Planning renewable electricity capacity using JADE

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Purpose of this talk

- Introduce the JADE package.
- Present some results from applying JADE to future New Zealand electricity system in 2035.
- Compare results from two JADE papers on EPOC website:

  https://www.epoc.org.nz/papers/JADEOnslow.pdf

  - enumerates wind investments and optimizes each case
  - exogeneous investment

  https://www.epoc.org.nz/papers/HoleSDDP.pdf

  - automatically solves for optimal investments
  - endogeneous investment

Outline

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What is JADE?

JADE.jl is a hydrothermal reservoir optimization model of the New Zealand electricity system that minimizes expected discounted social cost. It applies the stochastic dual dynamic programming algorithm as implemented in the Julia package SDDP.jl developed by Oscar Dowson.

JADE.jl is made available by Electricity Authority at

https://www.emi.ea.govt.nz/Wholesale/Tools/JADE

and source is on github at

https://github.com/EPOC-NZ/JADE.jl

What is SDDP.jl ?

- open source Julia implementation of SDDP.
- built on `JuMP.jl` modelling language.
- supports a number of open-source and commercial solvers.
- support for:
  - infinite horizon problems
  - convex risk measures
  - mixed-integer state and control variables
  - partially observable stochastic processes

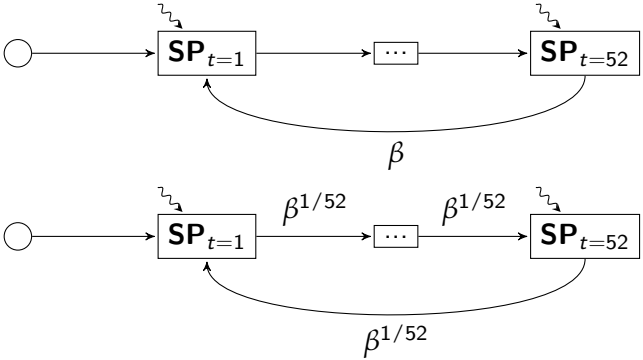
https://odow.github.io/SDDP.jl/stable/

Outline

JADE policy graph for a planned year

- 52 weekly stages
- $\mathbf{SP}_{t=52}$ has terminal future-cost function

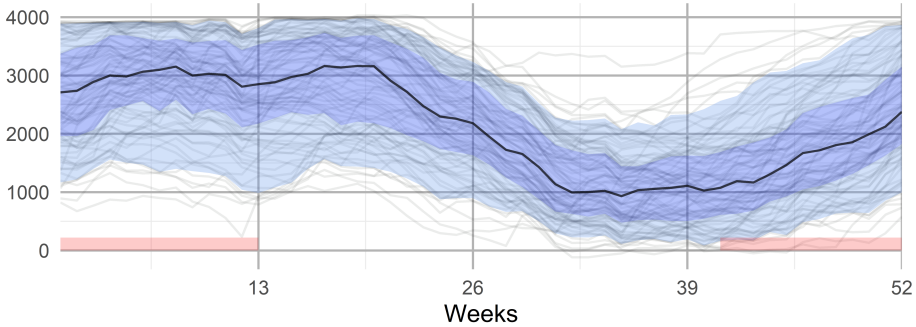
JADE steady-state policy graph



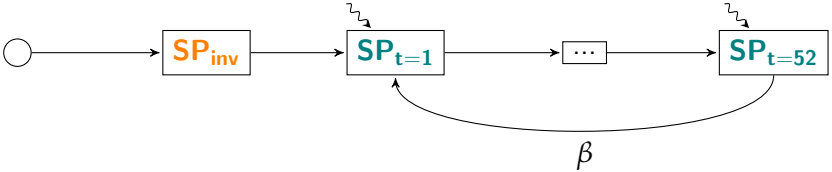
- 52 weekly stages
- annual (weekly) discount factors β ($\beta^{1/52}$) on edges

Capacity planning by enumeration (exogenous investment)

- Train steady-state water release policy using JADE with different levels of wind and enumerate to optimize capacity.
- Simulate policy with 89 consecutive years of inflows (1932-2020)



Capacity planning by policy graph (endogeneous investment)



Add capacity investment node SP_{inv} to the steady-state policy graph.

