Performance of Electricity Markets & Power Plant Investments in the Transition to a Low-Carbon Power System

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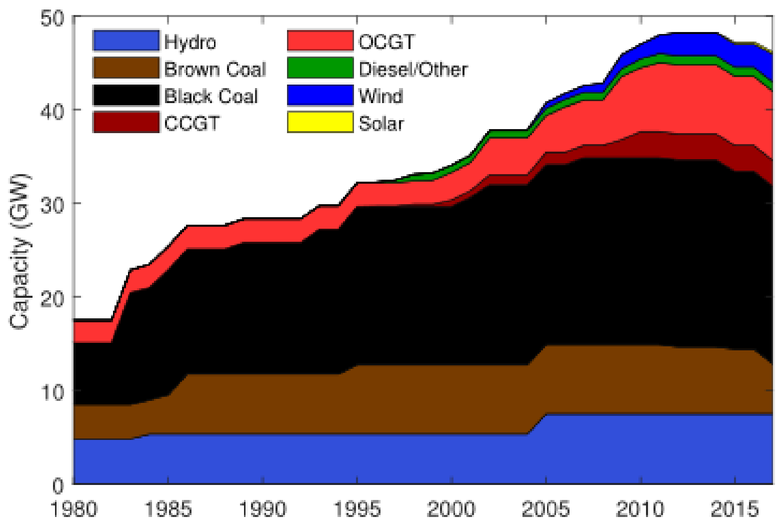
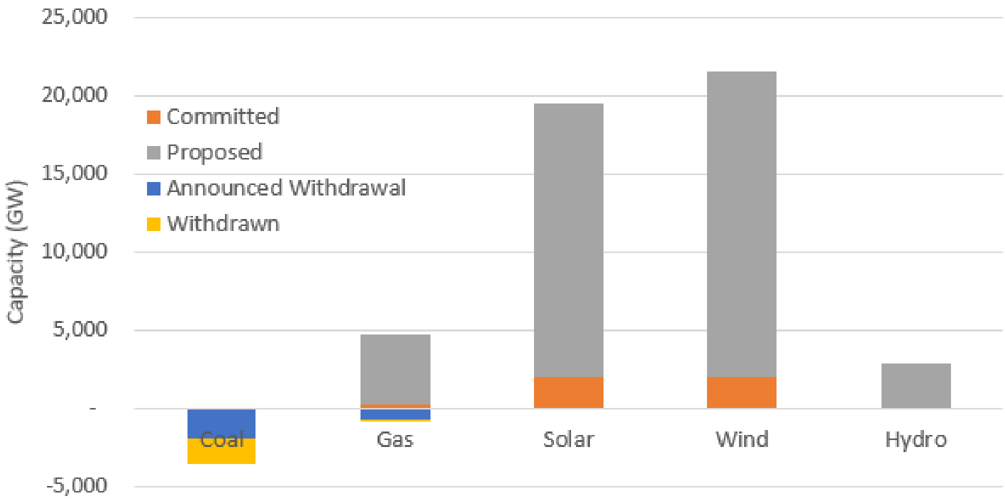
Motivation

NEM capacity by year



NEM Capacity Investments and Retirements



- Wind & solar differ from coal, gas & hydro in at least three ways:

  1. Their (zero emission) output is dependent upon instantaneous weather conditions, which increases the variability and uncertainty of net load.
  2. They usually do not contribute ‘inertia’ or other ancillary services to the grid.
  3. They have no fuel cost, and therefore very low short-run marginal costs.

- These characteristics create challenges for planning and operating power systems and wholesale electricity markets.

Theory of Optimal Spot Pricing

- Liberalised electricity markets commonly use *short-run marginal pricing.*
- The *Theory of Optimal Spot Pricing** has shown that this results in investor profits that are exactly zero, allowing for a return on investment, when the investment and operational decisions are optimal.
- However, this result requires assumptions which do not hold in the real-world. In particular, it is known that unit commitment decisions violate this theory.
- Traditionally, such violations have been small, but increasing variability and uncertainty from increased use of variable renewable generation (VRG) could affect this, since
    1. VRG generally have required some form of subsidy, which means the generating fleet is no longer least cost optimal;
    2. The dynamics of VRG can lead to more/stronger violations of the assumptions of optimal spot pricing.

