Modelling Including Multiple Stores.

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Why Multiple Stores Lead to Reduced Cost

Energy Storage systems have four main metrics:

- Cost per unit of rated input power (£/kW(e_{input}))
- Cost per unit of rated output power (£/kW(e_{output}))
- Cost per unit of storage capacity (*volume*) (£/kWh(e_{output}))
- Round-trip efficiency (%)

Different systems are good in different ways. No one system is ideal for all purposes. At large scales, these metrics are constants.

Understanding Multiple Stores – Start with the Single Store Case.

Consider, initially, that we have just one store in the system.

Four distinct parameters determine both the system cost and whether that system will meet all demand.

- Rated input power *G* (GW(e_{input}))
- Rated output power *H* (GW(e_{output}))
- Storage capacity (*volume*) *V* (GWh(e_{output}))
- Over-generation factor* *X* ( )

If parameters (*G*, *H*, *V*) lie within reasonable bounds, then there will be some minimum value *X* or which all demand is met ($X = X_{min}$).

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* *X*=1.2 indicates: *total quantity of electrical energy generated in the record exceeds the total quantity of electrical energy consumed by 1.2.*

Testing Whether a Single-Store System is Adequate to Meet Demand.

Any given single-store system is described by the 4-tuple, (G, H, V, X).

We can test whether this system will meet all demand by

- Initialising the energy in store at some value such as $0.7 \times V$
- Stepping through each (1-hour?) period in the record and …
- If supply exceeds demand, put (some of?) the excess into store
- If demand exceeds supply, draw (some of?) the shortfall from store
- Adjust the energy level in the store

We might check that the energy in store at the end is close to or equal to the energy that was in store at the start of the record.

No “scheduling” problem here and no purpose for “forecasting”.

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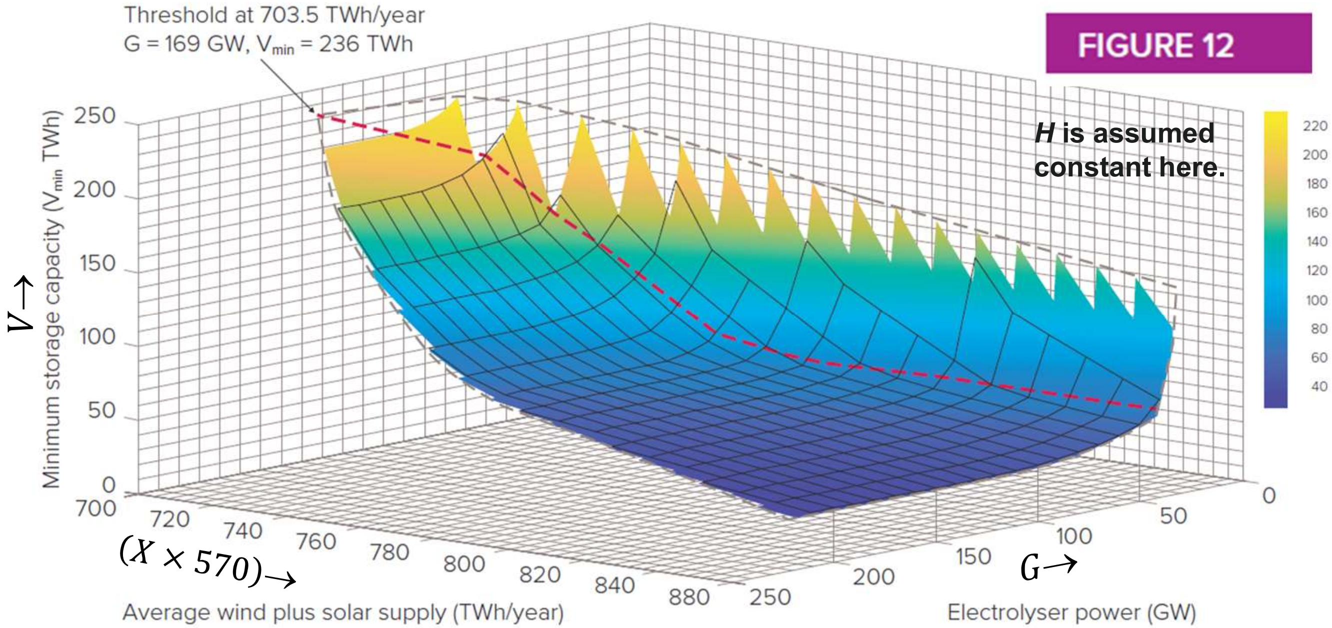
Optimising the System with a Single Store

Any given single-store system could be optimised by exploring the 3D space … (G, H, V). For each "point" in this space, we calculate the associated value X_{min} as a dependent variable.