Capacity investment becomes a state variable

Given capacity investment node $\mathbf{SP_{inv}}$ in the policy graph:

1. define state variable x^{inv} with initial value 0.
2. define investment decision u_{inv} in $\mathbf{SP_{inv}}$.
3. add constraint $x'_{inv} = x_{inv} + u_{inv}$ in $\mathbf{SP_{inv}}$.
4. add constraint $x'_{inv} = x_{inv}$ in $\mathbf{SP_t}$.
5. add the stage objective $C_{inv}(x_R) = c_{inv} u_{inv}$ in $\mathbf{SP_{inv}}$.
6. constrain operational decisions using x^{inv} in $\mathbf{SP_t}$

Outline

New Zealand electricity network

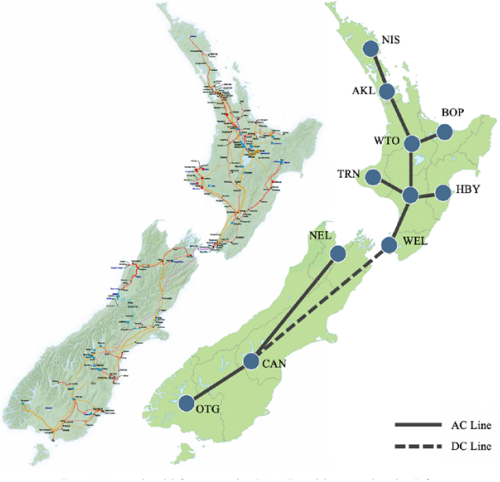


Figure: SPD network on left is approximated by an 11-node transmission system

Assumptions for load estimation

- 11 regions approximate NZ transmission network.
- 2020 regional demand estimated using vSPD.
- 2035 national demand increases from CCC "Demonstration Scenario" broken down by commercial/residential, industrial, PEV load. No reduction in Tiwai load.
- 2035 national supply increases from CCC "Demonstration Scenario" for solar and geothermal.
- Produces a load $\hat{d}_r(p)$ in region r in trading period p (net of extra solar and geothermal).

Load reduction costs

Proportion	Price ($ / MWh)
0.025	530
0.025	740
0.050	3180
0.150	5290
0.750	10580

Table: Prices for demand response and involuntary lost load.[2]

[2] Source: EA 2020 DOASA files.

Modelling wind for exogenous capacities

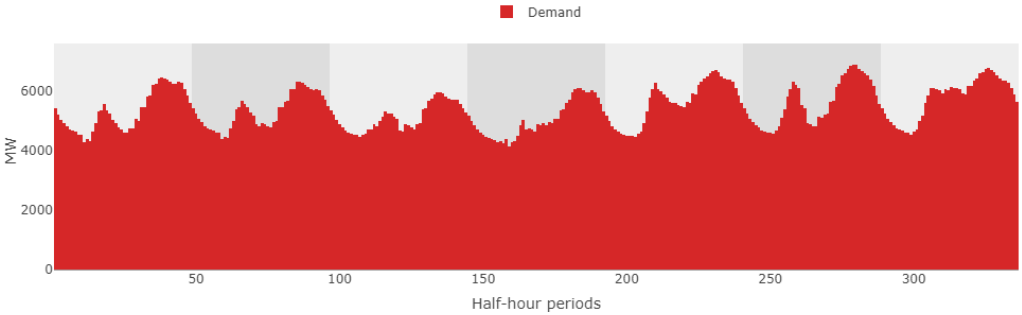
- Assume that wind capacity increases by E MW from 2021 to 2035.
- E is allocated to regions proportional to capacity of current new windfarm consents in each region.
- Load factor estimated from 2021 data for wind in region r in trading period p.
- Produces a forecast wind generation $\hat{w}_r(p)$ in region r in trading period p.
- National net load in trading period p is

$$n(p) = \sum_r (\hat{d}_r(p) - \hat{w}_r(p))$$

yields a national net load duration curve.