* e.g. Schweppe, F.C., Caramanis M.C., Tabors, R.D., Bohn, R.E., 1988, "Spot Pricing of Electricity", Springer University Press

Electricity Market Model

Model Overview

Sub-model name	Generation Expansion	Unit Commitment	Economic Disptach
Time frame	Years Ahead	Day-Ahead	Real Time
Decisions	Which units are built?	Which units should be turned on or off?	How should the online units be operated?

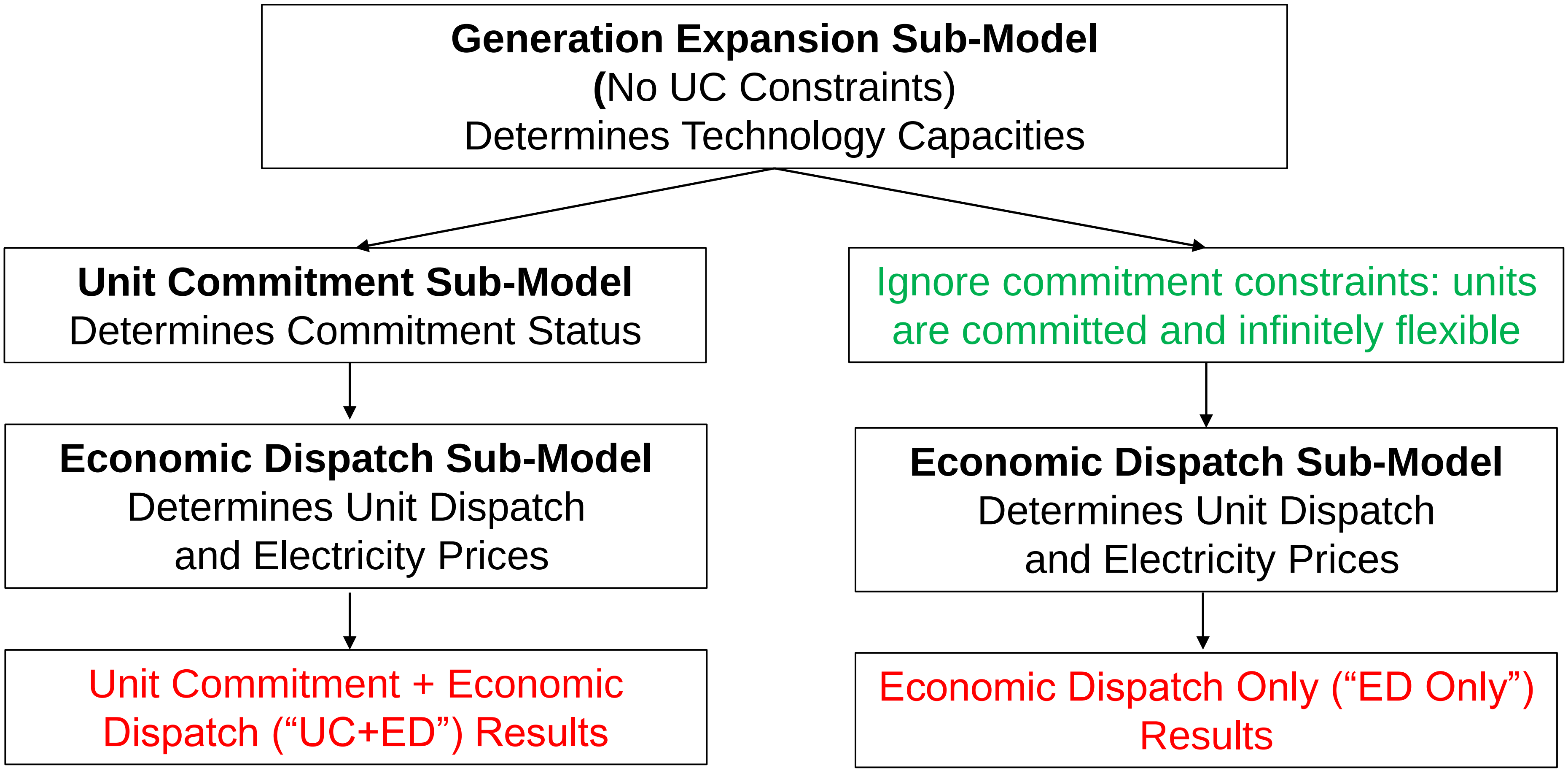
- The market model is comprised of three sub-models: Generation Expansion (GE), Unit Committment (UC) and Ecoonmic Dispatch (ED).

