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Energy Storage Challenges

Professor Richard Green

EPICS workshop, CSIRO, January 2026

Key questions

Sensitivity to scenarios?

Value of improvements?

What should we build?

How should we run it?

Multiple services?

Operating under uncertainty

How should we pay for it?

Normal market revenues? (which markets?)

Capacity market rules?

Special support schemes?

What does storage give us?

- Daily arbitrage (e.g. use PV output in the evening)
- System services (e.g. fast frequency response)
  - Will batteries saturate these markets?
- Seasonal shape (e.g. store summer output until winter)
- Seasonal gap-filling (e.g. week(s) of low wind output)

The first and third of these are predictable (the third in general terms; we can tell which seasons tend to have high renewable generation relative to demand). The second and fourth are not – we don't know when reserve will actually be needed, or which weeks will turn out to have high or low renewable output relative to the seasonal norm…

A modelling philosophy

"Sophisticatedly Simple Models"

Leave out the detail – unless it matters!

Lord Robert May

Prof Jim Al-Khalili

The Life Scientific, BBC Radio 4

https://www.imperial.ac.uk/news/197256/imperial-community-pays-tribute-lord-robert/

This refers to a conversation on a radio programme. Scroll down to the bottom of the web page and you will get my explanation of what they were talking about, and a link to the programme (or an extract…).

Missing money and market-based adequacy in deeply decarbonized power systems with long-duration energy storage