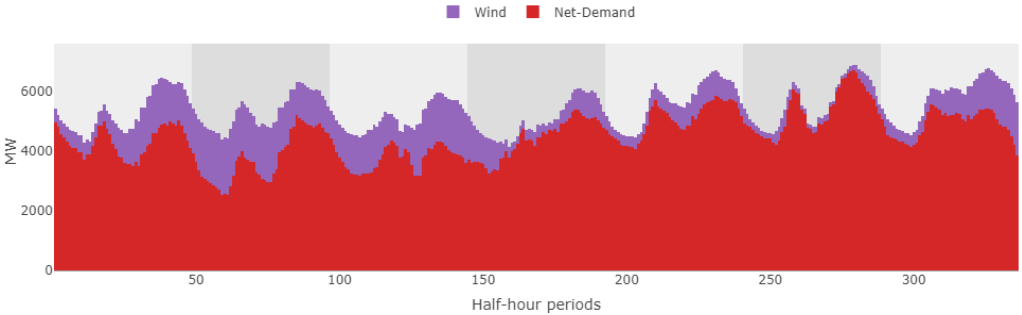
National load net of wind

National wind generation subtracted from load in each half hour.



National load net of wind

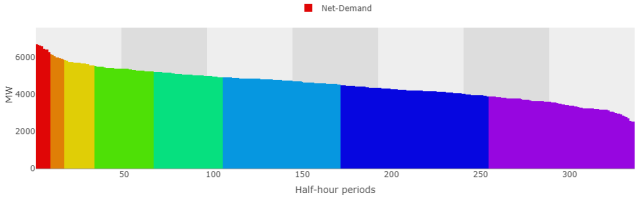
National wind generation subtracted from load in each half hour.

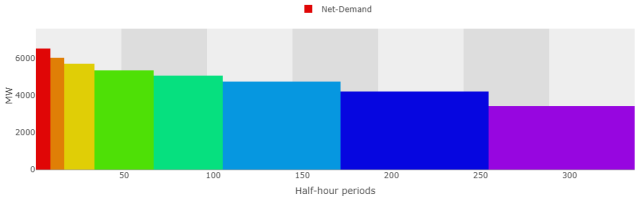


Note period 280: High load and little wind. Load duration curve should represent this.

National net load duration curve

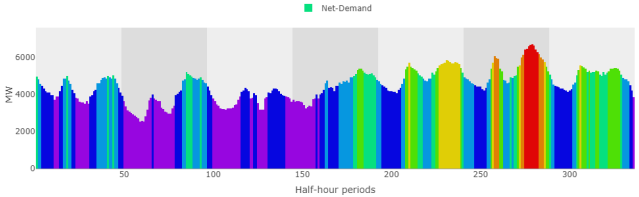
- Approximate by 8 load blocks of different widths.
- Assign average net-load to each block.

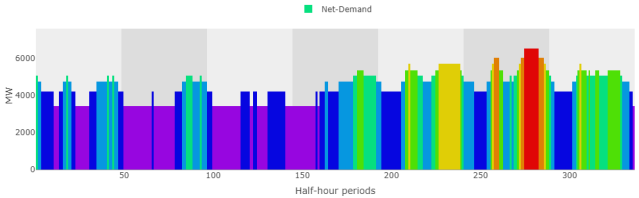




National net load duration curve

- Approximate by 8 load blocks of different widths.
- Assign average net-load to each block.
- Record which individual periods p contribute to each block b.
- Load in block b in region r is average of $\sum_{p \in b}(\hat{d}_r(p) - \hat{w}_r(p))$