- Each sub-model has three main components:

  - Objective function – the cost of meeting electricity demand.
  - Decisions variables – e.g. number of units built, power from each unit in each interval.
  - Constraints on system and generator operation.

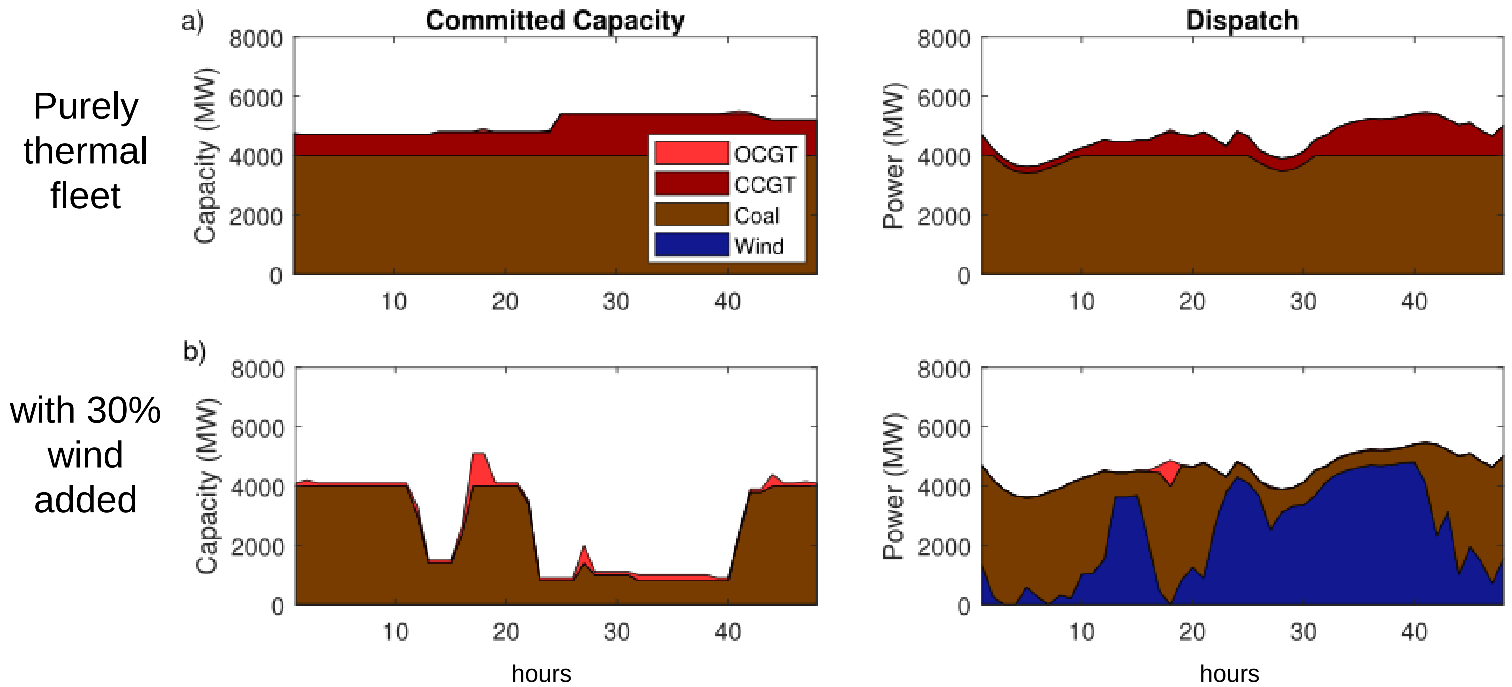
- The optimiser chooses decision variables that minimize the cost of meeting demand whilst respecting all constraints.

