Energy Storage

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- Energy storage, electricity and the grid
- How much storage would we need for NetZero?
- Alternatives to storage

Three Linked Crises

Ocean Acidification

Climate Change

Land Use & Biodiversity

CO_2 & CH_4

Energy
Coal, Oil & Gas
Renewables
Nuclear
Electricity
Heat
Fuels

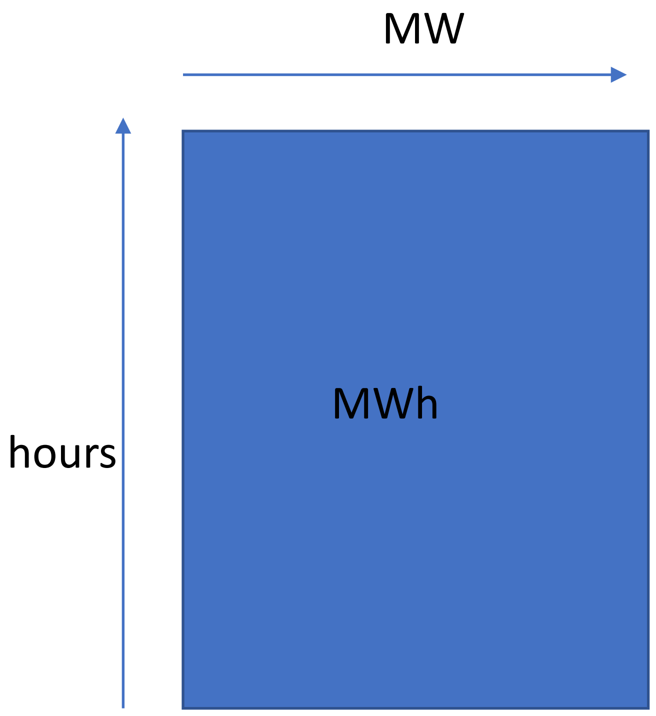
Food
Forestry

Why energy storage?

- Buffer between variable supply and variable demand
  - To help inflexible supply to follow variable consumer demand
  - To compensate for variable supply: renewable power peaks/troughs and breakdowns
  - To store excess energy when demand is low, or for export
- 'Persistence', not capacity factor, drives need for storage
  - How long are the gaps?
  - Range of timescales: seconds, hours, days, weeks and seasonal
- Important for all energy: easy for coal and oil, moderate for gas, harder for electricity
- Electricity is unlike coal, oil and gas
  - Is used as soon as it is produced
  - Cannot be stored as electricity at scale
  - Convert to some other form of energy – and back again
- Conversion, storage and regeneration needs expensive equipment and destroys energy
  - What are the technology options?
  - "Renewables and storage are getting cheaper" – how cheap do they need to be?
- What are the alternatives to electricity storage?
  - Energy is not just electricity - so don't solve electricity issues in isolation

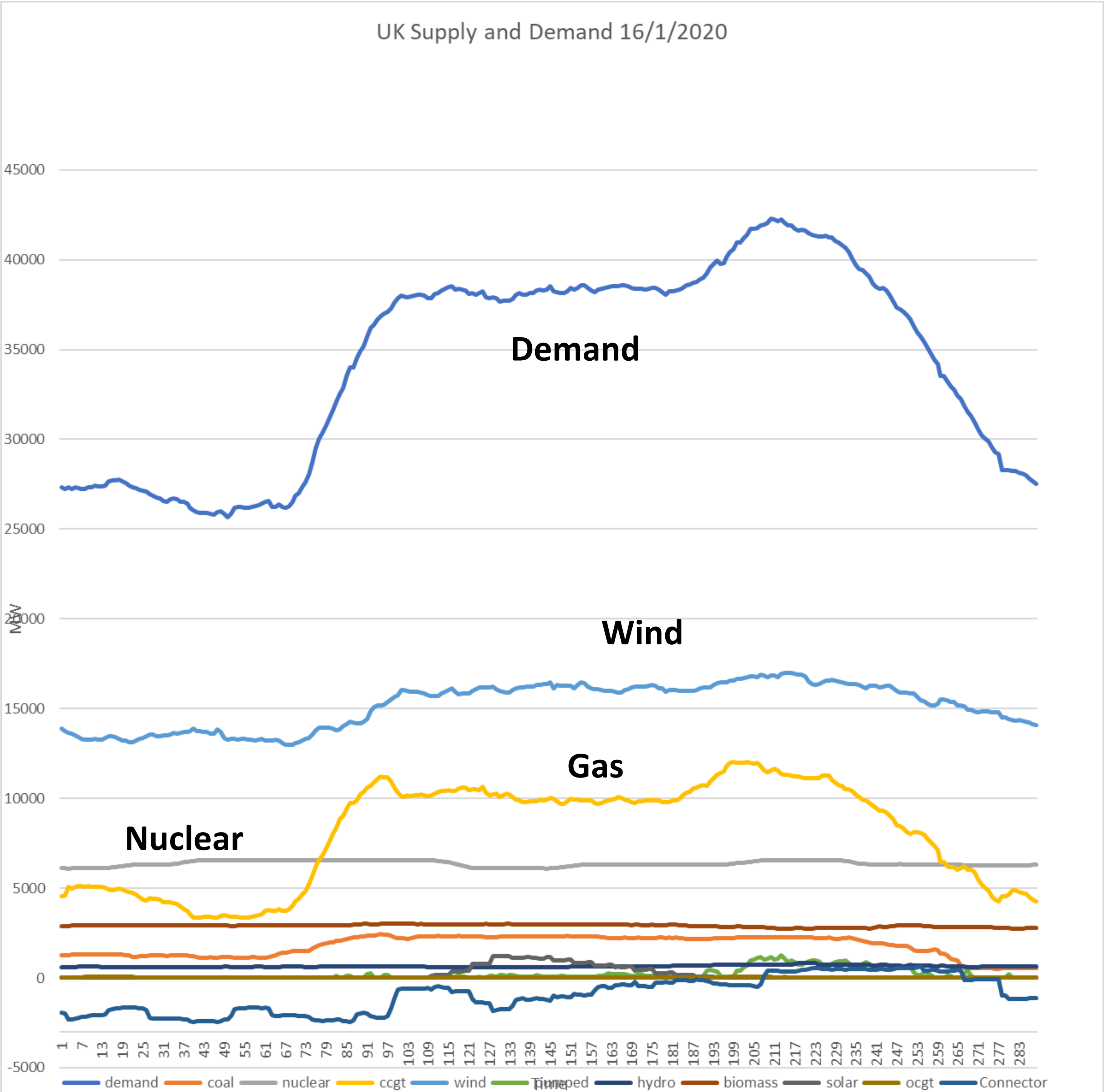
Characterising storage

- In/out Power (MW) and total Energy Stored (MWh)
  - Or MW and hours (=MWh/MW)
- Costs per MW AND per MWh are important
  - Depend on application
  - Cost per MWh supplied assumes cycles/day
- Round trip efficiency (energy out/energy in)
- Response time
- Rate of loss
  - Natural gas boils off, flywheels slow down
- Energy and power per kg and per litre



