



“The optimal mix of hydrogen storage and compressed air energy storage”

Dr. B. Cárdenas, Prof S. Garvey

Hydrogen Storage in Caverns.

Online event hosted by the Geological Society London, 12 of April 2021

We're going to need a lot of energy storage!



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Research efforts have focused on quantifying the amount of energy storage capacity that we'll need to support large shares of renewable generation.

There is broad consensus on some points:

- The profile renewable of generation should match as closely as possible to that of demand
- No storage required for penetrations $< \sim 25\%$
- Some storage required for penetrations to $\sim 80\%$
Exponential increase in capacity above $\sim 80\%$
- A small amount of over-generation (curtailment) is generally leads to a lower overall system cost.



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Energy storage capacity vs. renewable penetration: A study for the UK

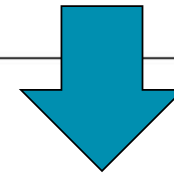
Bruno Cárdenas ^{a,*}, Lawrie Swinfen-Styles ^a, James Rouse ^a, Adam Hoskin ^a, Weiqing Xu ^b, S.D. Garvey ^a

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- Optimum mix for the UK is **$\sim 84\%$** wind and **$\sim 16\%$** solar PV
- The UK would need **~ 43 TWh** of storage for a 100% renewable penetration, considering **15%** curtailment and **70%** storage efficiency.

But how do we provide that storage capacity?



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We need to understand how that storage capacity will be provided.

Energy storage will be required over a vast range of discharge times :

- (I) *very-short duration storage* (<5 minutes)
- (II) *short-duration storage* (5 minutes – 4 hours)
- (III) *medium-duration storage* (4 hours – 200 hours)
- (IV) *long-duration storage* (>200 hours)

There is no single technology that is well suited to deal with the complete spectrum !

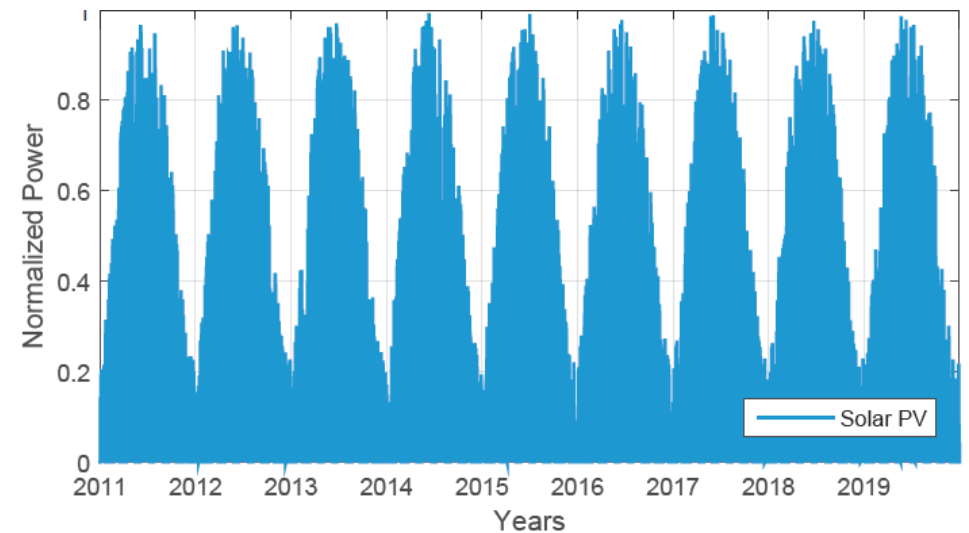
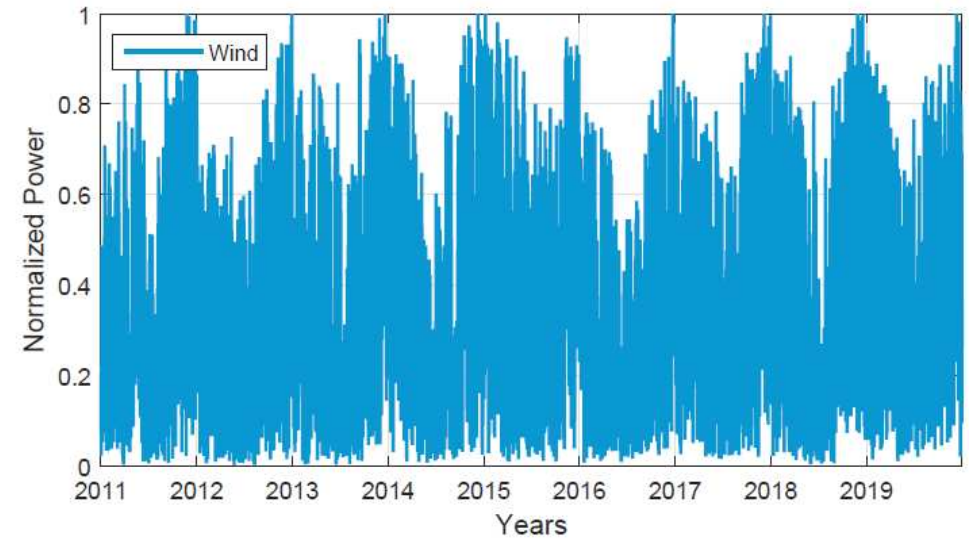
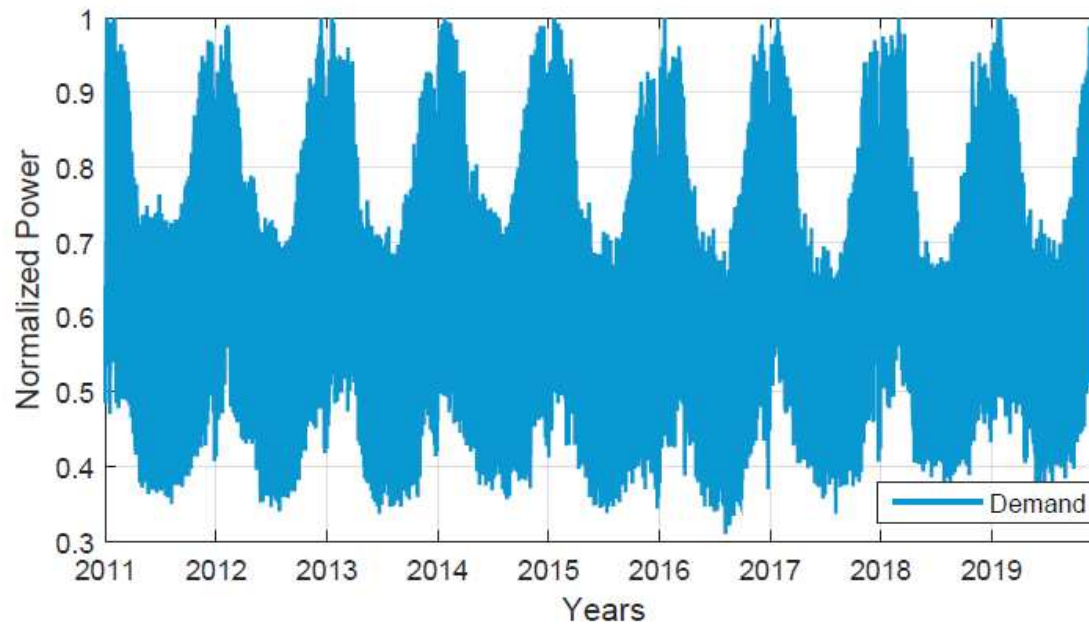
We carried out a study that shows that: the total cost of electricity in a 100% renewable grid can be minimized by using different storage technologies and fine-tuning their mix.