Generation Expansion with and without Unit Commitment



- Generation Expansion (GE) without Unit Commitment is computationally much more feasible for system planning.
- Comparison tests the importance of Unit Commitment and the generality of GE without UC.

Stochastic Unit Commitment Model



- The unit commitment sub-model is the most computationally demanding component, due to the extensive use of integer or binary (on/off) decisions.
- Unit Commitment Constraints: minimum stable generation, minimum up and down times, ramping limits, start-up and shut down costs, 5 types of reserves, Rate of Change of Frequency
- Stochastic optimization is used: the commitment schedule had to work across multiple VRG and demand scenarios.

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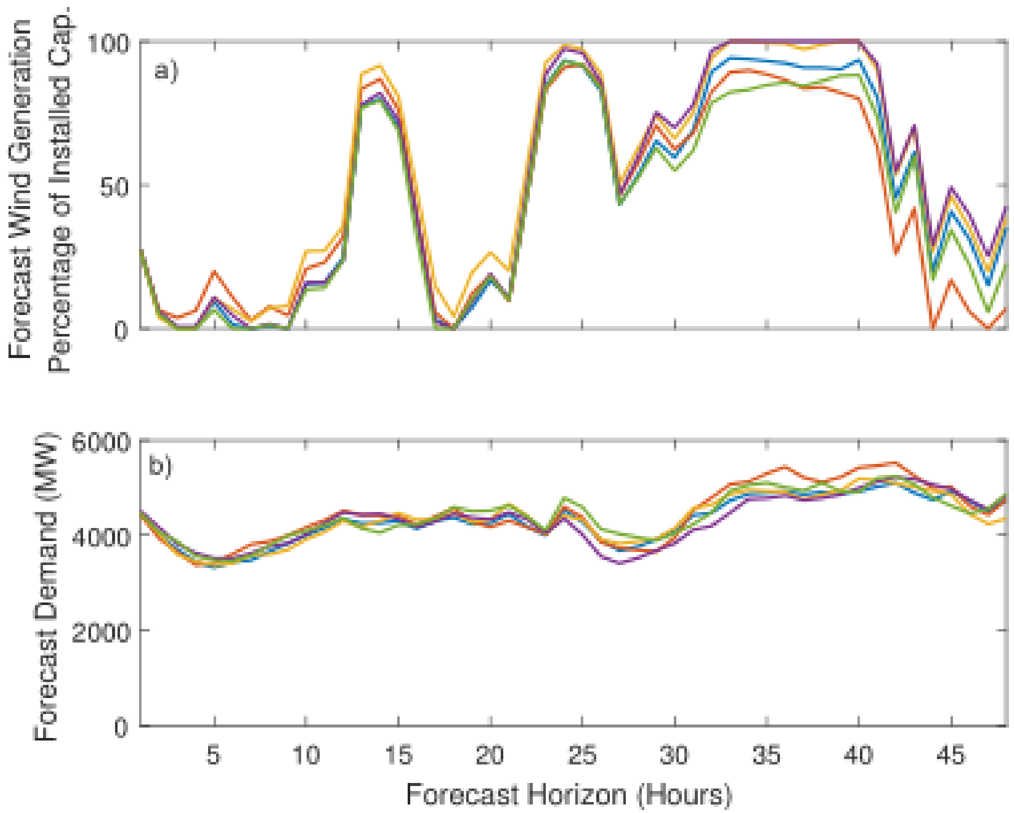
Day-Ahead Uncertainty