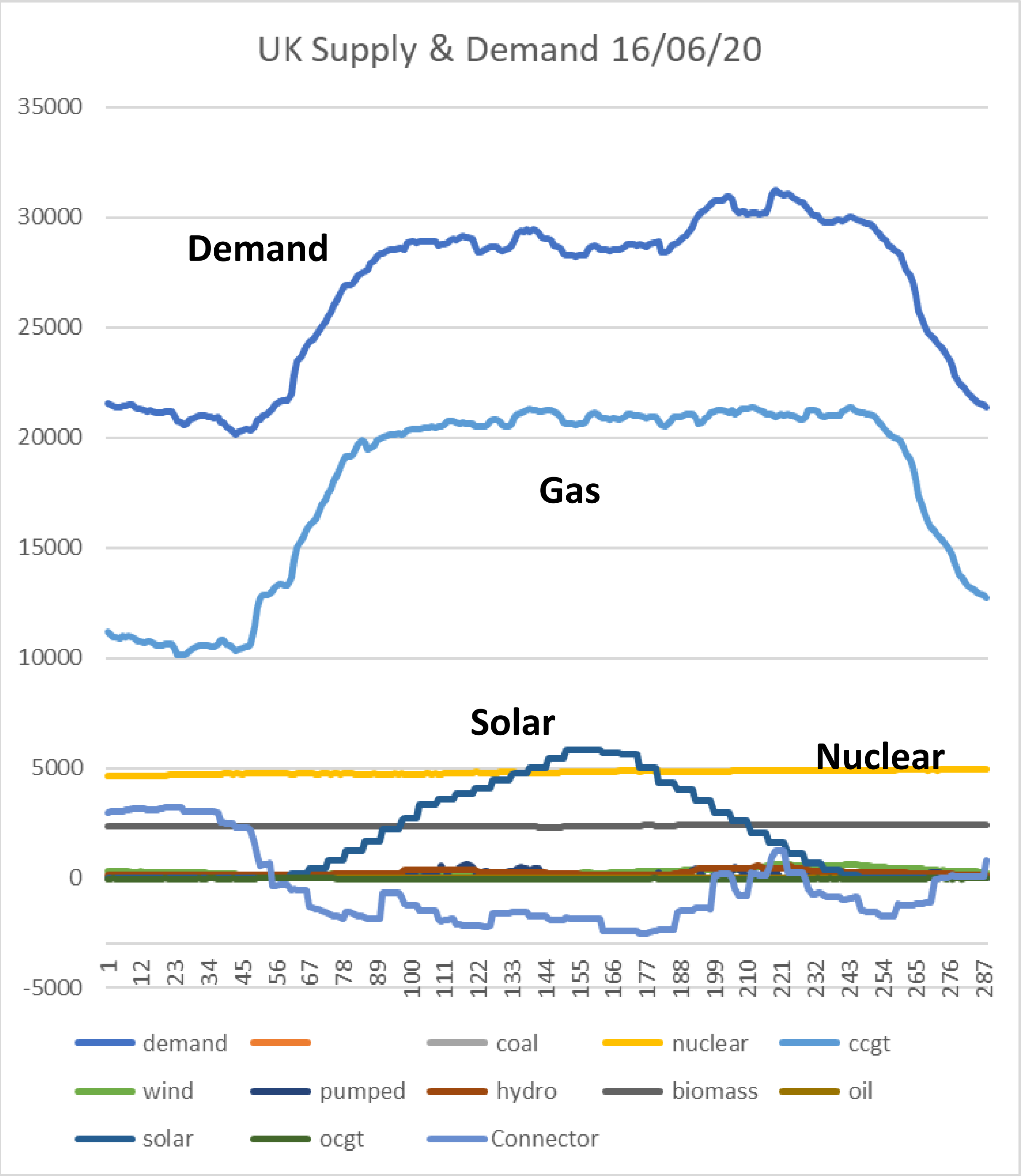
UK daily supply & demand - winter

- Gas fired power (CCGT) supplies low cost flexible generation
- Coal, interconnectors & pumped storage help
- Wind biggest single source
- Nuclear & biomass flat, no solar

