  - Full or Empty
Optimum Ratio of energy Capacity to Power (GWh/GW)

Inter-Seasonal Storage => Fuel Storage

Intermediate Timescales:
Daily, weekly, Monthly, Weather

Store Energy Capacity, GWh

Store Power Rating, GW

Peak Lopping. Flexible Demand?

Low Cost
High CCS & Bioenergy
High Nuclear
Markal 326
National Grid
Mark Brinkley
High Renewables
CPRE
Atkins
Friends Of The Earth
Value of Storage

1. Replacing generating capacity
   - power stations you don’t have to build or maintain.
   - Capital expenditure (CAPEX) saved

2. Fuel saved
   - More efficient power stations used
   - Cheaper fuel
   - Renewables or nuclear

3. Carbon saved
   - Lower carbon power stations used
Value of Storage vs. Store Power

- Markal 3.26
- High Renewables
- High Nuclear
- High CCS & Bio-Energy
- Low Cost
- Friends Of Earth
- CPRE
- Mark Brinkley
- National Grid
- Atkins
- 6 Hour
- 24 Hour

Lifetime Value Of Storage, £bn

Store Power Rating, GW
Value of Storage vs. Storage Capacity

Lifetime Value of Storage, £bn vs. Store Energy Capacity, GWh

- Markal 3.26
- High Renewables
- High Nuclear
- High CCS & Bio-Energy
- Low Cost
- Friends of Earth
- CPRE
- Mark Brinkley
- Atkins

1500 GWh
Capital Costs Per Power and Energy for Energy Storage

- Sodium-Sulphur Battery
- Isentropic Heat Storage
- Compressed Air Energy Storage
- H2 Underground + Gas Turbine

Costs are shown in £GB.
Cost of Storage with Increasing Timescales

- **Batteries**
  - Up to 1 hour

- **Above-Ground Heat or Cold (?) Storage, or Flow Batteries**
  - Up to 12 hours

- **CAES & Pumped Hydro**
  - Up to 2 weeks

- **Hydrogen & Fuels**

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**Graph Details:**
- **Y-axis:** Added Cost Per Unit of Energy, $/kWh
- **X-axis:** Storage Energy to Power Ratio, GWh/GW
- **Legend:**
  - H2 Tank + Gas Turbine
  - H2 Underground + Gas Turbine
  - H2 Tank + Fuel Cell
  - Isentropic Heat Storage
  - CAES
  - Nickel-Cadmium
  - Sodium-Sulphur
  - Vanadium Redox
  - Pumped Hydro
Size of Storage and Appropriate Technology by Application

- Batteries for Short-Term
- Hydrogen for Inter-seasonal
- CAES for weather-related variation, on time up to 2 weeks
- Thermal Energy Storage for up to about 2 days

<table>
<thead>
<tr>
<th>Store Energy Capacity, GWh</th>
<th>Bottom 100,000</th>
<th>Bottom 10,000</th>
<th>Bottom 1,000</th>
<th>Bottom 100</th>
<th>Bottom 10</th>
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<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
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</table>

Legend:
- Low Cost
- High CCS & Bioenergy
- High Nuclear
- Markal 326
- National Grid
- Mark Brinkley
- High Renewables
- CPRE
- Atkins
- Friends Of The Earth
Optimum Ratio of energy Capacity to Power (GWh/GW) (High Renewables Scenario)

- Lower gradient at small storage volumes, suitable for a short-term of storage technology
- Higher gradient at larger volumes, suitable for a longer-term storage technology
Optimum Solution is Multiple Stores Working Together

Peak of each curve is the economic optimum level of storage.
Optimum Storage Power

- Markal
- High Renewable
- High Nuclear
- high CCS
- Low Cost
- FOE
- CPRE
- Brinkley
- Nat. Grid
- Atkins

Storage Power, GW

- CAES
- Heat
Optimum Storage Energy Capacity

![Bar chart showing storage capacity for different scenarios. The chart compares various technologies and their contribution to storage capacity. The technologies include Markal, High Renewable, High Nuclear, high CCS, Low Cost, FOE, CPRE, Brinkley, Nat. Grid, and Atkins. The chart uses different colors to represent CAES and Heat storage capacities.](chart.png)
Components of Value of Energy Storage

- Carbon
- Fuel
- Capital

Bar chart showing the components of energy storage value with different labels and categories.
Energy Storage Cycle Time vs. Weather Predictability

Limit of accurate forecasting: 2 days

Limit of approximate forecasting: 5 days

(Mark Brinkley scenario is an outlier for several reasons)
Modest Improvement in Load Factor of CCS
Reduction in Curtailed Low Carbon Energy at Economically Optimum Level of Energy Storage

![Bar chart showing reduction in curtailed low carbon energy with and without storage.](chart.png)
Conclusions – Part 1

- The need for energy storage is increasing
- The optimum ratio of GWh/GW (time constant) increases exponentially with power rating
- Strong law of diminishing returns with energy capacity, GWh
- The cost-effective technologies appear to be heat storage and Compressed Air (CAES). Flow batteries are another possibility.
- Storage is cost-effective for cycle times of approximately 2 to 5 days but no more:
  - Poor Economics of long-term storage
  - Inadequate long-term weather forecasts
Conclusions – Part 2

- Energy storage can substantially reduce the following parameters but it is not economically feasible to build enough storage to eliminate them:
  - Curtailed low-carbon energy
  - High carbon peaking generating plant

- Energy storage can increase the utilisation factor of fossil-fuelled plant with CCS, but it is not economically feasible to use storage to bring it up to the levels anticipated in the DECC 2050 Calculator Model
Next Steps

- Forecasting Errors – How the optimum size, despatch algorithm and value of storage change with imperfect forecasting
- Extend FESA to a European model – the optimum role of storage alongside interconnectors
- Demand response – where (in timescale) does DR finish and storage begin?
- Alternative supply scenarios – more electricity generation mixes, e.g. from ETI, Shell, UKERC