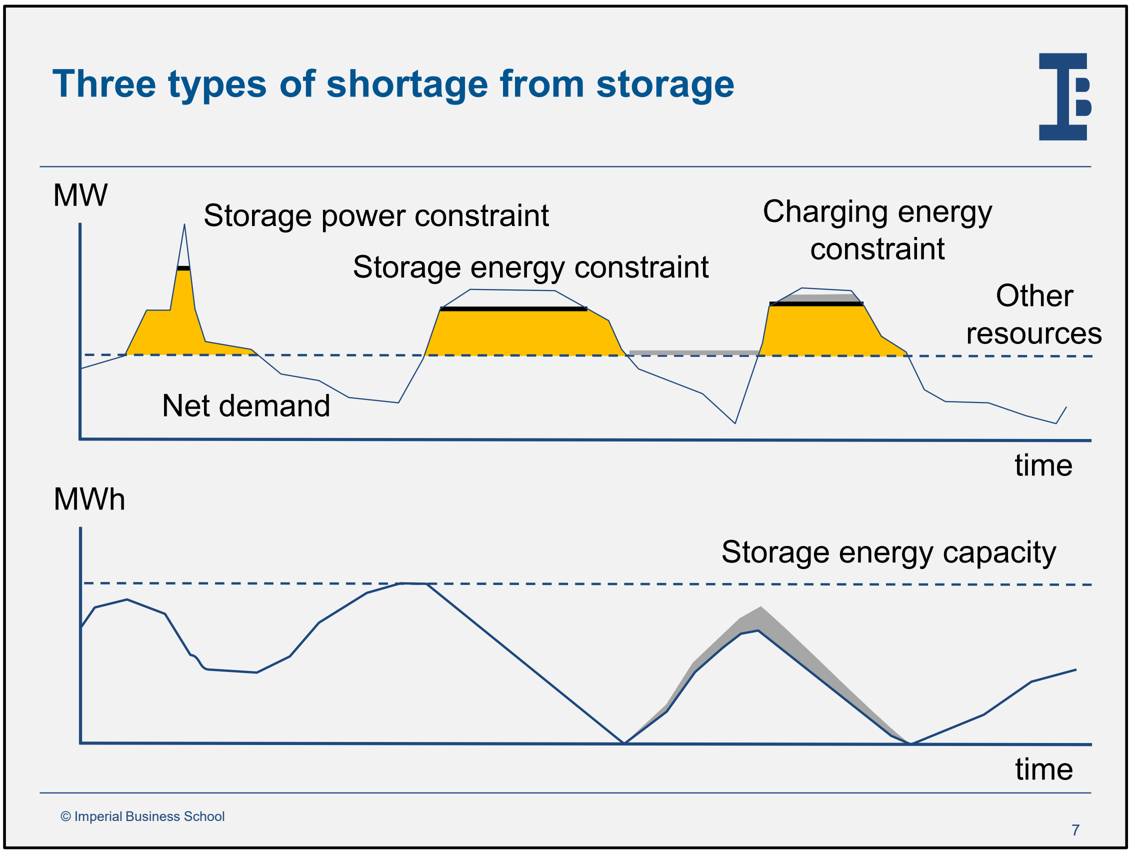
Adam Suski, Elina Spyrou, Richard Green

IEEE Transactions on Energy Markets, Policy and Regulation, 2026

https://dx.doi.org/10.1109/tempr.2025.3648914

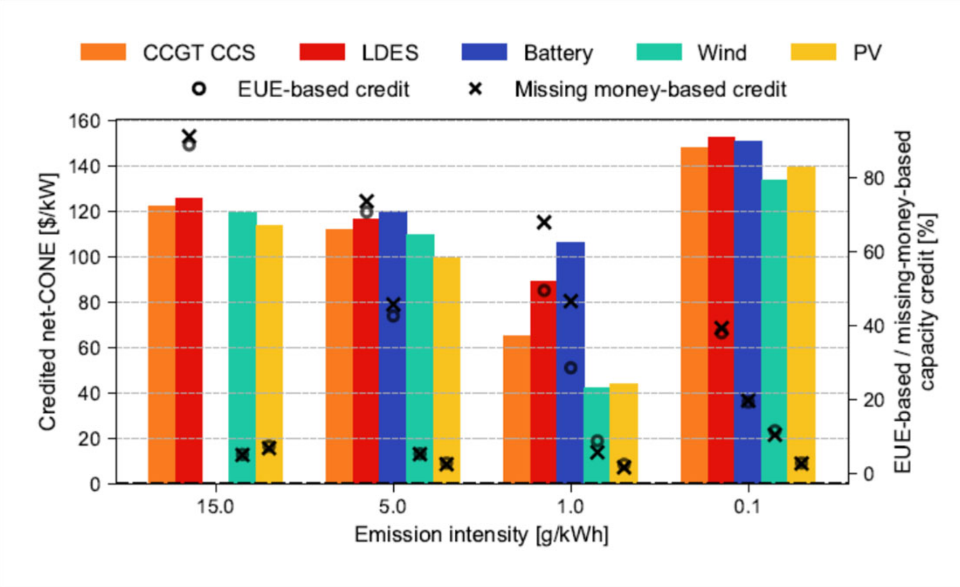
Are capacity markets adequate for storage?

- "Missing money" when system operators stop prices from rising to VOLL is proportional to generation at peak times
  - Unless price-responsive demand sets prices > MC_peaker
- Capacity market pays resources in proportion to their contribution to reliability
  - In a non-storage system, this contribution is proportional to their relative availability (and generation) at peak times
- Capacity market revenue therefore proportional to missing money for all technologies
- We find this does not hold in a system with price-responsive demand and energy storage
  - Contribution to reliability not proportional to missing money



This slide shows that shortages can come from a lack of available power capacity (storage or generation), a lack of storage energy capacity, or a lack of energy within the store at the start of a shortage event (which may be due to a charging power limit or just the amount of surplus energy (relative to demand) in the period since the storage was last emptied (which is the case here). The black lines show the direct contribution to reducing unserved energy of a perfectly reliable generator. In a market with storage and a charging constraint, additional generation during the constrained charging period allows the store to enter the shortage period with more energy. This creates an extra route to reduce the unserved energy for generators that are available during the relevant time period. The perfectly reliable generator will be, variable renewable generators may be, storage on its own will not be. This opens a wedge between the contribution to reducing unserved energy from a reliable generator and from energy storage.