Wind representation: endogeneous investment

- wind generation $\bar{w}_r(b, t, E)$ available in region r for load block b is (approximately) linear function of expansion E.
- For load block b, region r, week t fit

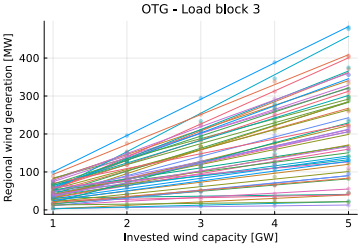
$$\bar{w}_r(b, t, E) = \lambda_r(b, t)E + g_r(b, t)$$

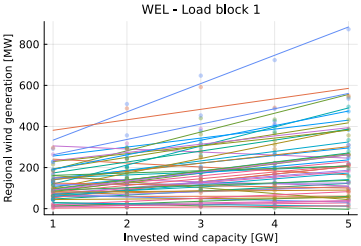
.

- Add constraint on wind generation variable:

$$w_r(b, t) \leq \lambda_r(b, t)x_{inv} + g_r(b, t)$$

to stage t problem of JADE model.





Exogeneous model: direct search for best E

- Train model with several different wind expansion values E.
- For each value of E
  - Simulate each trained model with historical inflows 1932-2020.
  - Estimate expected GWAP for wind generation.
- Select E where GWAP for wind generation equals LCOE of wind.

Optimal wind capacities for 2035 under three scenarios

- Onslow
  - Lake Onslow has 5000 GWh of storage and 1500 MW of capacity;
  - No thermal peakers;
  - E = 3725 MW;
- Green Peakers
  - 500 MW capacity in Waikato with SRMC $160/MWh;
  - No Lake Onslow;
  - E = 3900 MW;
- Wind Only
  - No thermal peakers and no Lake Onslow;
  - E = 4800 MW;

Total storage over 6 reservoirs not including Onslow

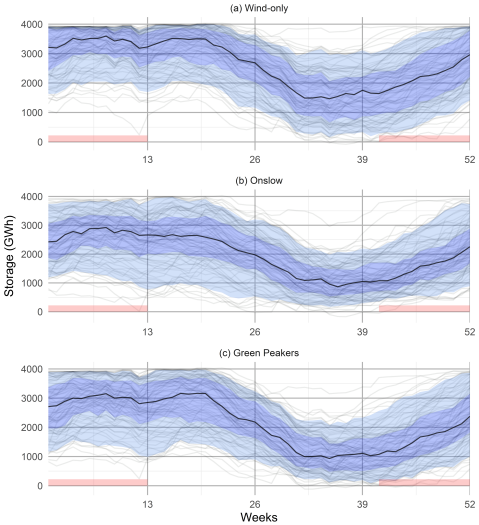


Figure: Total hydro-storage trajectories in existing reservoirs, simulated 1932-2020.