Electricity Demand and Renewable Generation



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** Profiles with a resolution of 1 hr (>78k datapoints)



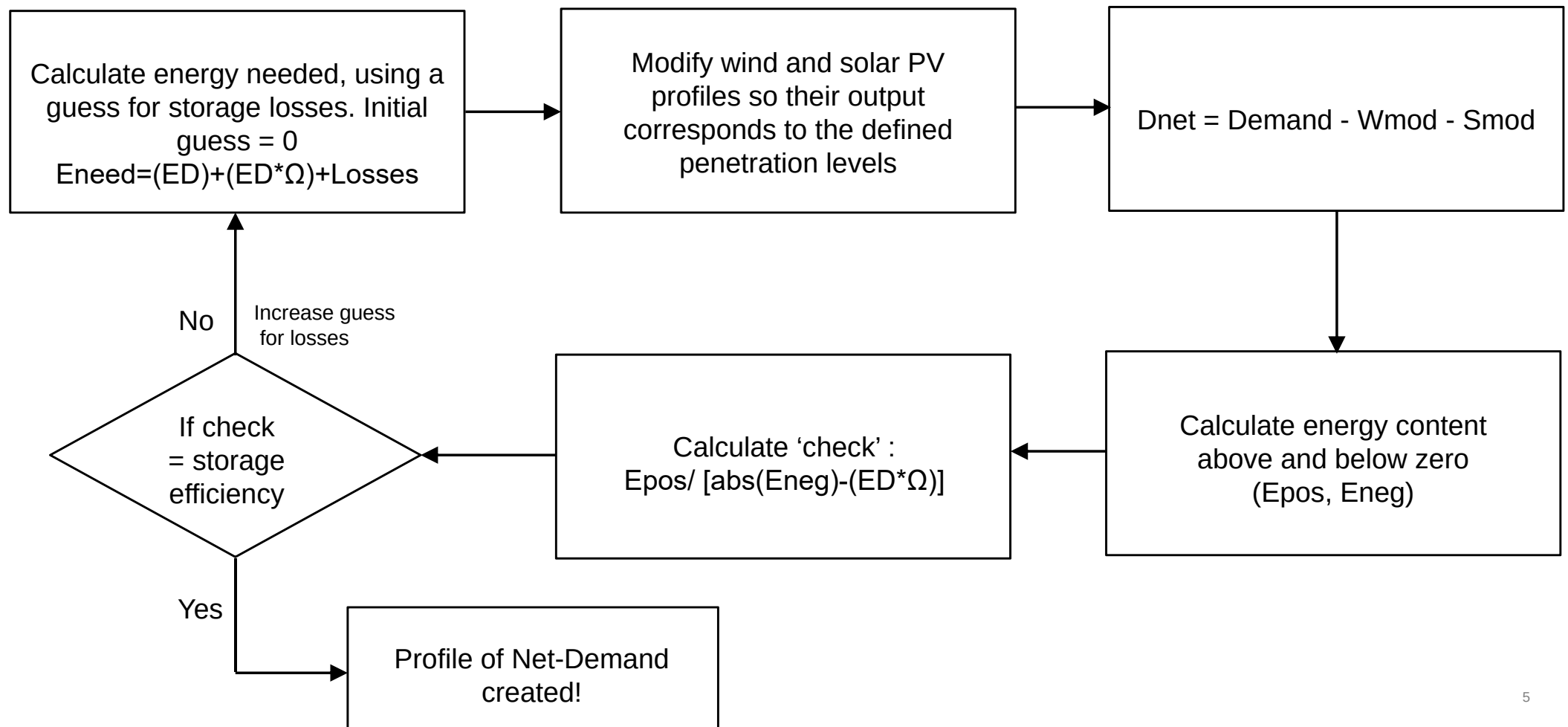
<https://gridwatch.templar.co.uk/index.php>

<https://www.bmreports.com/bmrs/?q=generation/fueltype/current>

Renewables Ninja. Data available online: www.renewables.ninja

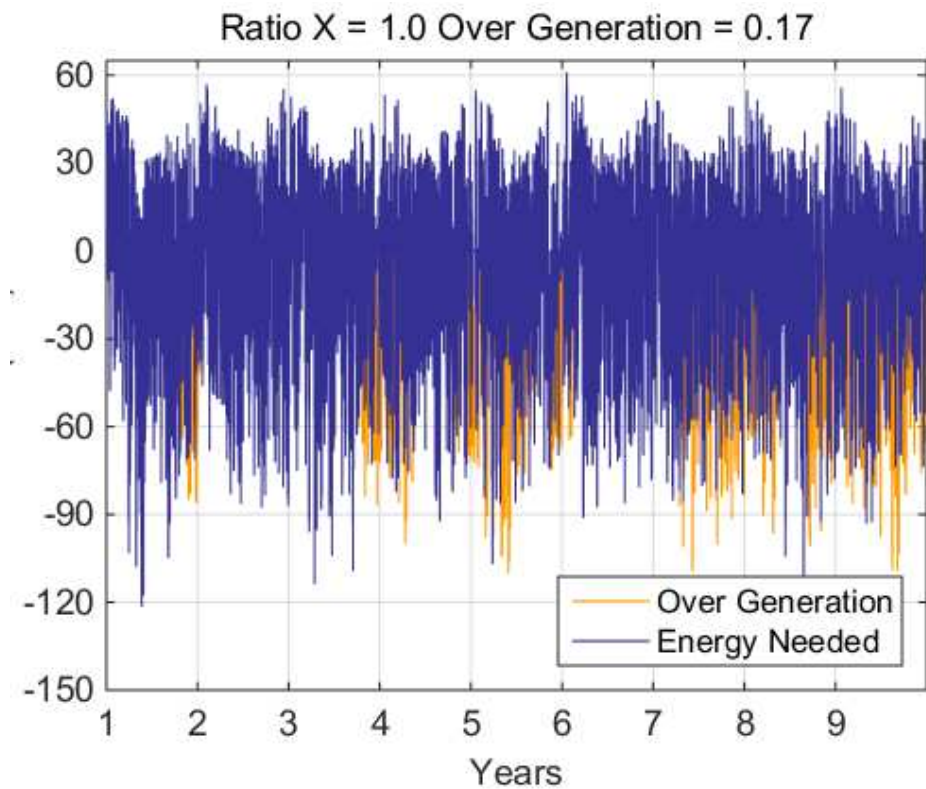
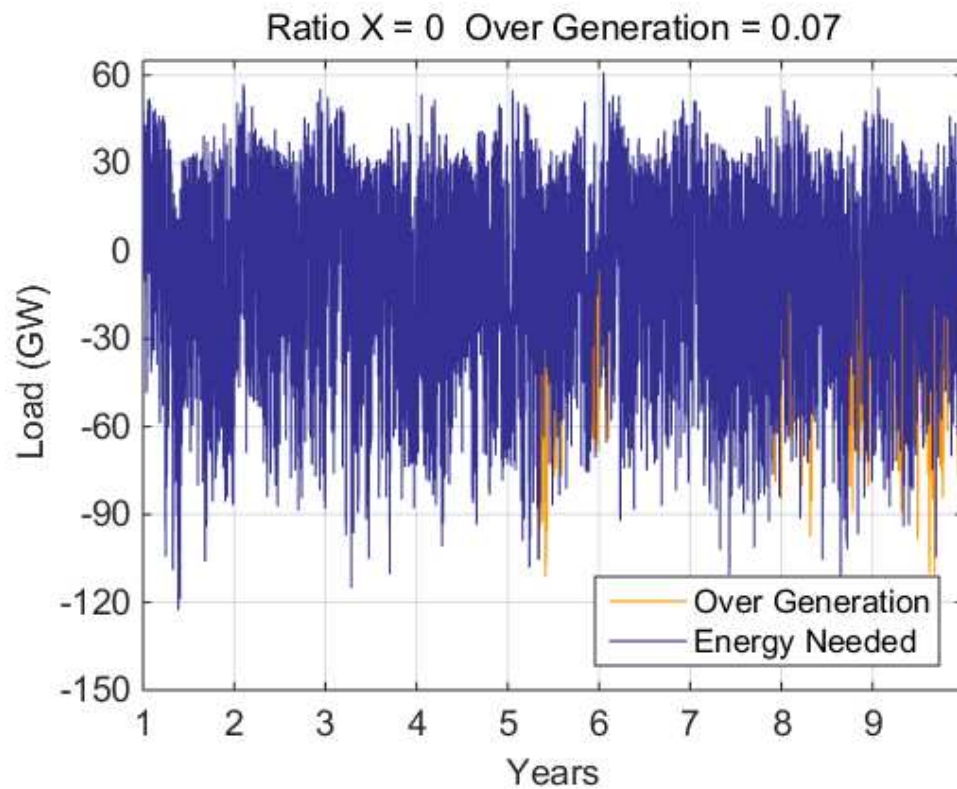
Creating Profiles of Net-Demand