Missing money (columns, lhs) and reliability contributions (points, rhs)



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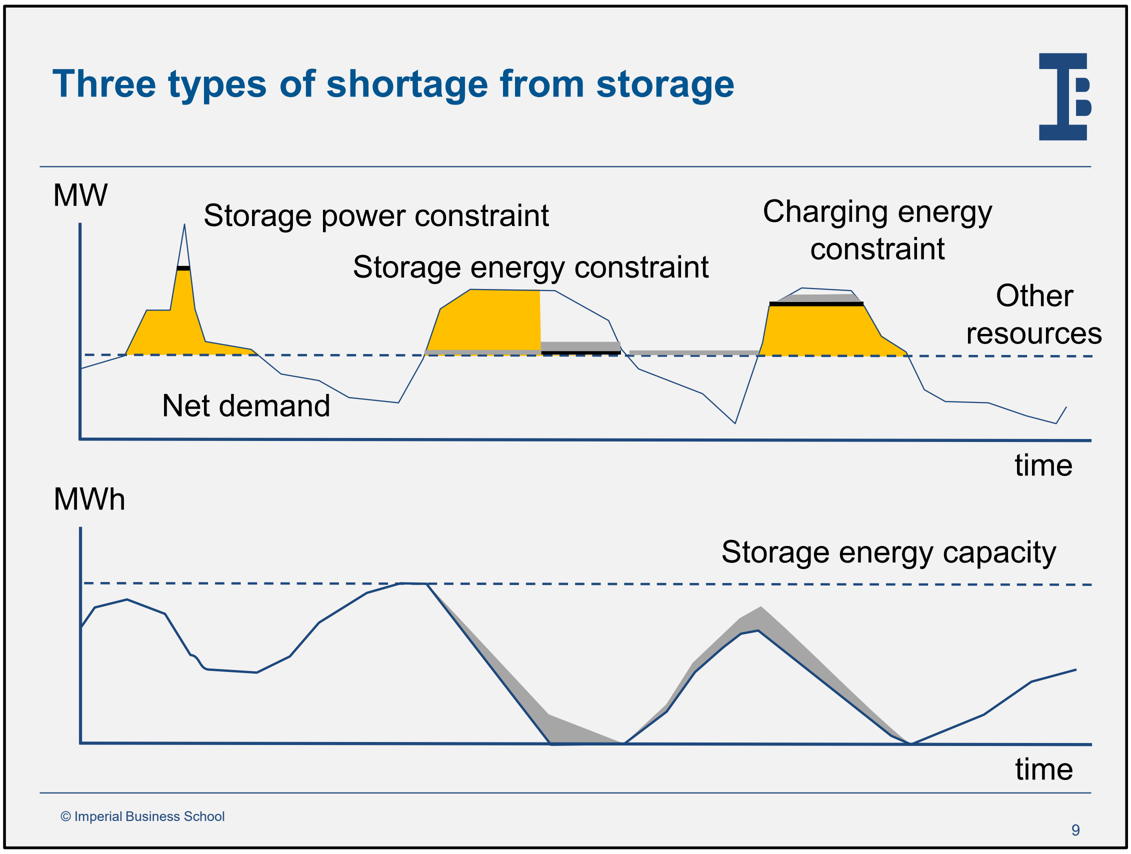
This slide shows the amount of missing money for each technology under four different constraints on the emissions intensity per kWh of total output (batteries are not used in the highest-intensity scenario). We ran our model (scaled down, but "GB-like") with VOLL pricing to get the optimal capacity mix and then re-ran it with the same capacity but a price cap to calculate the missing money.

The renewable generators typically have slightly less missing money (relative to their contribution to reliability) than the reference CCGT, while the storage has more. The difference is greatest in the 1 g/kWh case. The circles show the capacity credit of each technology relative to CCGT in terms of the expected reduction in unserved energy, while the crosses give the credit that would be needed to give capacity market revenues equal to the amount of missing money. In other words, particularly in the 1 g/kWh case, long-duration energy storage needs more money from the capacity market than a credit based on its contribution to reducing unserved energy would give it.