Endogenous investment E optimized using JADE

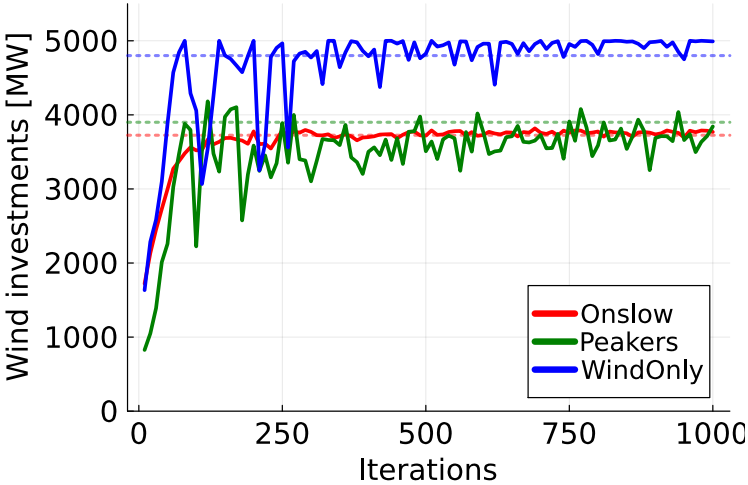


Figure: Convergence of wind investment in JADE

Convergence of bounds

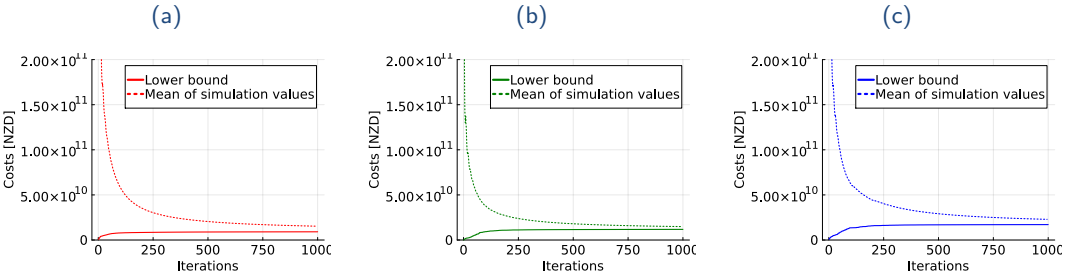


Figure: Convergence plots of the lower bound and the rolling mean of simulation values from the forward pass for each of the three cases when the model is trained with 1000 iterations: (a) Lake Onslow; (b) Green peakers; and (c) Wind only

Optimal endogeneous investments

Invested capacity	Onslow [MW]	Peakers [MW]	WindOnly [MW]
Wind - North Island	1267	1391	1964
Wind - South Island	0	0	0
HVDC capacity	(1732,1532)	(1000, 800)	(1300, 1100)
Green peaker	-	789	-

Table: Endogeneous investments in wind and NI peakers, and expanded HVDC

Invested capacity	Onslow [MW]	Peakers [MW]	WindOnly [MW]
Wind - NZ	3725	3900	4800
HVDC capacity	(2600,1600)	(1700, 1200)	(1800, 1400)
Green peaker	-	500	-

Table: Exogeneous investments in wind, peakers and expanded HVDC

Duration curve of HVDC flow

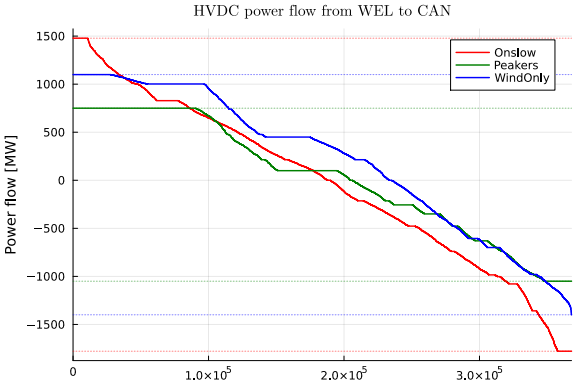


Figure: Duration curve for flow North to South on the HVDC cable.

Outline

What does JADE show us?

- Optimal operation of electricity system with storage is not simple. With more renewables, SRMC energy offers to WEM will not follow historical patterns. Need a model like JADE to understand such a system.
- Optimal hydro storage trajectories differ depending on scenarios.
- Optimizing a combination of capacities in endogeneous model gives richer set of outcomes than just optimizing wind (exogenoeusly).
- Presence of a large pump storage facility yields lower levels of wind investment than its absence (but less energy is wasted).