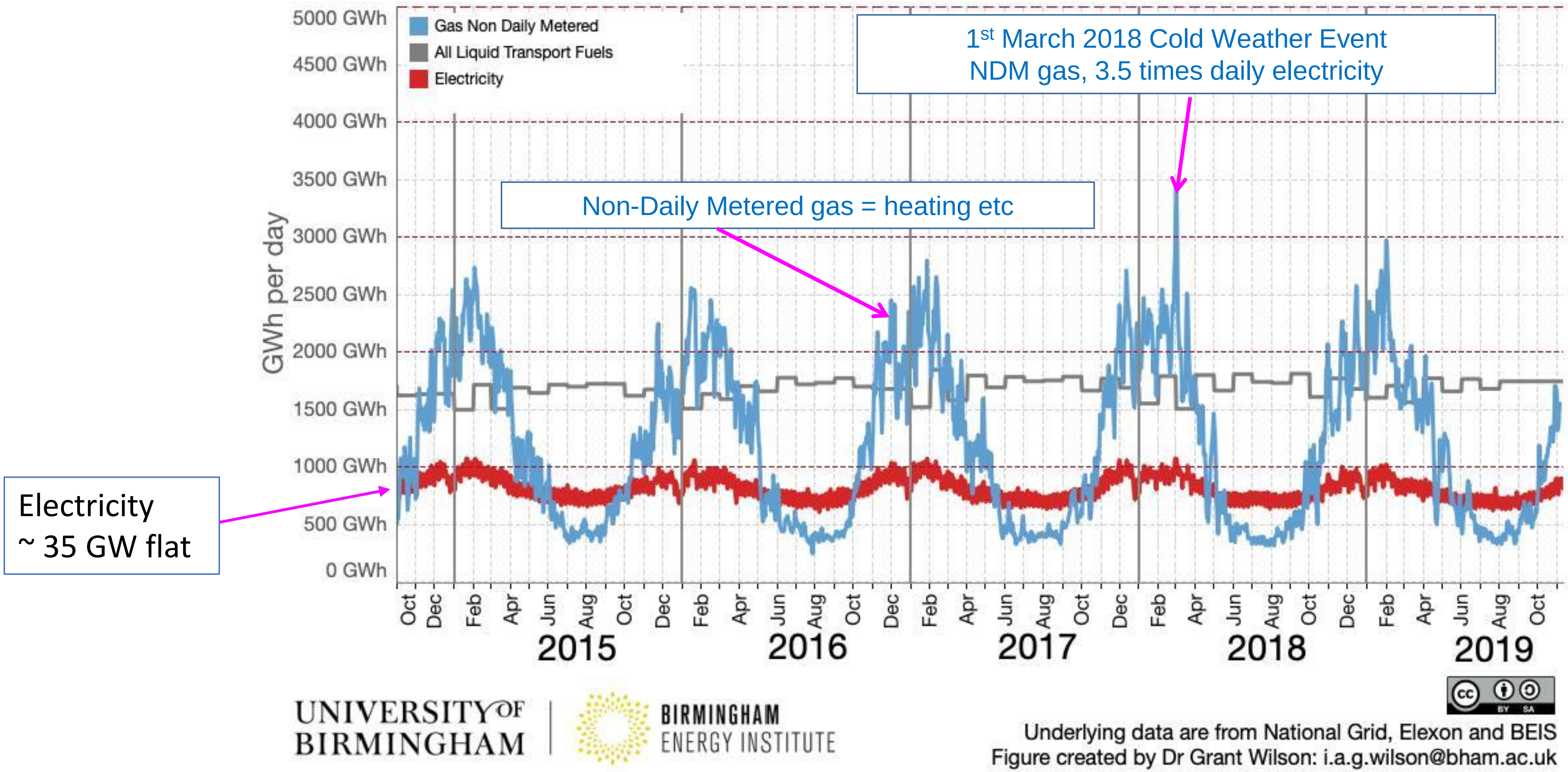


UK daily supply & demand - summer

- Gas fired power (CCGT) supplies low cost flexible generation
- Nuclear and biomass flat
- No wind, solar max ~50% capacity
- Short term storage can help handle hourly variations
  - But what about longer durations?