If all MWh of unserved energy are equal, the computer could give a different pattern with fewer hours of shortage, but the same MWh. In this case, an extra MW of perfectly reliable generation will have the same impact on expected unserved energy, but the mechanism will have a different split between direct generation (black) and changes in the use of storage (grey)

Always *look* at your results (charts of output time series may be under-rated!) and be aware that computational results may be very close to but not quite equal to those that interpreting the optimality conditions of the underlying problem ought to tell you that you were going to get…

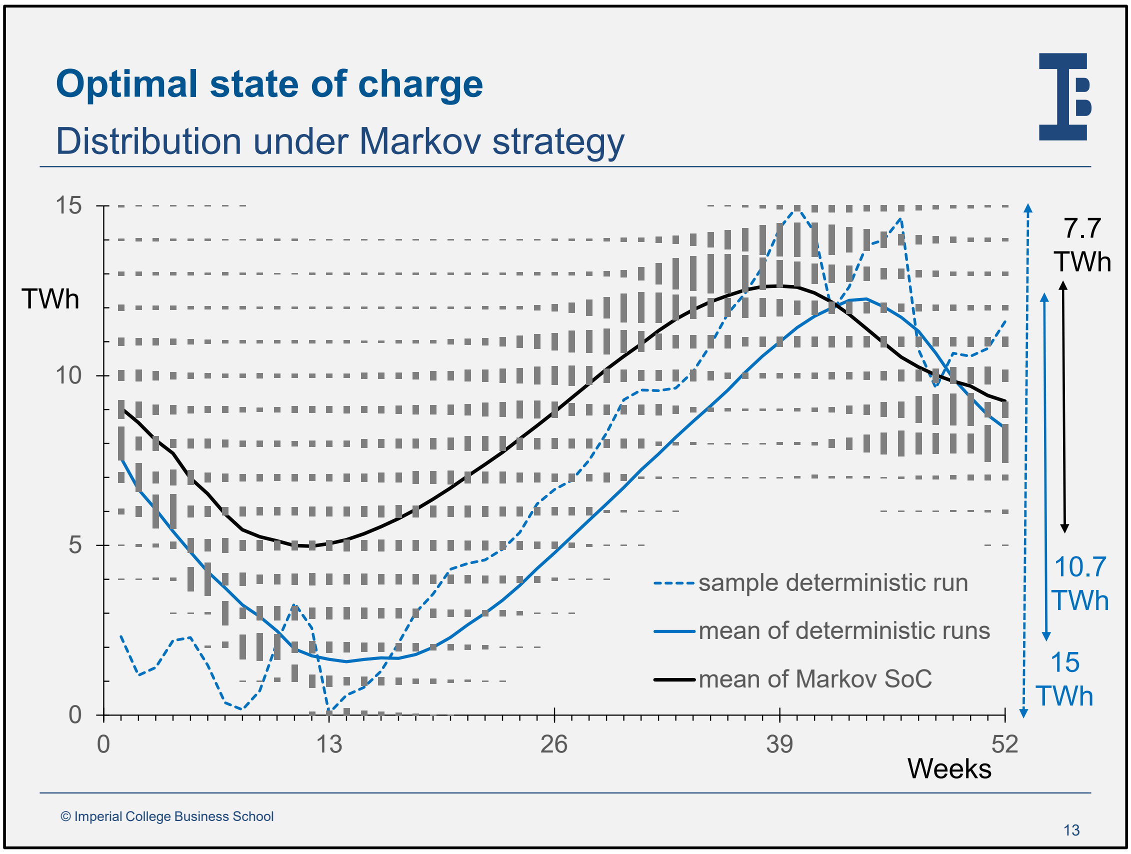
Optimal electricity storage in a carbon-free system: Taking things week by week!