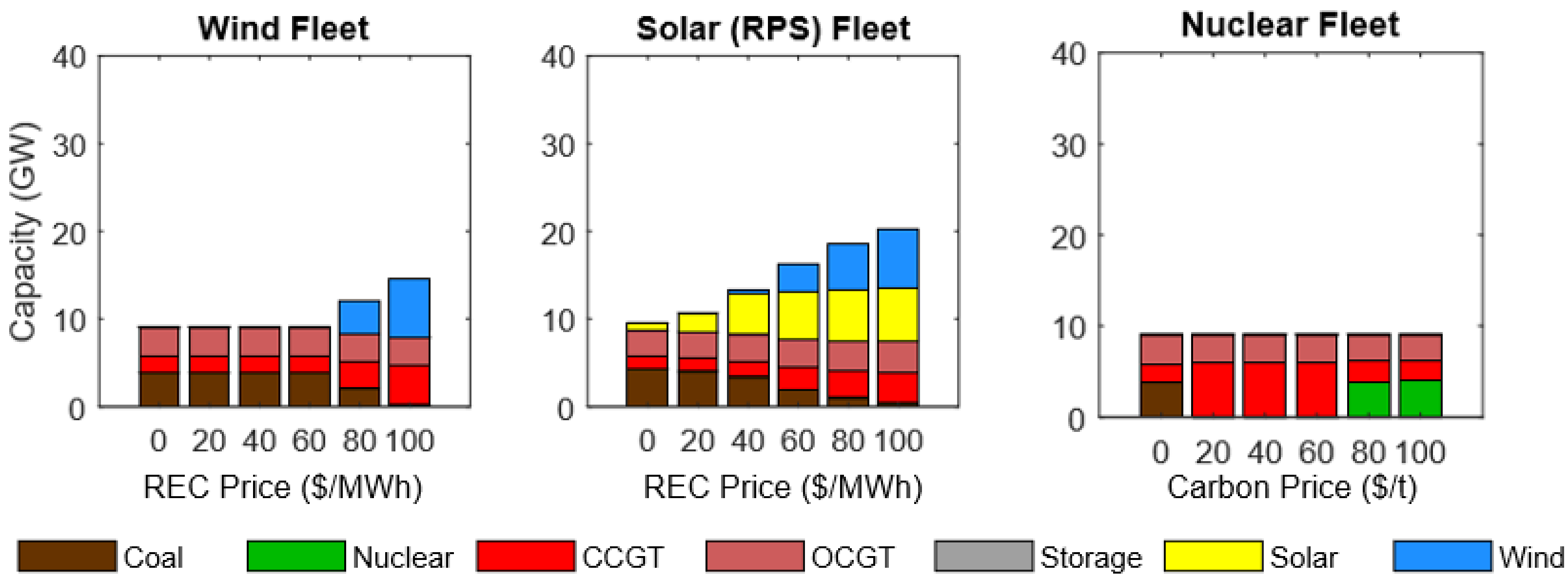


- Several forecasts for wind, solar and demand were included. The commitment schedule must work over all forecasts.
- These forecasts were generated with an *Auto-Regressive Moving Average* model and historical market data.

L. Soder, "Simulation of wind speed forecast errors for operation planning of multiarea power systems," in , 2004 International Conference on Probabilistic Methods Applied to Power Systems. IEEE, 2004, pp. 723–728.