- We use a 'Ratio X' as our 'control variable': It indicates the fraction of the energy that will pass through CAES. $X=1$ means 100% through CAES



Net-Demand Profiles

- The figures show examples of net-demand profiles for different Ratios X. We can see the full profile (inc. overgeneration) and profile curtailed in a non-prescriptive way.
- To remove over-generation (Ω) we pass profiles through a time-stepping function that simulates the charge/discharge of a store

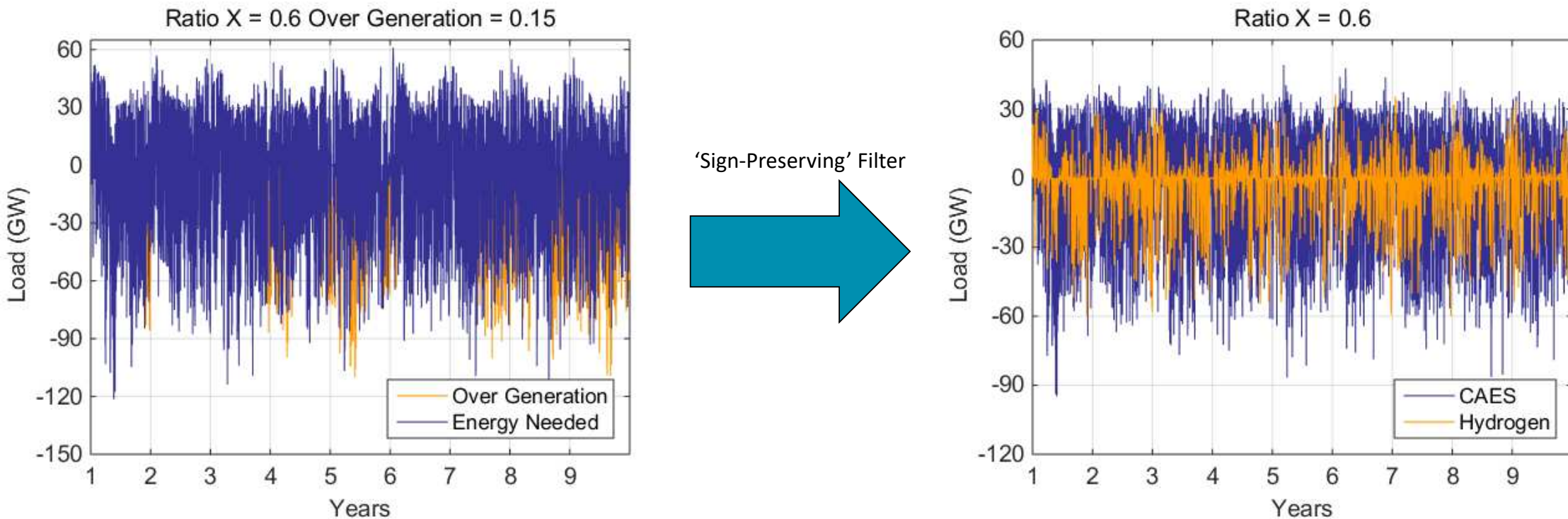


Creating Work-Cycles for H₂ and CAES



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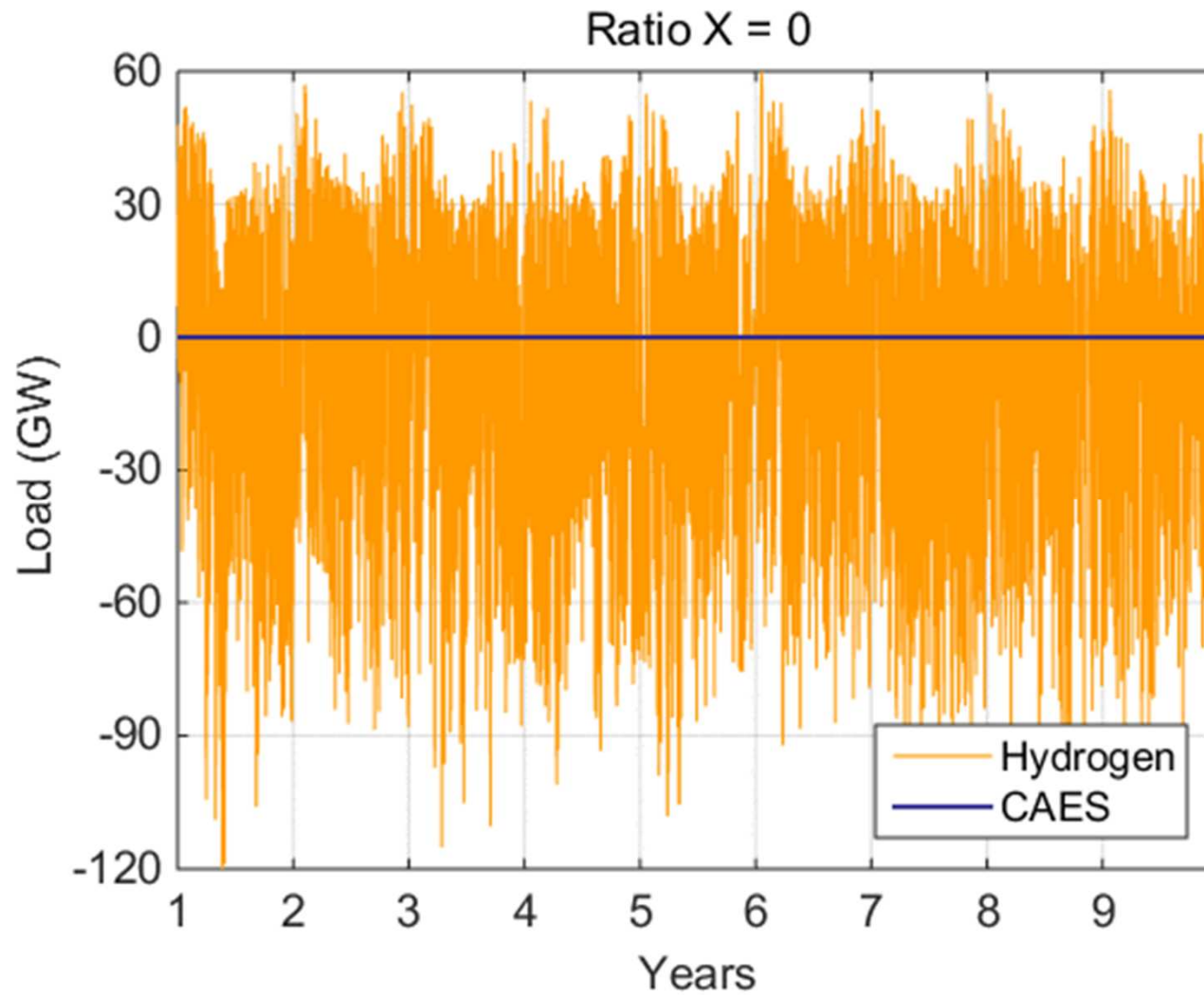
- The profiles of Net-Demand for different Ratios X are passed through a special signal-splitting tool to create 2 profiles.
- The low-frequency one is assigned to H₂ while the higher-frequency one is assigned to CAES
- The tool has the special feature of no 'counter-flow' of energy, both profiles have the same sign as the original at all times.