Joachim Geske and Richard Green

work in progress…

Our approach

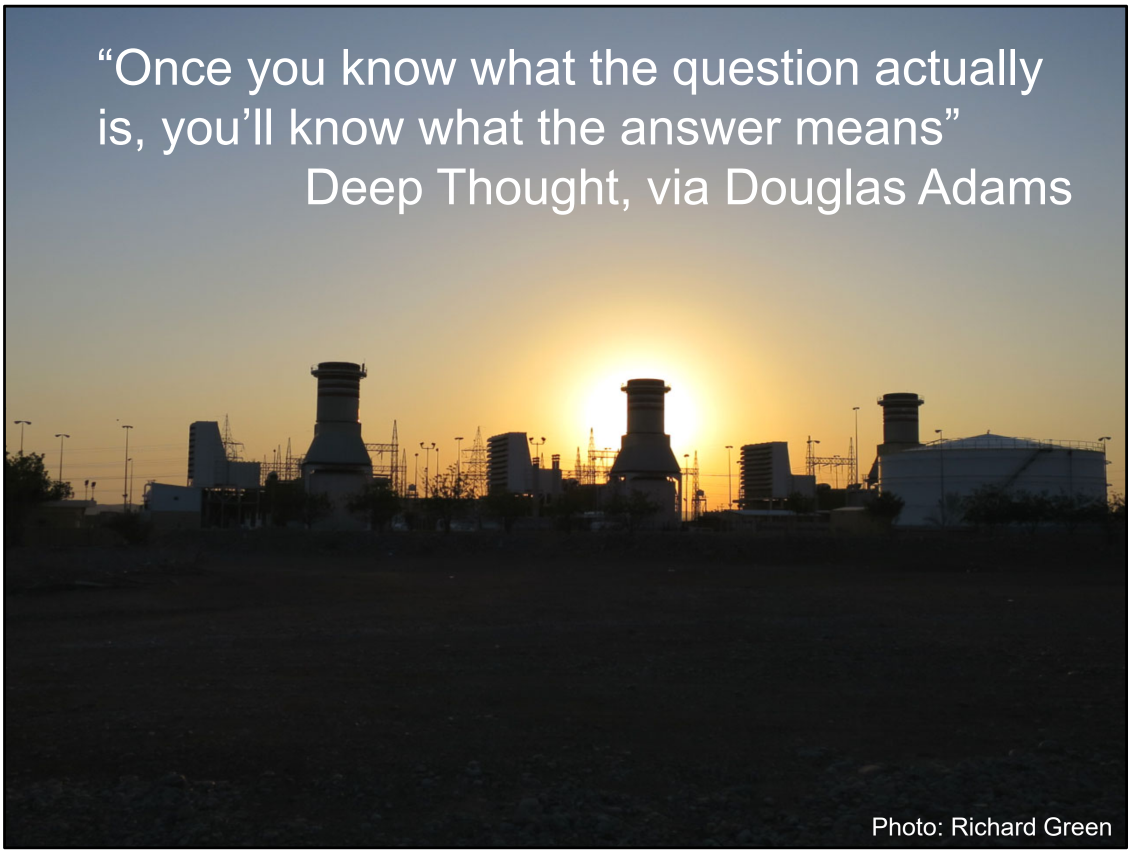
- Markov chain of weekly net demand patterns
  - Optimising generation given (dis)charging and capacity levels is a separable problem
    - You *could* add complex engineering constraints
- Time-varying transition probabilities over the year
  - Winter can have much higher (cold) or lower (windy) net demands than the summer months
- Limit the (dis)charging decision to discrete set of choices (depending on week of the year and state of charge) and a linear program minimises expected cost
- Step-search for improvements in capacity mix
  - Converges to equilibrium reasonably well…



These are provisional results from a simulation of the German energy market (with no foreign trade). The dotted blue line shows the evolution of state of charge under a single perfect foresight run – the full 15 TWh of long-term energy storage capacity is used. The solid blue line is the average of a set of such runs – even if they all reach zero at some point (I haven't checked), they do so at different times. The bars show the distribution of states of charge under our Markov strategy – it's unlikely that the storage will ever be fully charged or fully discharged. Energy is held back in the early spring in case there's a bad week still to come, and later in the spring, it may not be worth discharging if the weather is good, prices low and there's no certainty that summer prices will be low enough to recharge at a price that would make the (earlier) discharging profitable. The black line shows the expected state of charge. I want to calculate lots of individual sequences of weeks and the resulting state of charge trajectories, as that would let us calculate the mean "swing" across those trajectories, but have not yet done so. In the meantime, the "swing of the average charge" is 8 TWh, noticeably lower than the 11 TWh swing of the average charge under the deterministic scenarios.

Unending uncertainty

- The incentive *not* to use storage is stronger
- "effective capacity" per GWh of energy capacity is lower
- Cost per GWh of "effective capacity" is higher
  - This does *not* mean that we don't need storage!


"Once you know what the question actually is, you'll know what the answer means"
Deep Thought, via Douglas Adams
Photo: Richard Green