System cost is then determined from the 4-tuple (G, H, V, X_{min}).

'Straightforward to put this into an optimisation for minimum cost.



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Understanding Multiple Stores – Now with 2 Stores.

Consider now that we have two stores in the system.

Seven distinct parameters determine both the system cost and whether that system will meet all demand.

- Rated input powers G_1, G_2 (GW(e_{input}))
- Rated output powers H_1, H_2 (GW(e_{output}))
- Storage capacities (*volumes*) V_1, V_2 (GWh(e_{output}))
- Over-generation factor* X ( )

If parameters (G_1, G_2, H_1, H_2, V_1, V_2) lie within reasonable bounds, then there will be some minimum value X or which all demand is met ($X = X_{min}$).

* X=1.2 indicates: *total quantity of electrical energy generated in the record exceeds the total quantity of electrical energy consumed by 1.2.*

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Testing Whether a 2-Store System is Adequate to Meet Demand.

Any given 2-store system is described by the 7-tuple, (G_1, G_2, H_1, H_2, V_1, V_2, X).

We can test whether this system will meet all demand by

- Initialising the energy in each store #*i* at some value such as $0.7 \times V_i$
- Stepping through each (1-hour?) period in the record and …
- If supply exceeds demand, spread (some of?) the excess into stores
- If demand exceeds supply, draw (some of?) the shortfall from stores
- Adjust the energy levels in the stores

<u>Scheduling needed to decide which store has priority for filling/emptying</u>

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A Primitive Scheduling Approach for a 2-Store System

A primitive approach for scheduling a 2-store system would be to prioritise the store with the higher round-trip efficiency at all times. Then:

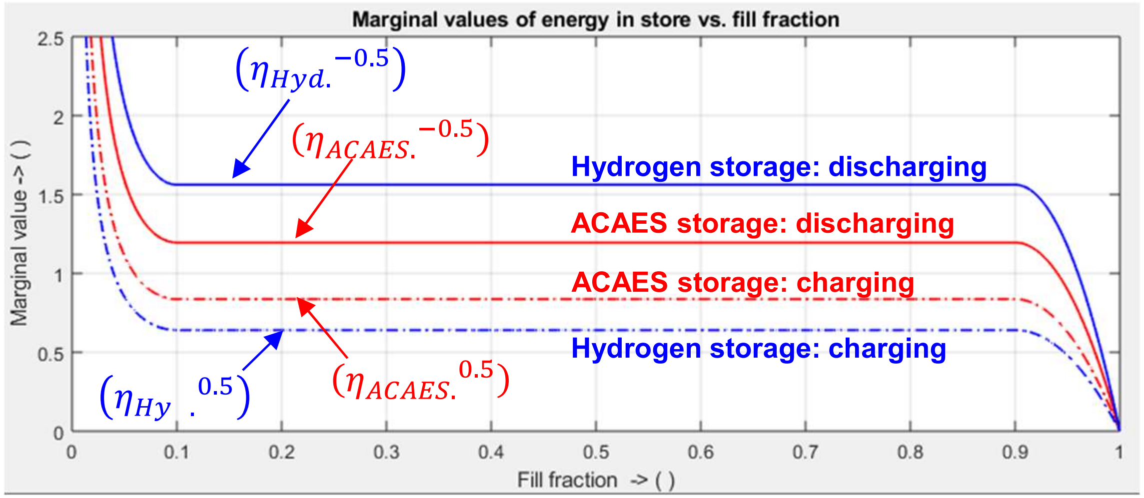
- If supply exceeds demand, put as much as possible into the more-efficient store (respecting limits on input power and energy in store)
- If demand exceeds supply, draw as much as possible from the more-efficient store (respecting limits on output power and energy in store)

This primitive approach does not lead to near-optimal solutions because the more-efficient store is often either full (or empty) so that its input (or output) power is not then *in-play*.

A good scheduling approach ensures that the power-conversion machinery of both stores is nearly always *in-play*. Informally … keep the state of charge of each store away from the limits.

A Near-Optimal Scheduling Approach for Multiple Stores

A good scheduling approach for the operation of multiple stores in a system is described by Zachary *et al*. [1]



The scheduling algorithm is *greedy*.

Within constraints, energy is preferentially put into the stores with highest marginal value and energy is preferentially withdrawn from stores with lowest marginal value.