Examples of Different 'Splits'



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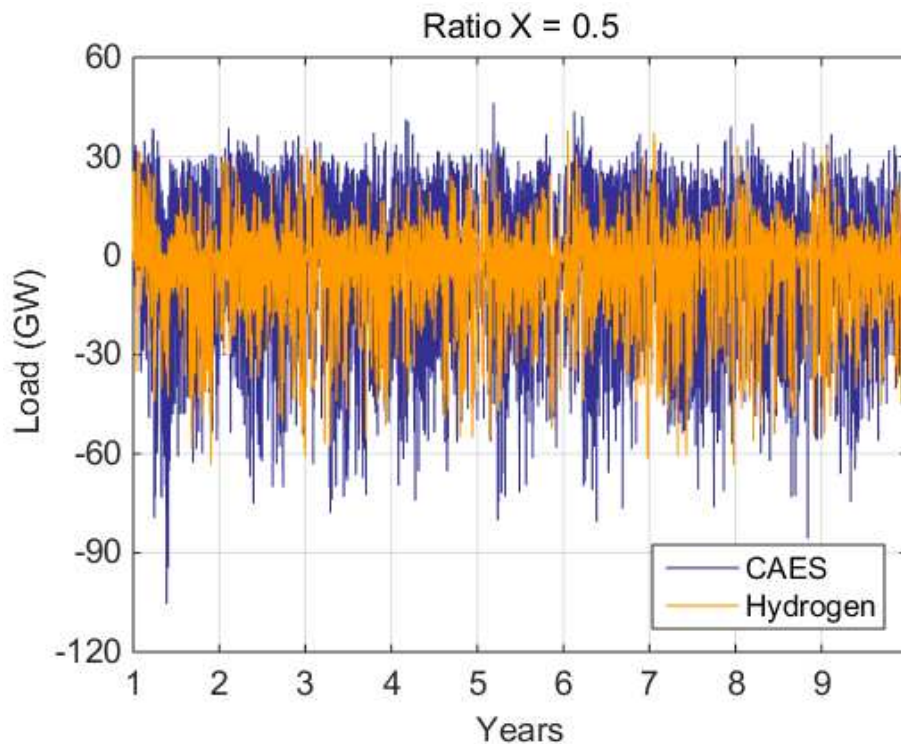


Post-Split Optimisation of Work-Cycles

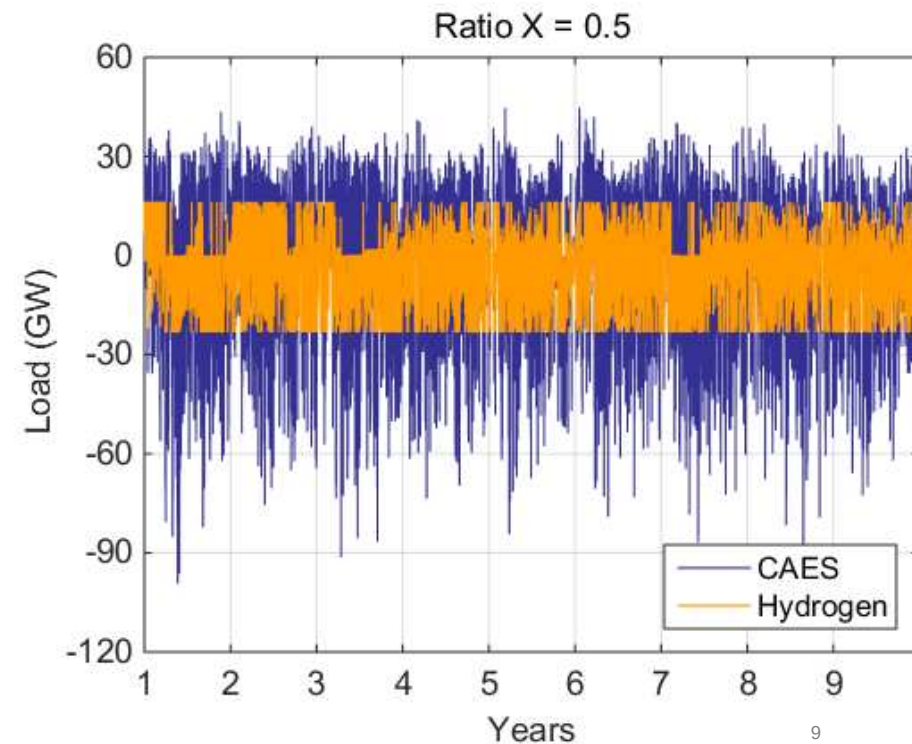
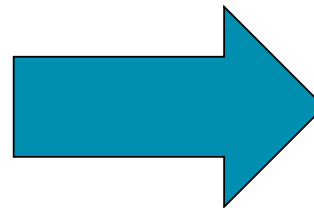


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- Each pair of work-profiles or 'split' can be optimized to achieve a lower overall system cost. This is done in 2 stages:
 - Stage 1: Flatten hydrogen's charging/discharging power, as it has a higher cost than CAES.
 - Stage 2: Reduce CAES storage capacity (without reducing the energy that passes through it) as it is more expensive than H2.
- Despite the re-shaping, the overall effect stays the same. The sum of both profiles replicate exactly the profile of Net-Demand.