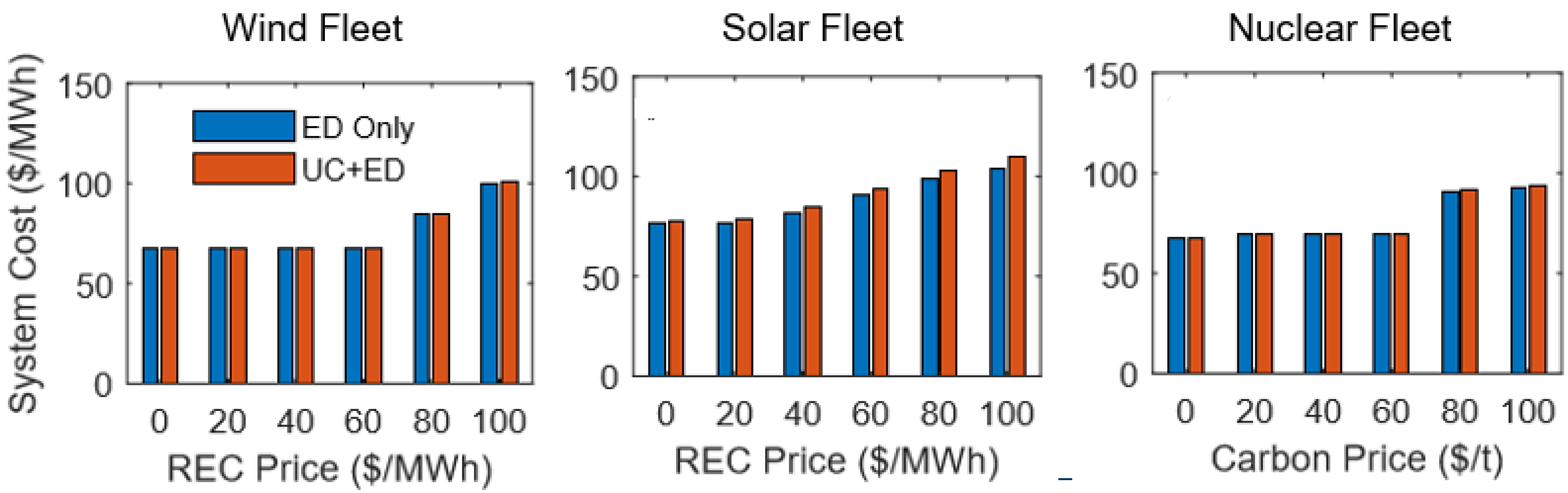
Revenue Sufficiency with Increasing Variable Renewables

Capacity Decisions



- Different cost and policy inputs can be used to understand the impact of different technologies.
- For today's talk:
  - *Wind Fleet* uses a Renewable Portfolio Standard with wind cheaper than solar.
  - *Solar Fleet* uses a Renewable Portfolio Standard with solar cheaper than wind.
  - *Nuclear Fleet* uses a carbon price that promotes nuclear and gas over coal without renewables.

Total System Costs



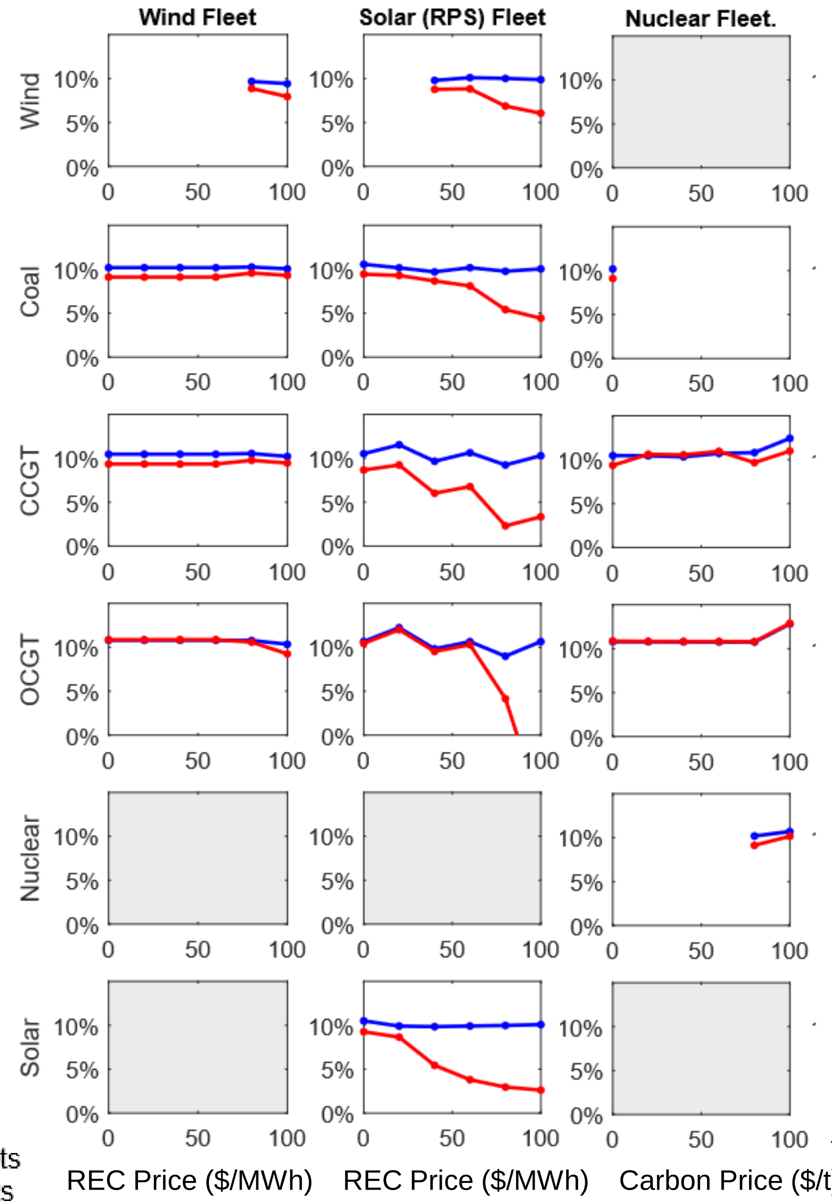
- The figure shows the total costs of building and operating each fleet for a year, averaged over all electricity demand.