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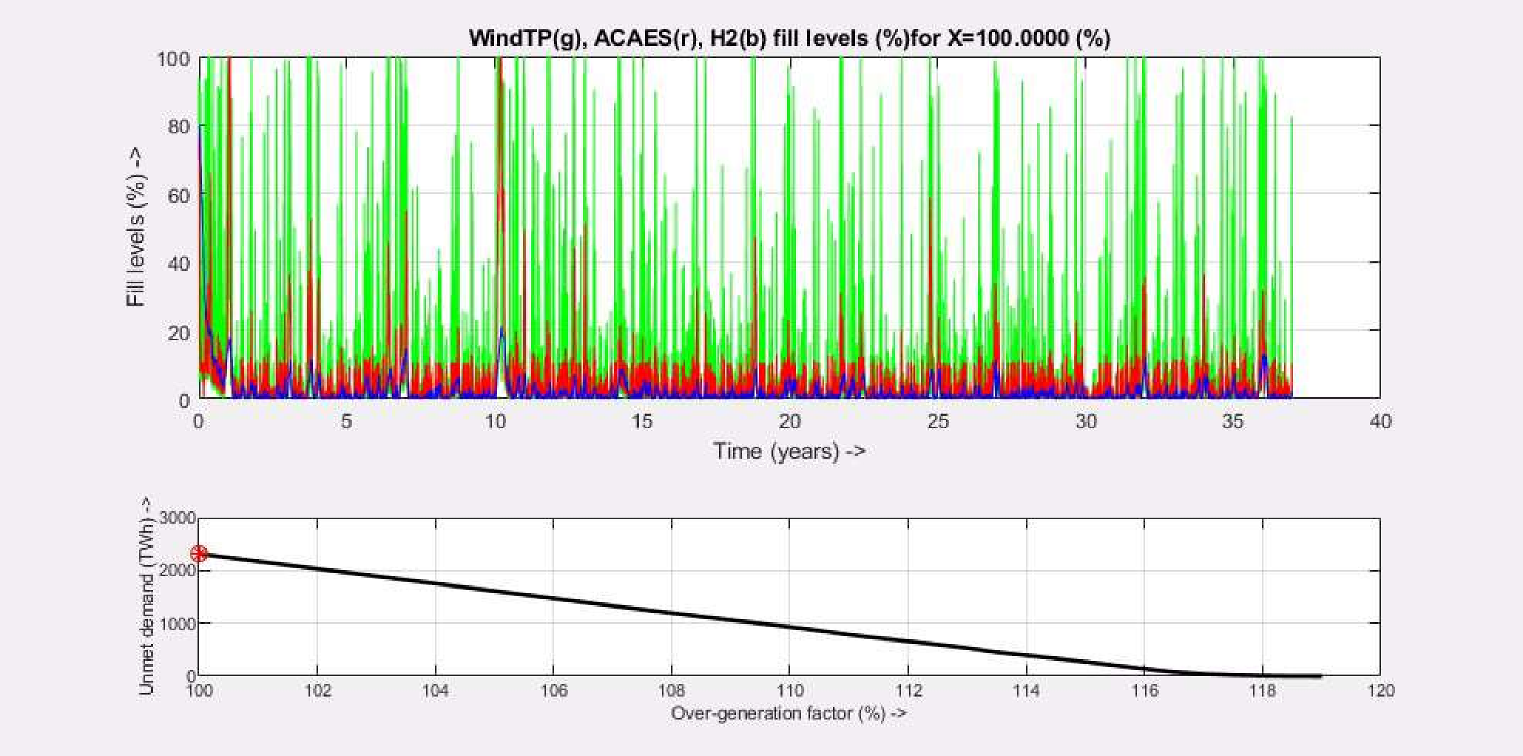
[1] Zachary, S. *Scheduling and dimensioning of heterogeneous energy stores with application to future GB storage needs.* In review. https://arxiv.org/abs/2112.00102.

Scheduling Illustration:

Illustration of scheduling working with a 3-store system:

#1: Wind-Integrated Storage. G_1=30GW, H_1=20GW, V_1= 1,050GWh, η_1=80%
#2: ACAES. G_2=15GW, H_2=10GW, V_2= 2,800GWh, η_2=65%
#3: Hydrogen Storage. G_3=37GW, H_3=65GW, V_3=80,000GWh, η_3=41%