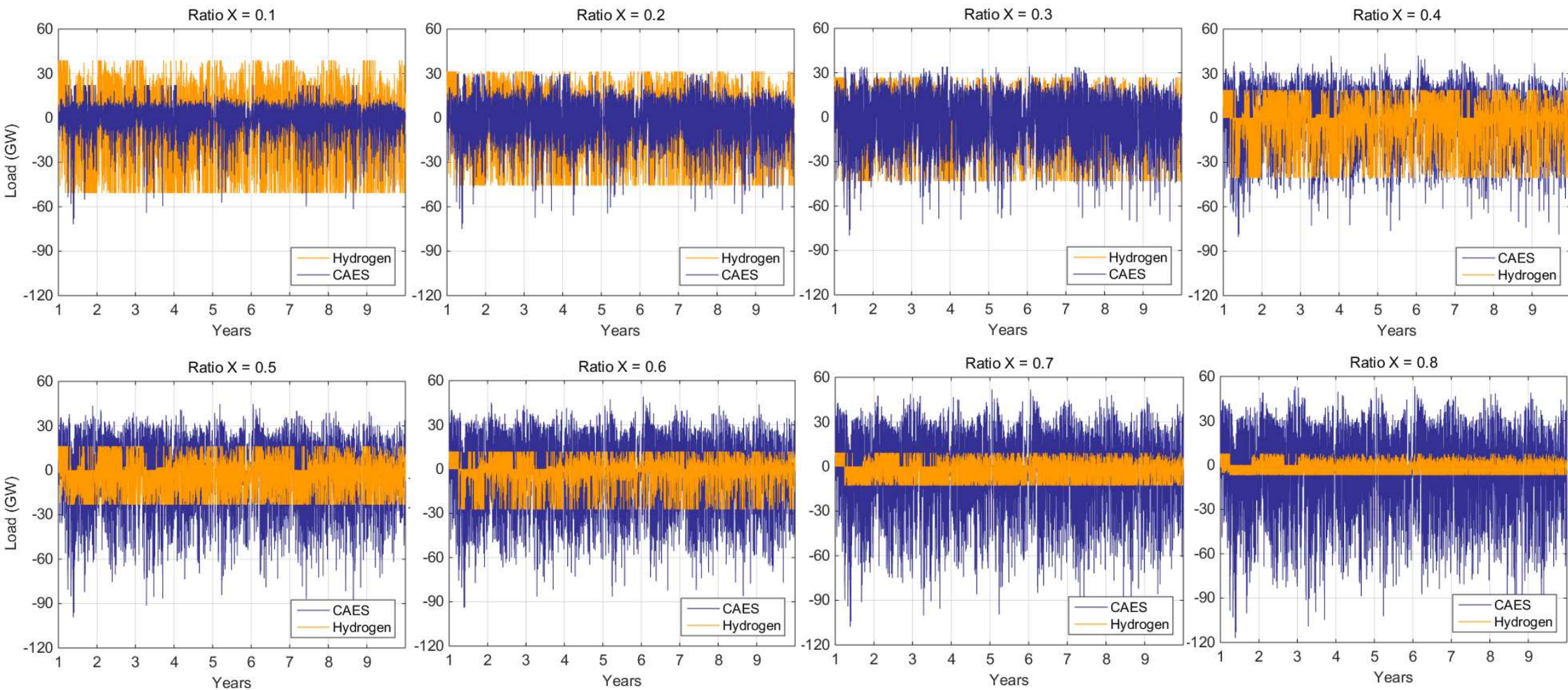
Signal Optimisation
Functions



Examples of Different (Optim'd) Work-Cycles



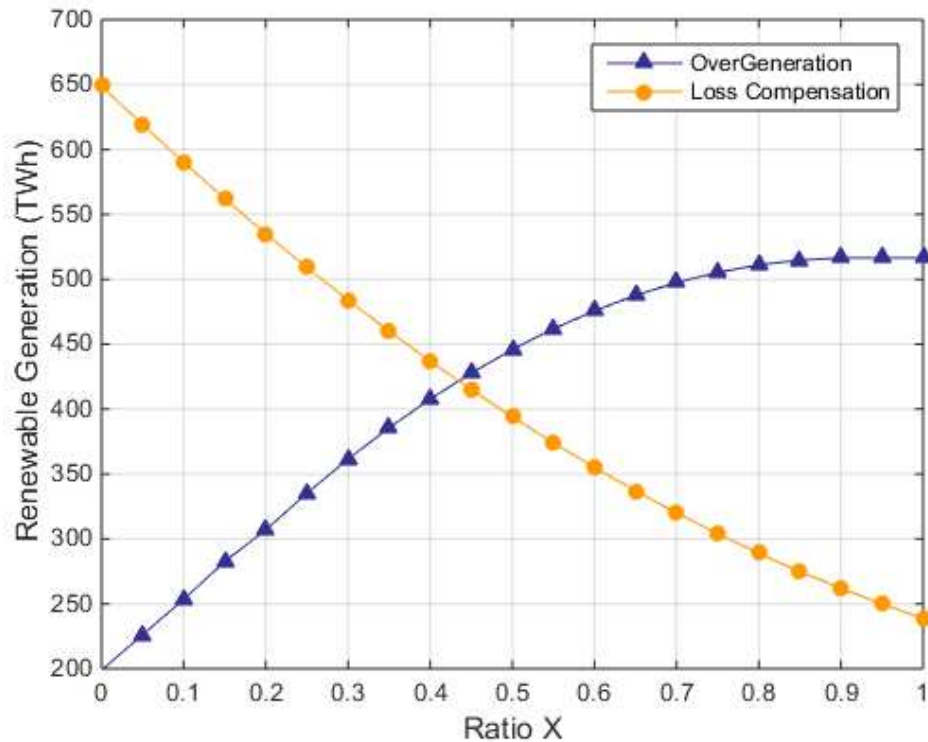
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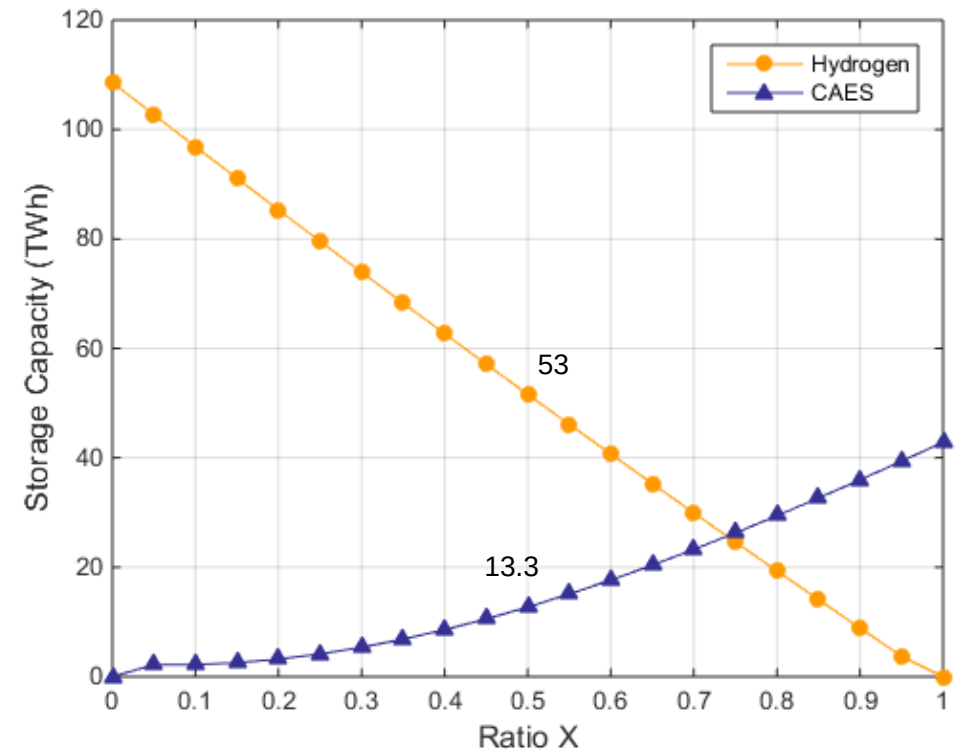
Factors that influence overall cost of electricity