- Total cost increases with environmental policy due to the need to use more expensive but cleaner generation.

- With increasing wind/solar, a divergence in total costs predicted by the ED Only and UC + ED models can also be seen. This is because of start-up costs and the need to curtail wind/solar when unit commitment constraints are included.

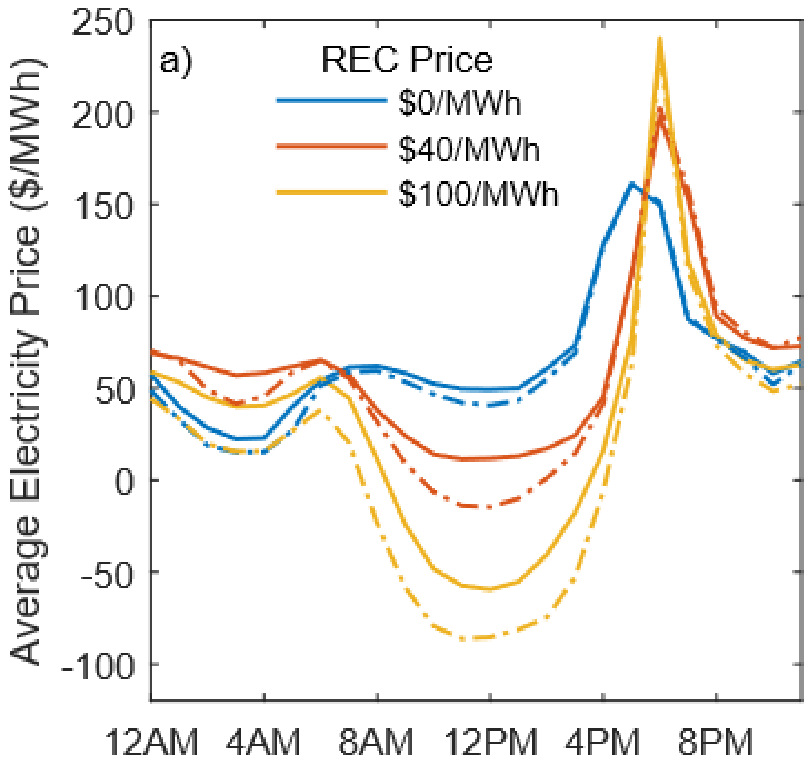
Revenue sufficiency

- The figure shows the internal rate of return for each technology.
- 10% was used as a hurdle rate and to annualise the capital cost of each technology.
- With no/low environmental policy, each unit makes a 10% rate of return, and unit commitment constraints do not impact this.
- Rates of return are sufficient in the wind and nuclear fleet even for high environmental policy costs and with unit commitment constraints included.
- However, many technologies perform very poorly once solar penetration increases (i.e. for REC Price >= $40/MWh)



The (in-) famous *Duck Curve*

- Average electricity prices across the day for the Solar Fleet with increasing REC price:



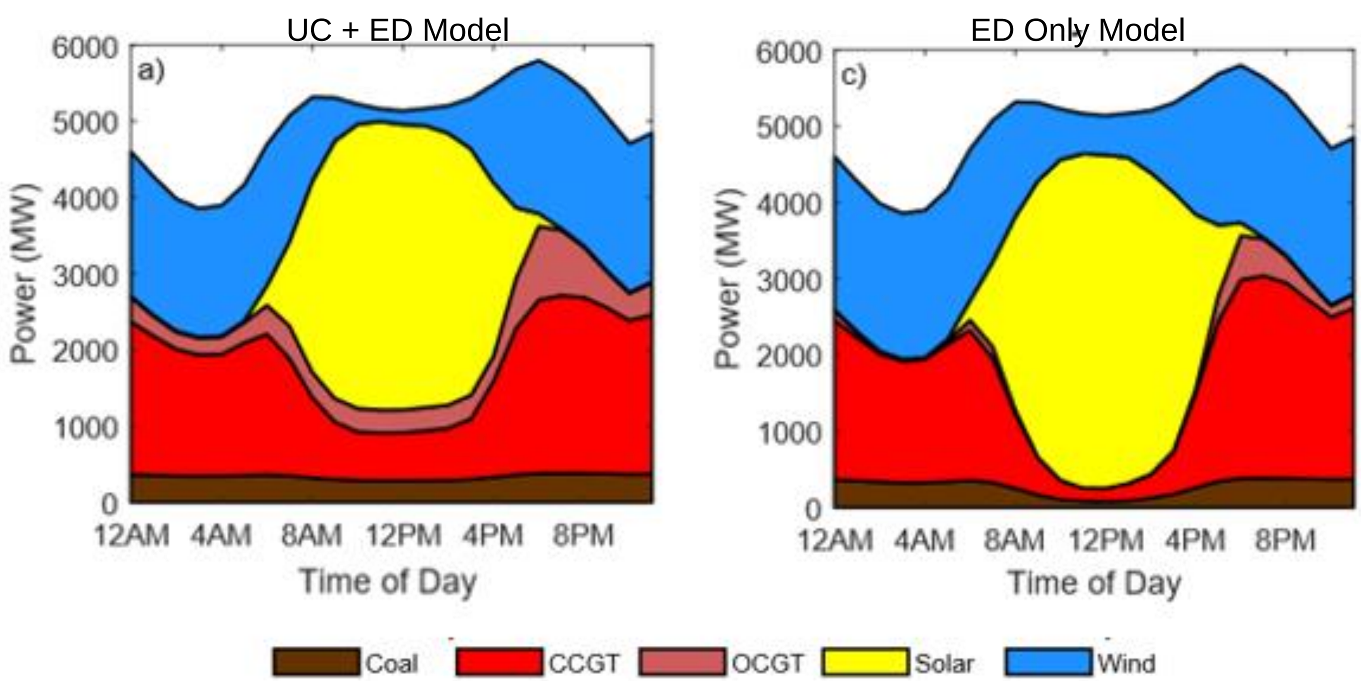
- The *Duck Curve* becomes increasingly apparent with increasing REC price as solar generation increases.

- The difference between the *ED only* and *UC+ED* prices also increase.

Impact of Duck Curve on Revenue Sufficiency

- These results are caused by unit commitment constraints impacting electricity dispatch and hence electricity prices.
- Solar (and wind) generation is then more frequently curtailed to allow thermal generators to run at their minimum stable level, in order to obtain sufficient operating reserves and inertia to respect system security constraints.

Average generation by time of day with a $40/MWh REC Price



Conclusions

Conclusions & Implications

- A generation expansion and unit commitment model was used to explore the impact of wind and solar generation on revenue sufficiency via pure short-run marginal pricing.
- Short-run marginal pricing should allow units to exactly recover their investment and operating costs if the fleet is optimal, but this relies on non-convex system constraints being small.
- Cost recovery was observed at all levels of abatement in the wind and nuclear fleets.
- However, once the solar penetration reached roughly 20%, increasingly poor financial performance was observed for several technologies as a result of the concentrated nature of solar generation, i.e. the duck curve.
- This points to the need to consider commitment constraints in the planning problem.
- It also suggests that uplift payments may increase in markets with a high share of solar generation.

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