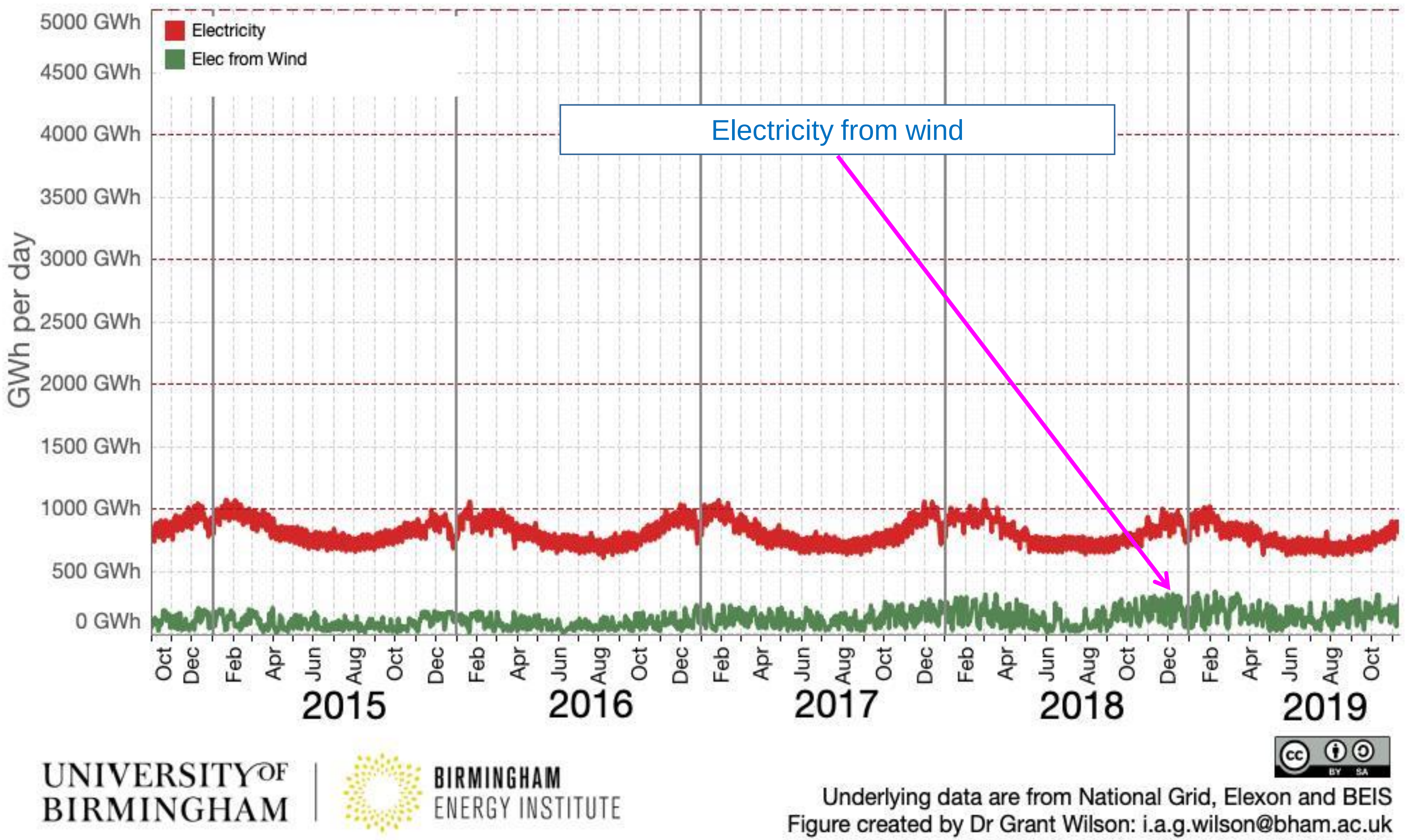


UK Annual Energy

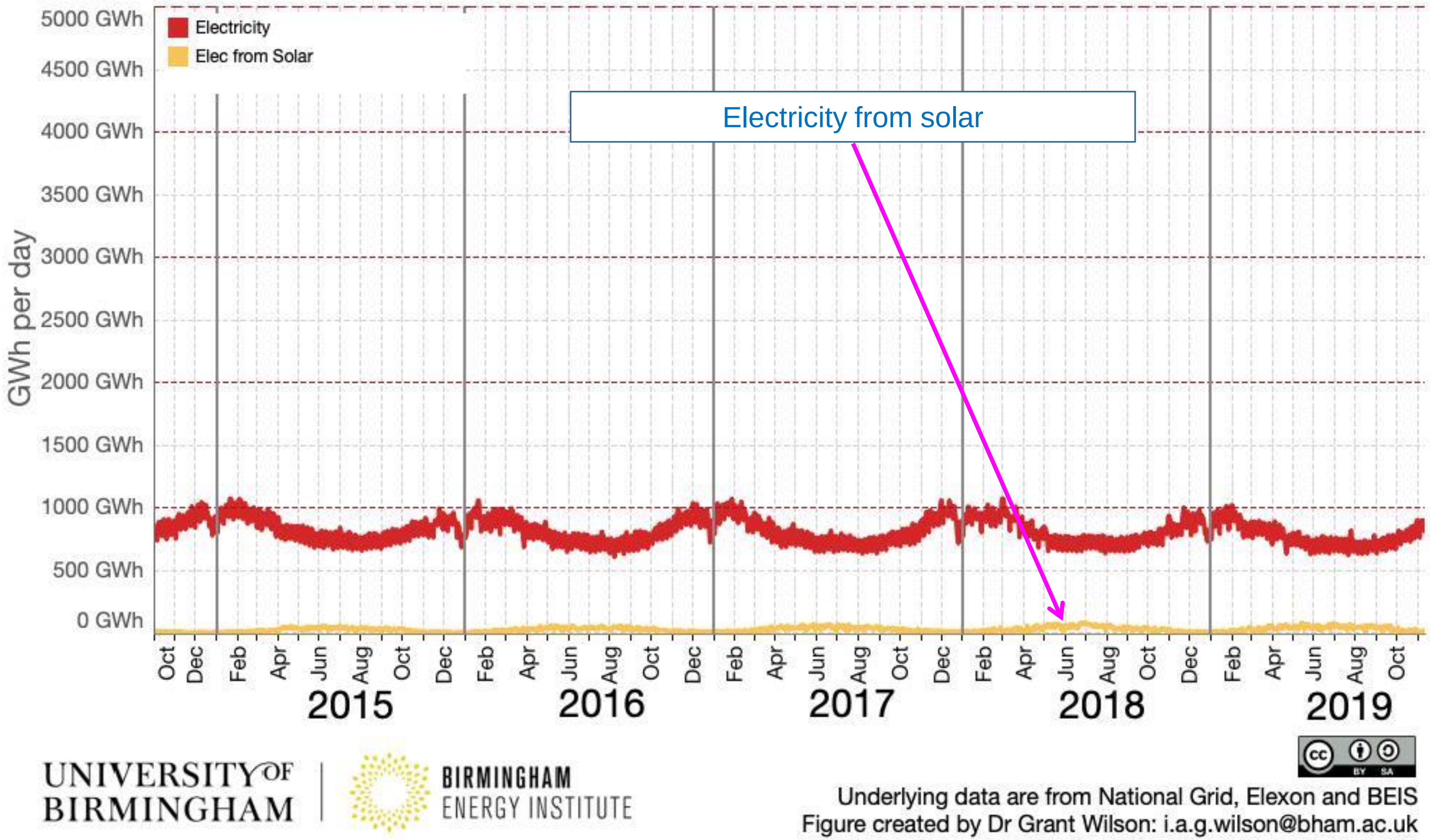


"Baseload" is unfashionable – but UK needs over 700 GWh every day

UK Annual Energy - Wind

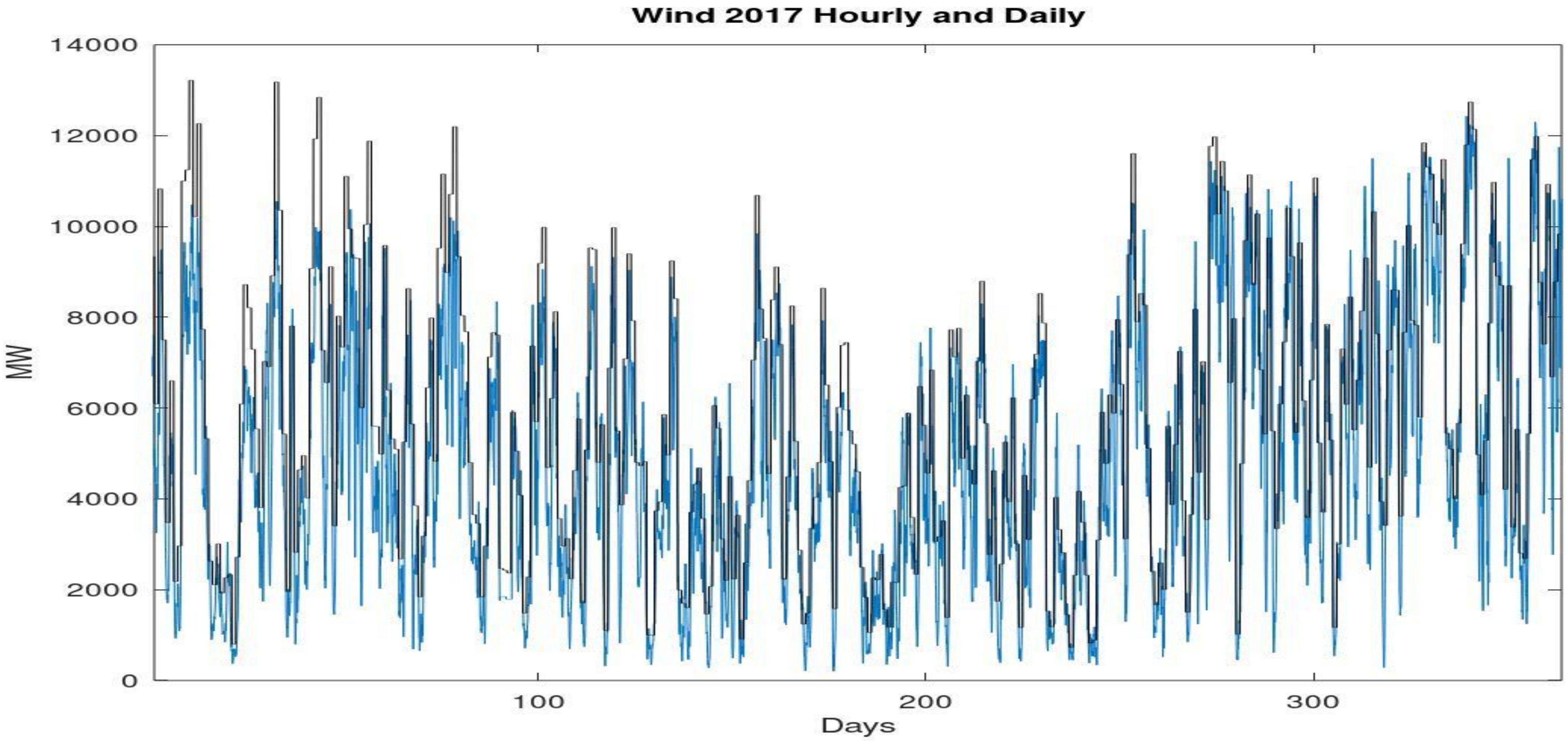


UK Annual Energy - Solar



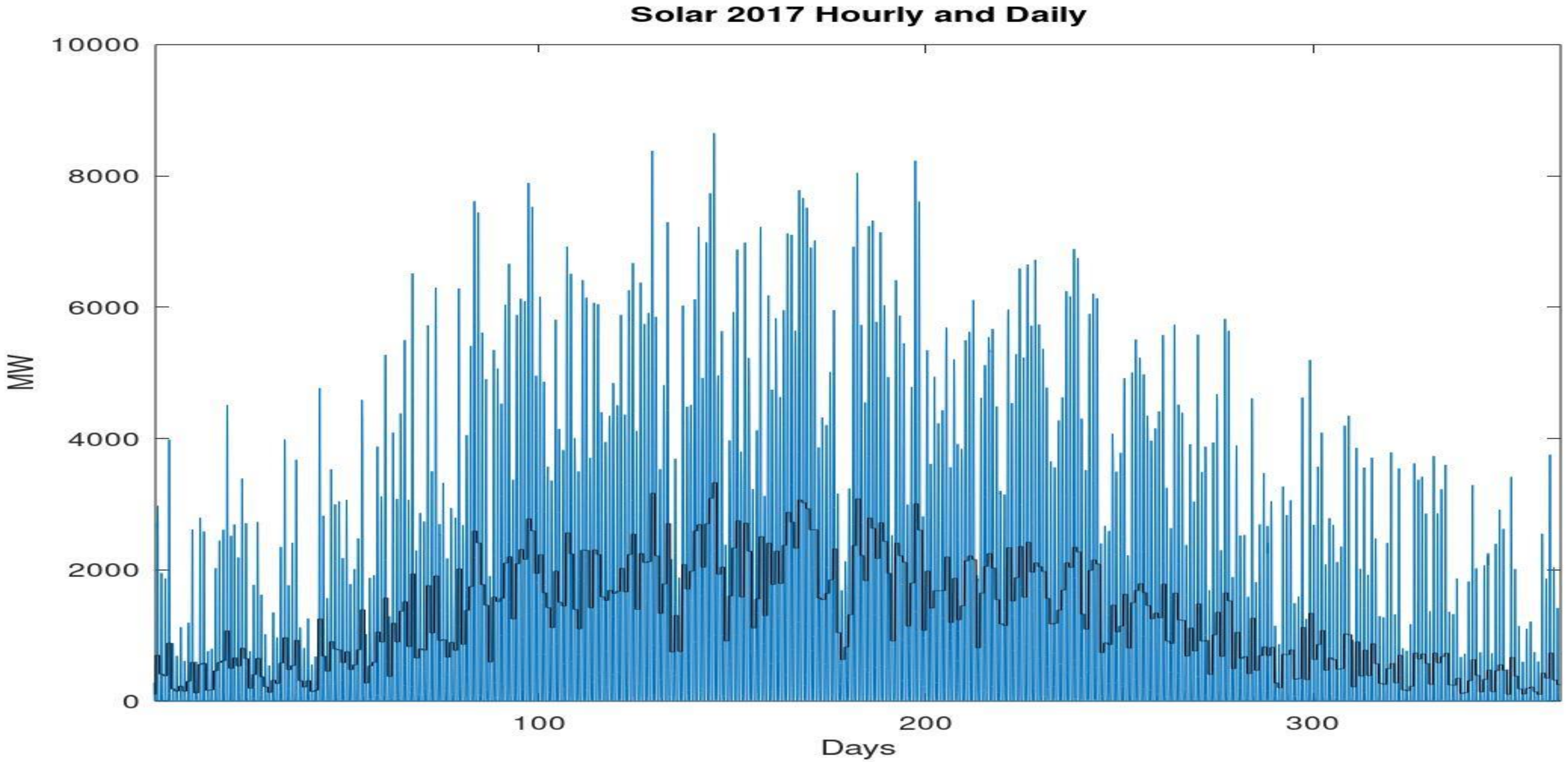
UK Wind Power hourly & daily

Average/max 38%



UK Solar Power hourly & daily

Average/max 13%

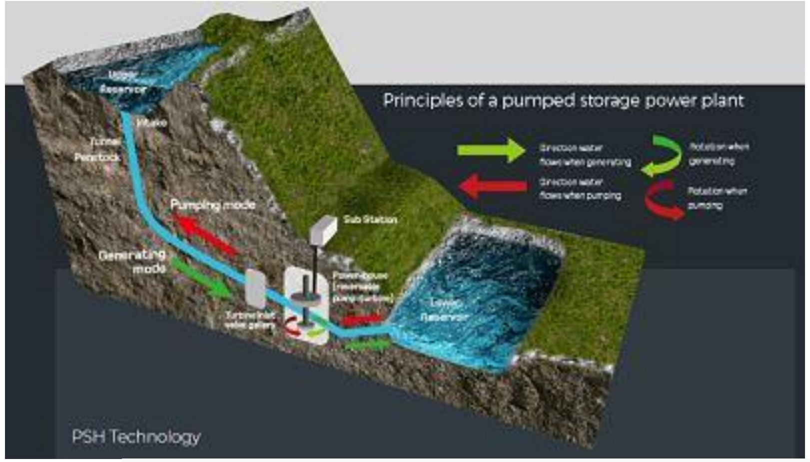


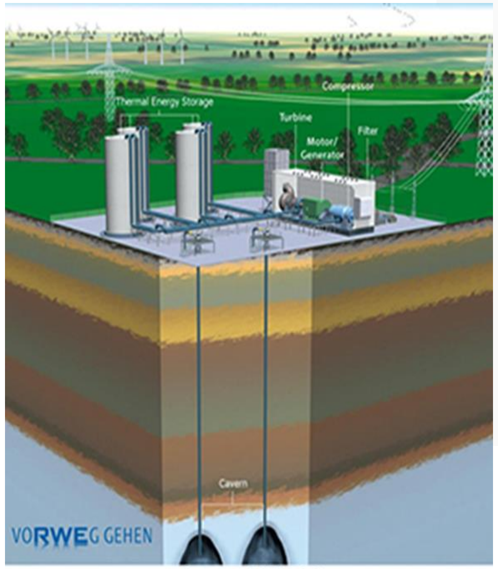
Net Zero - 100% renewable power?

- Handle 1 in 20 year windless period (anticyclone)
- Renewables + Storage supply all demand
  - Net of interconnectors and other clean generation
  - Storage must combine with renewables to create near flat daily power
- Is this a problem?
  - "Renewables are getting cheaper, batteries are getting cheaper"
  - So "Everything is going to be alright" (Bob Marley)
  - How cheap is enough? We need "Numbers, not adjectives" (David Mackay)
- Technology options for electricity storage
  - Short term storage can be expensive but must be efficient – many cycles per year
  - Long term must be cheap (fewer cycles), can be less efficient
  - Batteries $100/kWh target, need $10/kWh (MIT and this analysis)

Storage Technologies

- Mechanical
  - Potential energy: **Pumped hydro**, weights in shafts, cranes lifting blocks….
  - 1 MW = 10 T rising at 10 m/s
  - Kinetic energy: Flywheels
- Electro-Chemical
  - Conventional batteries: **Li-Ion**, Li-Sulphur..
  - Capacitors
  - Electrolysis of water to **hydrogen**, oxygen
  - Liquid metal
  - Flow batteries: Vanadium Redox, Sodium-Sulphur, Zinc-air, graphite-sulphur…
- Thermo-Mechanical
  - **Compressed air**
  - Liquid air
  - Pumped heat