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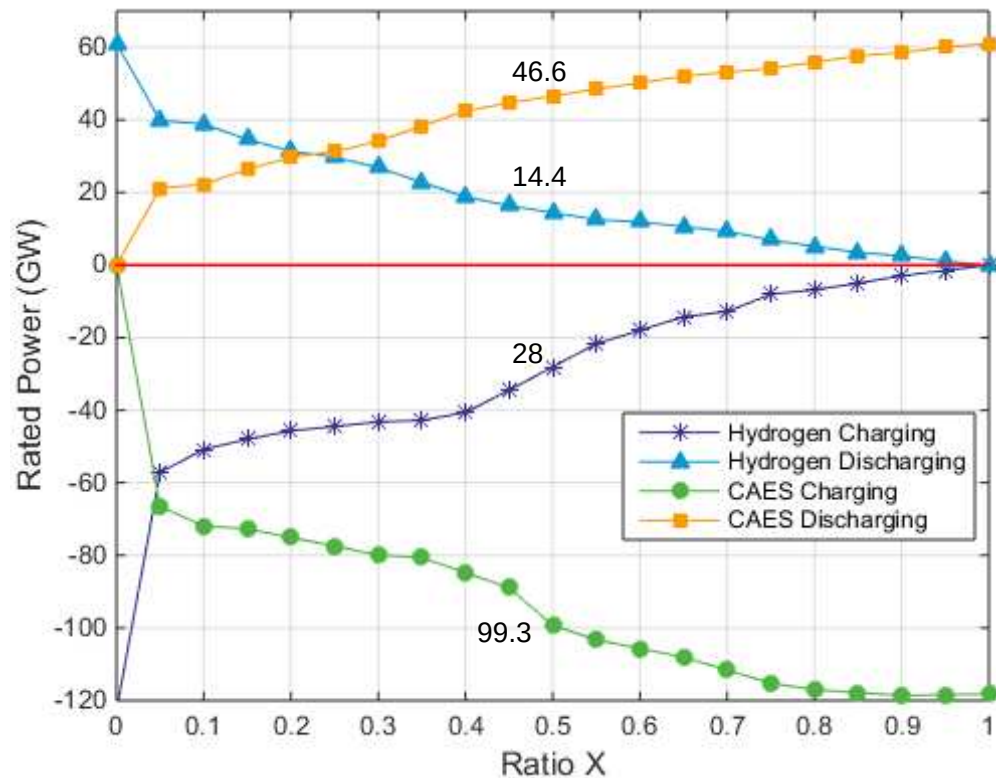
- H2 has a lower efficiency (45%) than CAES(70%). If more energy is passed through the H2 store, renewables need to produce more to compensate for losses
- We know that a small % of overgeneration is good. Systems with more H2 allow less overgeneration because there is already a large 'extra' put in to compensate for losses.



Hydrogen requires much larger capacities than CAES for two reasons:

- 1) Lower efficiency.
- 2) Operates in a lower-frequency cycle. Energy stays in storage for longer.

Factors that influence overall cost of electricity



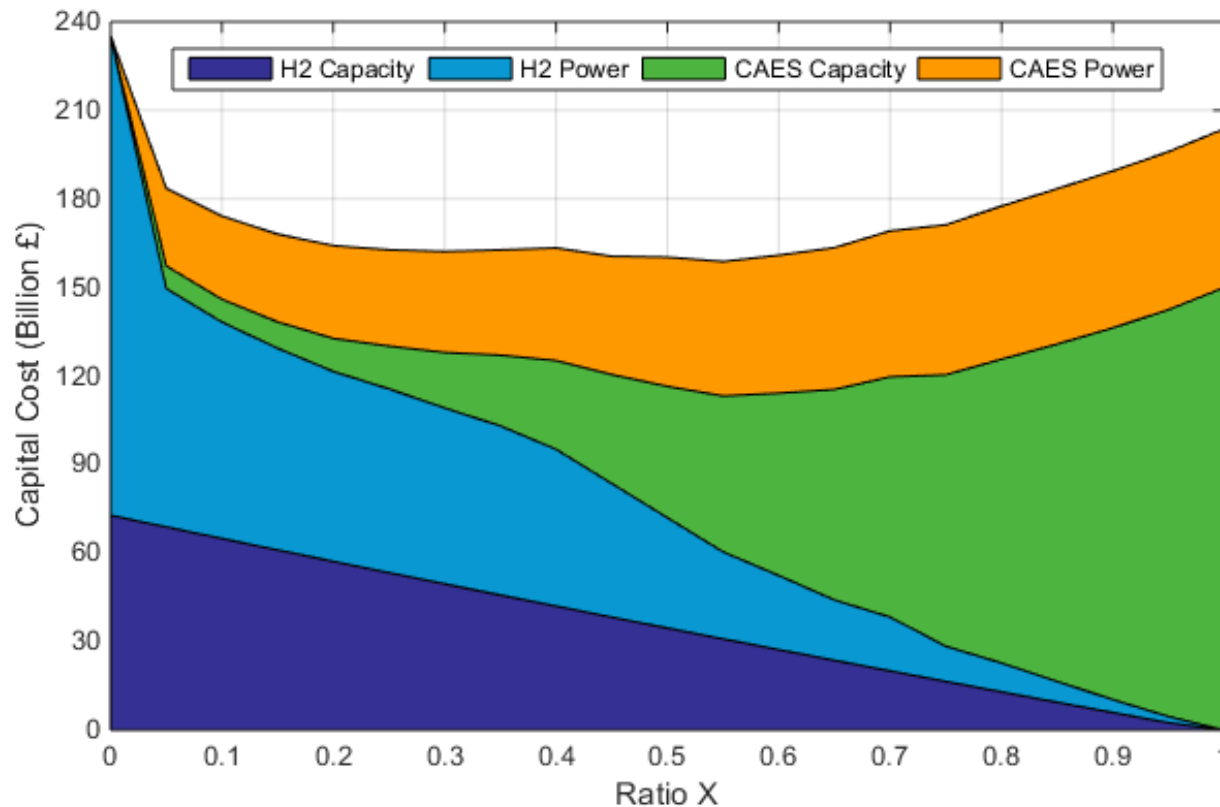
- The rated charging and discharging powers of CAES increase as X moves towards 1.
- Analogously, the rated charging and discharging powers of H₂ increase as X moves towards 0.
- Regardless of the value of X , the maximum rated discharge power of either store is ~60 GW, as it is limited by demand, which also peaks at ~60 GW.
- The rated charging and discharging powers of H₂ would have been considerably larger if the post-split signal optimization had not been carried out.

Capex of the Stores



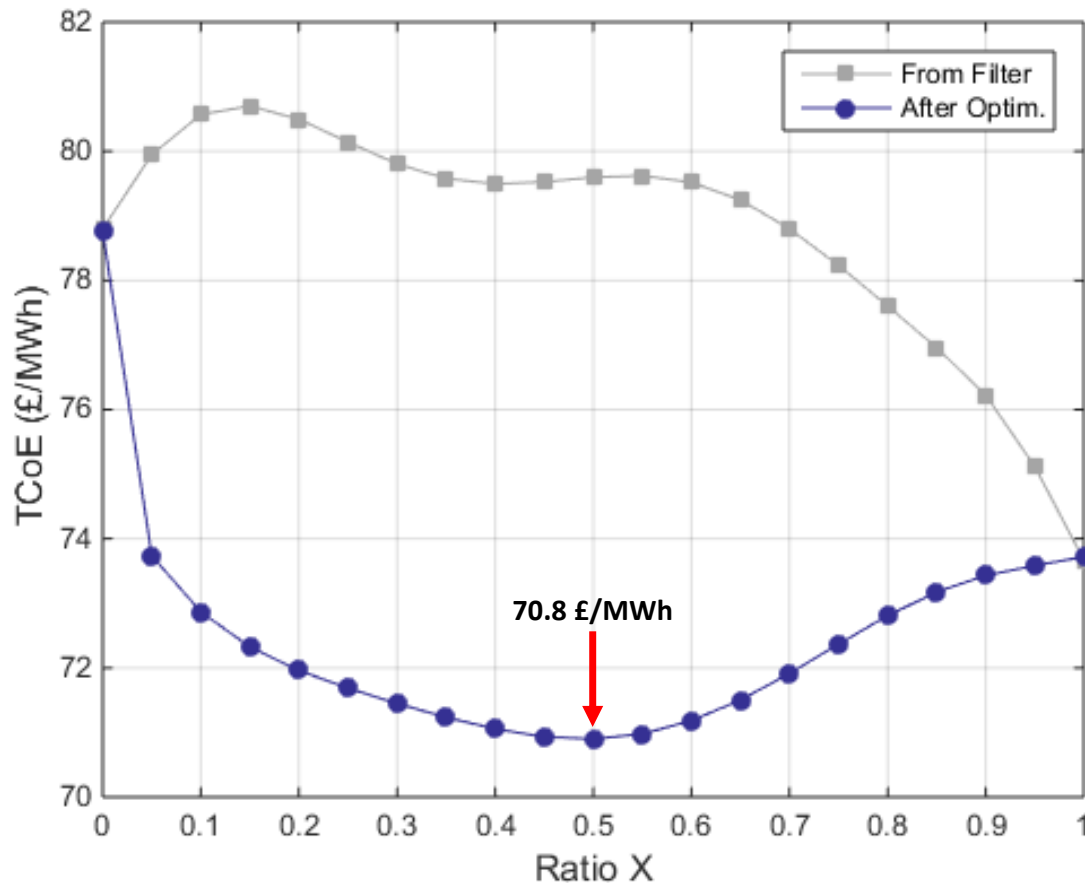
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$$C_{store} = \alpha \cdot Size + \beta \cdot \max(|P_c|) + \gamma \cdot \max(P_d)$$