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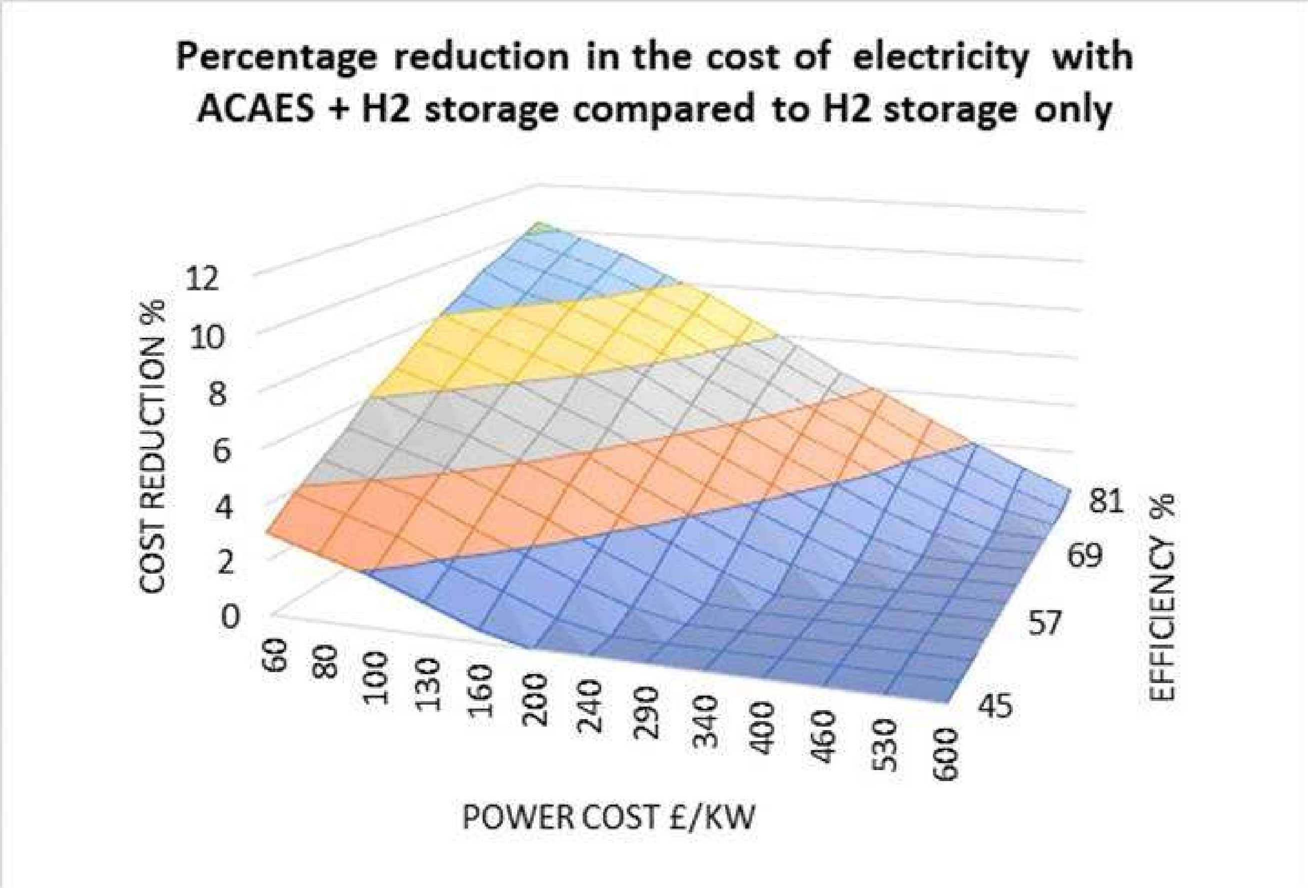
Optimisation Results for a 2-Store System

Combining ACAES with hydrogen-based storage provides for significant cost reductions – dependant on machinery costs and round-trip efficiency



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Closing Remarks

Hydrogen storage will obviously be needed in very large measures in a cost-optimal Net-Zero UK. If we allow only 1 store, it must be hydrogen

Blending stores could give significant cost reductions – credibly ~10%.

Employing multiple stores requires a *scheduling* algorithm. A good one exists ([1]) but further improvements are possible.

With multiple stores, *cross-charging* sometimes helps to keep all power-conversion resource *in-play* and *forecasting* becomes relevant.

Optimisations indicate (as in [2]) that although hydrogen stores must be much larger in capacity (*volume*) than medium-duration storage such as ACAES, (~80TWh:~3TWh depending on assumptions), ~65% of all energy emerging from storage will come from the medium-duration store.

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[2] Cosgrove, P., Roulstone, T. and Zachary, S., 2023. *Intermittency and periodicity in net-zero renewable energy systems with storage*. Renewable Energy, 212, pp.299-307.

Thanks for listening

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