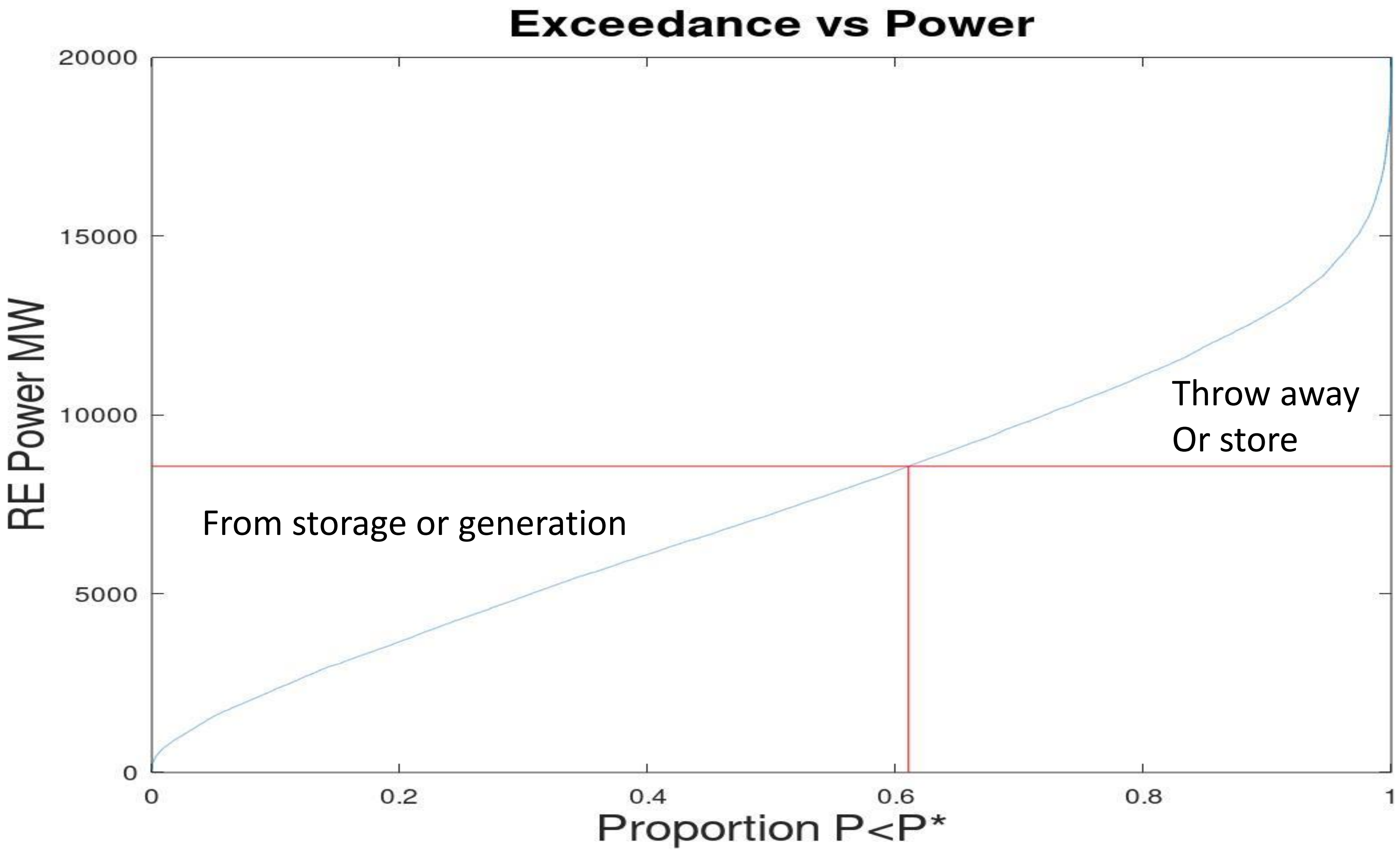




Source: RWE AG

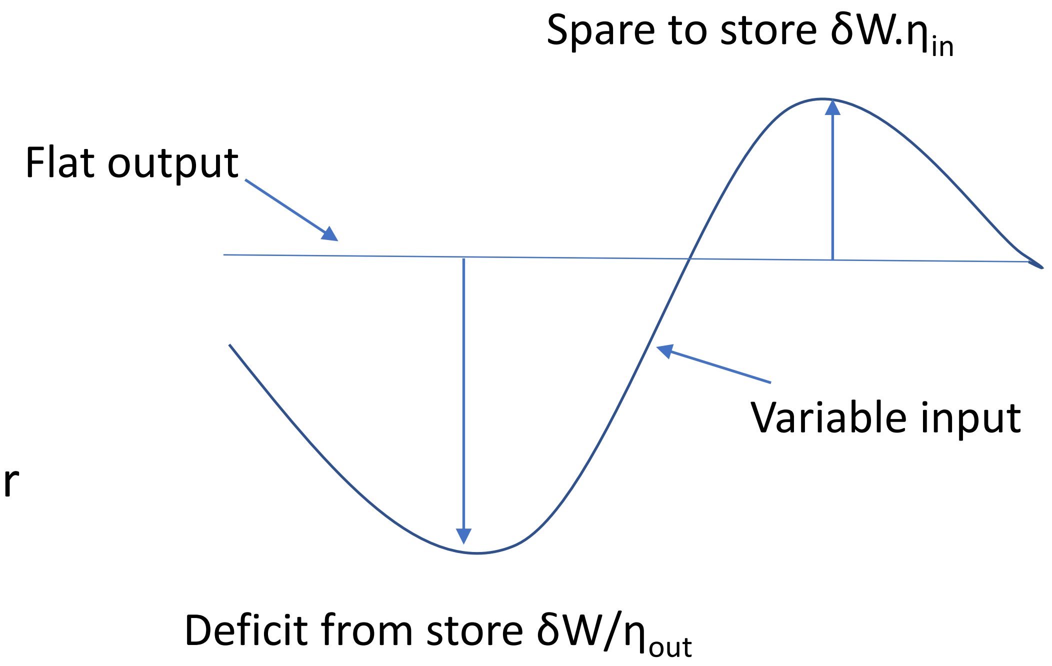
Conventional batteries too expensive for long term applications
Lowest cost: Electrolytic hydrogen, salt cavern storage and CCGT
Flow battery and thermo mechanical technologies prospective