	Value	Unit
CAES storage capacity cost (α)	3.5	£/kWh
CAES charging power cost (β)	300	£/kW
CAES discharge power cost (γ)	300	£/kW
H2 storage capacity cost (α)	0.67	£/kWh
H2 charging power cost (β)	1100	£/kW
H2 discharge power cost (γ)	450	£/kW

A mix of storage technologies minimizes TCoE



$$TCoE = \frac{C_W + C_S + C_{CAES} \cdot \left(\frac{\tau}{\lambda}\right) + C_{H2} \cdot \left(\frac{\tau}{\lambda}\right)}{E_D}$$

$$E_G = E_D + (E_D \cdot \Omega) + Losses$$

$$C_W = E_G \cdot P_W \cdot LCoE_W$$

$$C_S = E_G \cdot P_S \cdot LCoE_S$$

	Value	Unit
LCOE of Wind	40	£/MWh
LCOE of Solar PV	60	£/MWh
Lifetime of CAES (λ)	30	Years
Lifetime of H2 (λ)	30	Years

Breakdown of System Costs



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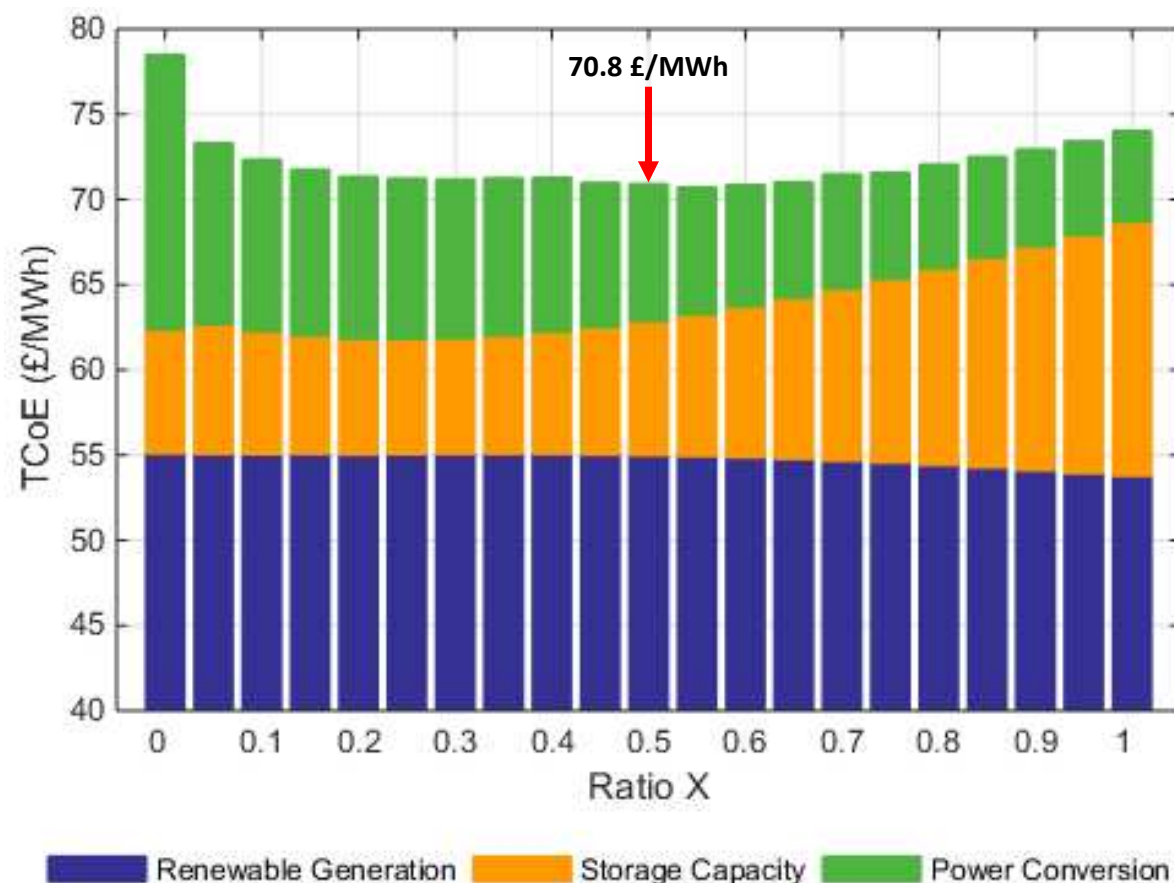
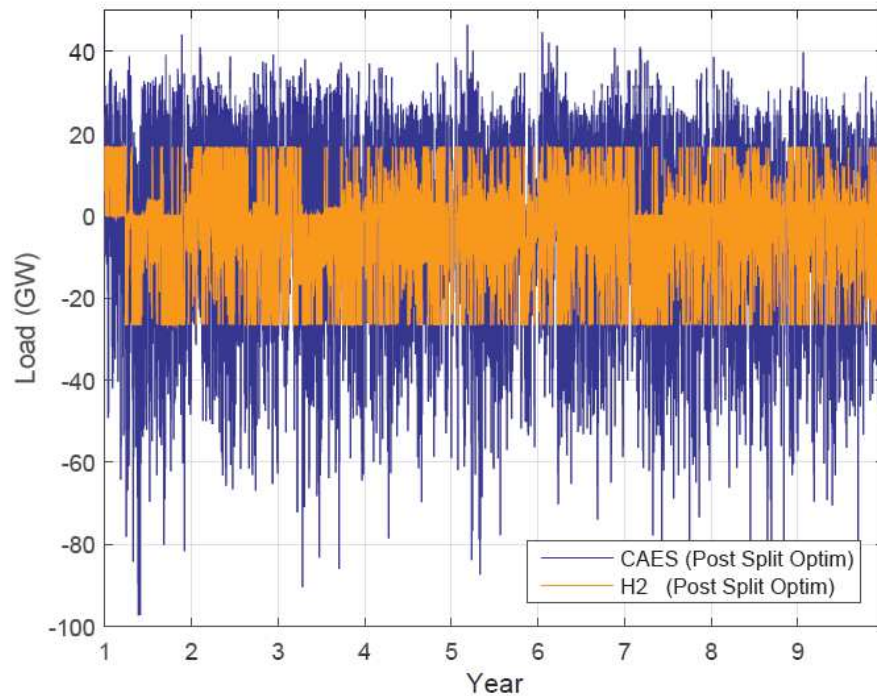