Renewable power distribution

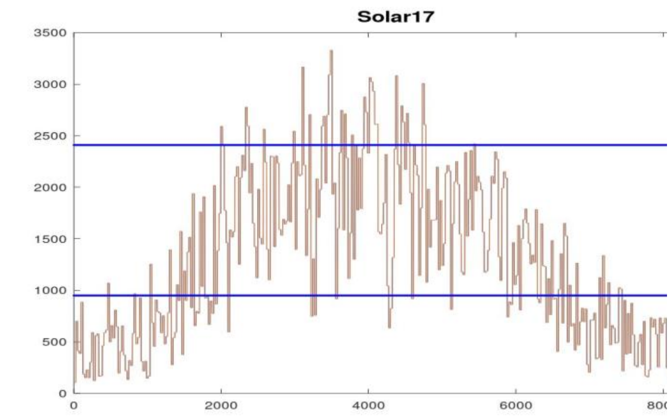


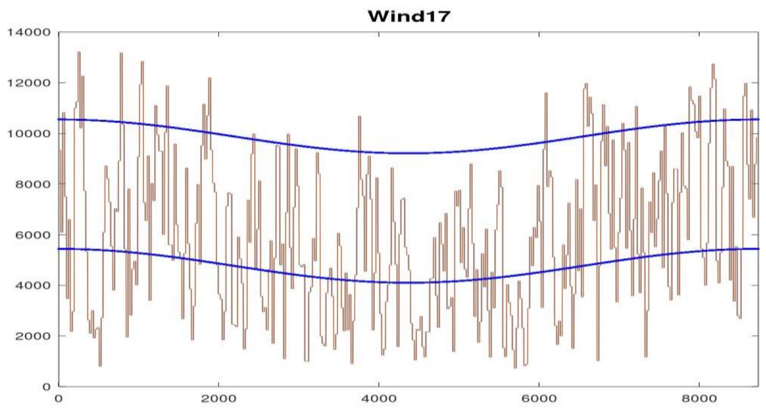
Storage model

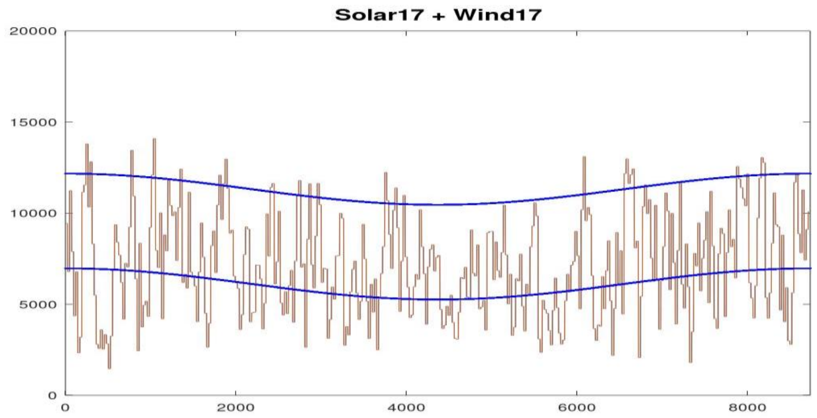
- How much storage do we need to convert UK wind and solar to flat?
  - Minimise cost of wind/solar + storage per flat MW of output
- Capital cost based
  - Avoid power prices based on inconsistent discount rates
  - No operational costs – optimistic!
- Based on 3 years of UK wind + solar hourly data
- Cost and conversion components
  - Fixed wind + variable solar generation
  - Convert electricity to stored energy
  - Storage
  - Convert back to power
- Adjust: delivered flat power level, storage capacity, solar capacity
  - Start and end storage levels must be equal
- Hourly to daily averaging

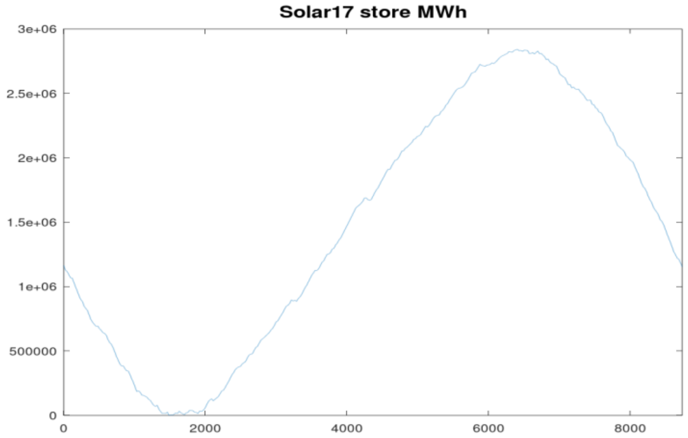


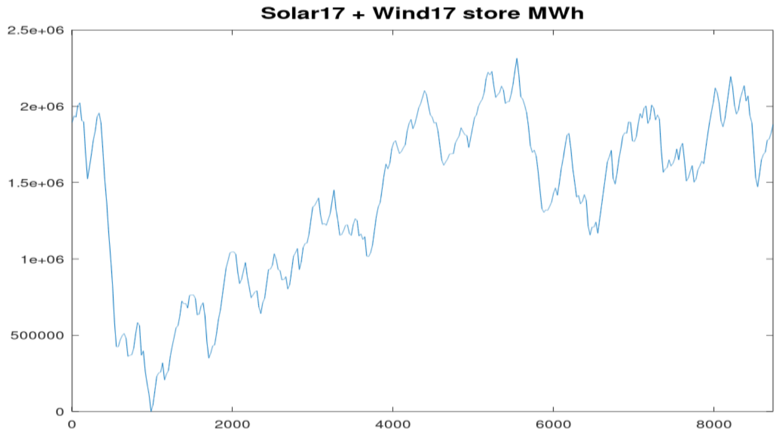
Wind and solar results











Annual Variation

Hydrogen dT=1	2017	2018	2019	3 years
Max Power MW	20008	19532	19275	20008
Mean Power MW	7166	7356	7869	7464
Min Power MW	293	101	357	101
Flat Power Out MW	5758	5828	6332	5948
Max Storage In MW	6692	7297	6929	6718
Storage, days	6.7	15.8	7.3	21.2
Percent from store	15.2%	16.5%	14.9%	15.5%
Rejected Power MW	133	136	161	176
InOut Loss MW	1275	1392	1376	1339
Wind MW/MWout	3.56	3.52	3.24	3.45
Solar MW/MWout	2.28	2.25	2.07	2.21
InCost $/W	0.70	0.75	0.66	0.68
OutCost $/W	1.14	1.14	1.14	1.14
VolCost $/W	0.30	0.70	0.33	0.94
WindCost $/W	9.24	9.13	8.40	8.94
SolarCost $/W	2.28	2.25	2.07	2.21
TotalCost$/.W	13.65	13.97	12.60	13.91

Wind only
Solar only
Wind + Solar

- Load factors: wind 33%, solar 11%
- Storage efficiency <44% for hydrogen
  - Power to hydrogen: 80%
  - Cavern storage: only compression loss
  - Hydrogen to power: 55%