Table. Individual contributions of different system components to the *TCoE* in the optimum system configuration ($X=0.5$)

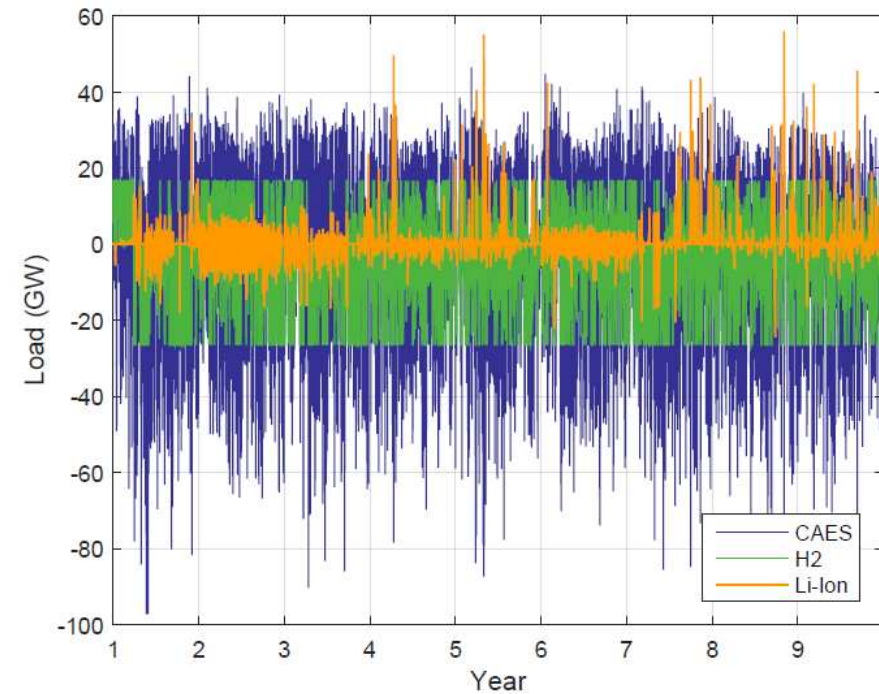
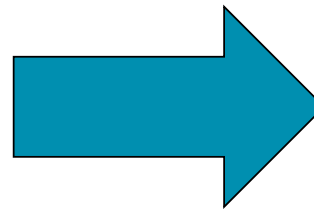
	£/MWh	% of TCoE
Baseload Generation	43.00	60.71
Over-Generation	6.45	9.11
Loss Compensation	5.64	7.97
Generation subtotal	55.09	77.78
H ₂ charge machinery	2.54	3.59
H ₂ discharge machinery	0.73	1.03
CAES charge machinery	2.96	4.18
CAES discharge machinery	1.34	1.89
Power conversion subtotal	7.57	10.69
H ₂ storage capacity	3.53	4.99
CAES storage capacity	4.63	6.54
Storage capacity subtotal	8.16	11.53
Total Cost of Electricity	70.8 £/MWh	

In reality, we will also need batteries

- H2 and CAES do not have the capability of ramping as fast as the work profiles dictate. Realistic ramping rates $\sim 5\%$ per minute for both stores
- We use a 'ramping-rate' function to find all the shortcomings of H2 and CAEs and assign those to batteries
- We use profiles with a resolution of 5 minutes here. Smaller resolution would be even better.



'Ramp-Rate' function



Summary of system costs inc. batteries

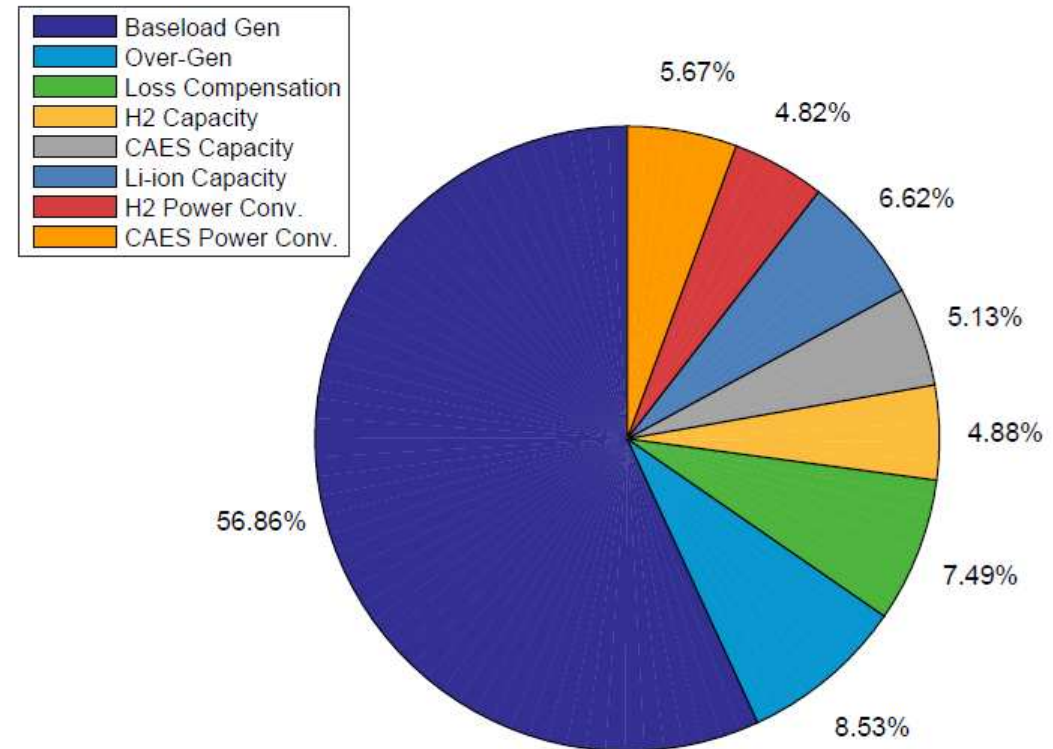


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	Parameter	Value	Unit
Renewable Generation	Total Generation	3864.2	TWh
	Baseload Generation	3015	TWh
	Loss Compensation	396.9	TWh
	Over-Generation ($\Omega=0.15$)	452.25	TWh
Energy Distribution and Losses	Ratio X	0.5	
	Energy put in storage	933	TWh
	H2 energy input	-466.8	TWh
	CAES energy input	-467.2	TWh
	Li-ion energy input	-0.93	TWh
	H2 total energy losses	256.8	TWh
	CAES total energy losses	140.1	TWh
Storage Capacity and Rated Powers	H2 storage capacity	55.35	TWh
	CAES storage capacity	11.13	TWh
	Li-ion storage capacity	167.7	GWh
	H2 rated charge/discharge power	-26.5/11.7	GW
	CAES rated charge/discharge power	-97.3/46.6	GW
	Li-ion rated charge/discharge power	-24.6/55.98	GW

TCoE = ~75.6 £/MWh

System requires a total energy storage capacity of 66.65 TWh :
~83% is provided by hydrogen, 16.7% is provided by CAES and the remaining 0.3% is supplied by Li-ion batteries





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Thank you!

Contact:

Bruno.Cardenas@nottingham.ac.uk