	Wind	Solar	Wind+Solar	Hinkley C	CCGT+gas+CO2
MW wind/MW out	4.47	0	3.45		
MW Solar/MW out	0	20.2	2.21		
Days storage	35.4	82.3	21.2		
% Output from storage	16.6%	56.3%	15.5%		
Rejected+loss %	26.1%	48.0%	20.3%		
Capex $/W	14.9	29.6	13.9	~10.0	5.9

Hydrogen dT=1	**$/W.out**
Electrolyser	0.68
CCGT H_2 to power	1.14
Cavern	0.94
Wind turbines	8.94
Solar panels	2.21
Total	13.91

Batteries dT=1	**$/W.out**
In $/W	0.3
Out $/W	0.3
Batteries $/W	71.3
Wind turbines $/W	7.4
Solar panels $/W	1.8
Total $/.W	81.2

Model conclusions

- High renewables penetration is possible for electricity market
  - Only 10-15% of ‘flat’ power from storage or infill generation
  - 2 to 3 weeks storage needed, big annual variation for wind
  - Or low cost backup generation, not used often
- Hydrogen storage in caverns is only current effective long term option
  - Dedicated $100/kWh batteries far too expensive
  - Renewables + hydrogen storage is fairly expensive, low round trip efficiency (44%)
  - Hydrogen not good for within days storage
- Overbuild renewables and throw away peaks to reduce storage costs
- Nuclear, even at Hinkley C prices, is still cheaper than RE + H_2 storage

- Aside: Levelised Cost Of Energy (LCOE) is not the right metric
  - Despatchable power and variable power are different products - conversion cost
  - Correct criterion is total cost of grid with and without specific project

Alternatives to Long Term Storage

- Renewable power + electricity storage only solves electricity
  - Electricity solves cars, buses, trucks, not ships or planes
  - What about heat, steel, chemicals, other industry?

- Proposal: solve long term power variation with ‘something else’
  - Flexible clean generation
  - Dispatchable demand

- How do we best use variable renewables?
- Make something we want and use it
  - Make hydrogen, use where it has maximum value
  - Create heat/cold and store

Aside: Maximising Value

- Money and CO_2 are fungible, fuels are not
- Hydrogen conversion from natural gas is 75% efficient
  - Replace with renewable H_2 and use gas for power generation – 1.33 times emission reduction
- No synfuel from power (60%) where gas, LPG or oil used for heat
  - Displace with resistive heating (110%) or heat pumps (350%)
- Ethanol from grain (50%) similarly wasteful
  - Burn the grain (or even wood!) for heat, displace fossil fuels at x2 efficiency
- Shell Qatar gas to diesel, (60%)
  - Displace Saudi oil burnt for power - 100% efficiency (politics prevented)

Flexible generation

- Will not soak up spare renewable or nuclear energy
- Low capital cost required, high cost to operate is acceptable
- Hydro-electric – excellent, but limited scope
- Open cycle gas turbines & IC engines are low cost ($0.2-$0.5/W)
  - Poor efficiency does not matter if not much used – emissions?
- NetPower Allam Cycle – gas / syngas CCS
  - Oxyfuel, high pressure CO_2, CCGT costs, 100% capture
- Moltex* Generation IV molten salt nuclear reactor
  - Consumes ‘spent’ fuel, converts 200,000 year problem to 300 year annoyance
  - Low cost reactor, heat storage, inherently safe, no radioactive gases

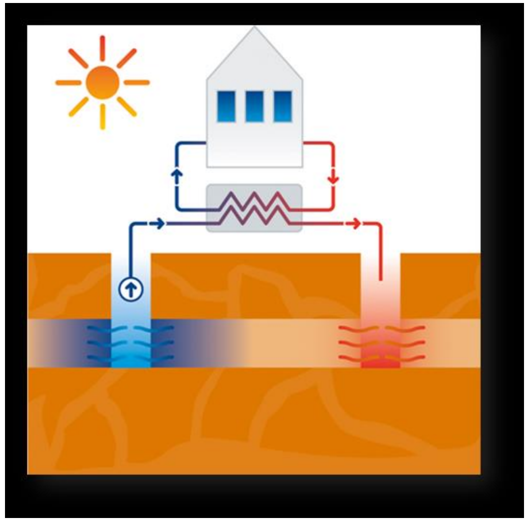
*Full disclosure – invested non life changing cash in Moltex crowdfunding round

Flexible demand

- Often much less expensive and more efficient to store demand
  - Capital expenditure to make equipment flexible & operating losses running at part load
- Power to H_2 (electrolysis) and N_2 (air separation) make ammonia
  - Displace conventional NH_3, also potential shipping fuel
  - Aids export of energy from countries with big resources and low demand
- Industrial processes options: air separation (oxyfuel), aluminium & iron smelting…
- Resistive heating: storage heaters
- Heat pumps: heat out per electricity in (COP) x3 to x4
- Refrigeration – store cold
- Charge/discharge automotive batteries
- Synthetic hydrocarbons
  - CO2 sequestration + conventional oil/gas can have same emissions, uses far less clean energy
  - Gasification of biomass/forestry/agricultural waste + H_2

Low temperature heat and cold storage

- Hot water
  - Pond
  - Borehole
  - Disused mine
  - Aquifer
- Phase change materials
  - Waxes
  - Salts
- Cold
  - Ice, brine
  - Borehole
  - Aquifer



Renewable energy to food

- Big Ag clears huge areas of rainforest for soy & palm oil
  - appalling biodiversity & CO_2 consequences
- Nature is very inefficient – but also very inexpensive
  - ~2% incident solar is converted to biomass, most not product
  - One hectare **sugar cane** ethanol: **100,000 km/y**
  - One hectare **solar PV electricity: 5 million** km/y
- What does this suggest for food?
  - H_2 from solar PV + electrolysers - efficiency 8-16%
  - Direct solar H_2, cheaper than PV + electrolysers
- Gas fermentation: feed H_2 + CO_2 to archaea (Solar Foods, LanzaTech)
  - Single cell proteins, oils, carbs or ethanol
- Direct solar option: GM cyanobacteria secrete product
  - ethanol, diesel, ?veg oil? given sunlight and CO_2
- Deploy in desert, not on fertile land
  - Massive land use/biodiversity benefit + CO_2 reduction
- Better way to export renewable resources than H_2 or ammonia

CO_2 out of the air or sea is critical for the climate
Also needed for net zero emissions food / fuel

Conclusions

- Electricity storage may not be the best complement to renewables
- Decarbonise heat with seasonal heat storage, powered by electric heat pumps boosting waste heat from industry and solar thermal
- Gas fired CCS and Gen IV nuclear can be part of the power solution
- Vehicle batteries are better value than stationary
- Renewable power in high resource areas can displace fossil fuels in chemical energy production AND play a part in eliminating industrial ag in the tropics
- Everyone has an agenda, do your own analysis