The End

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Outline

Duration curve of load shedding

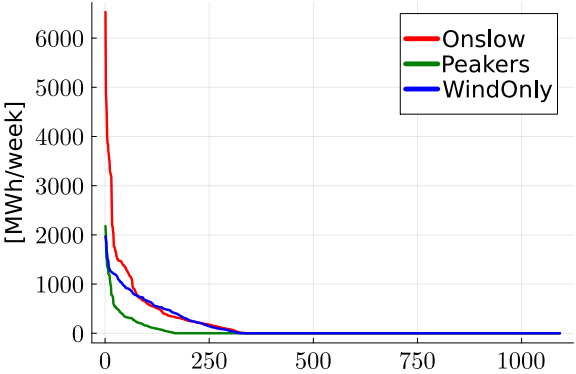

Figure: Duration curves of weekly load shedding for endogenous model simulated over 21 historical years.

Distribution of spilled energy for 2035 case studies

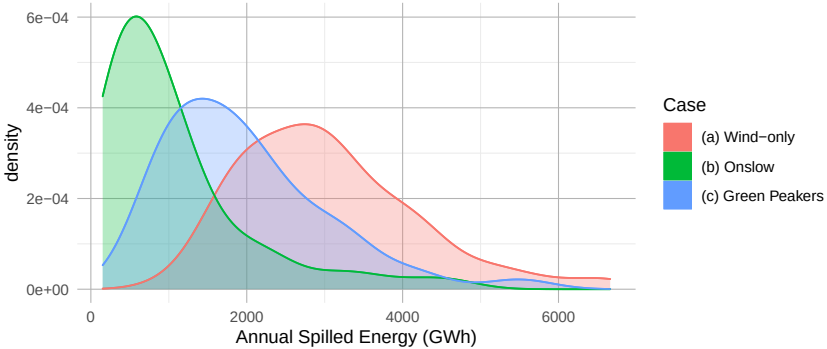

Figure: Distributions of annual spilled energy (in GWh) for each case.

Distribution of lost load for 2035 case studies

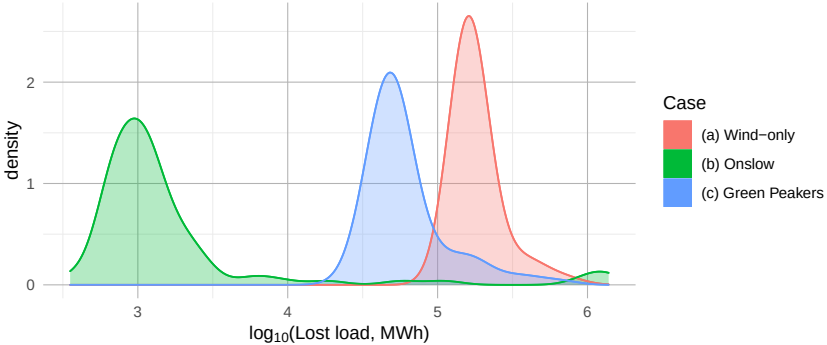

Figure: Smoothed distributions of annual lost load (in MWh) for each case (transformed using $\log_{10}$).

Distribution of annual expected cost for 2035 case studies

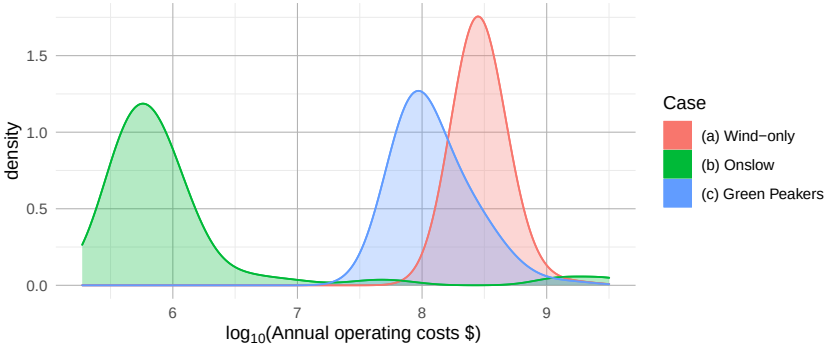

Figure: Smoothed distributions of annual load shedding + fuel costs (in $) for each case (the data has been transformed using $\log_{10}$).

Distribution of GWAP for wind for 2035 case studies

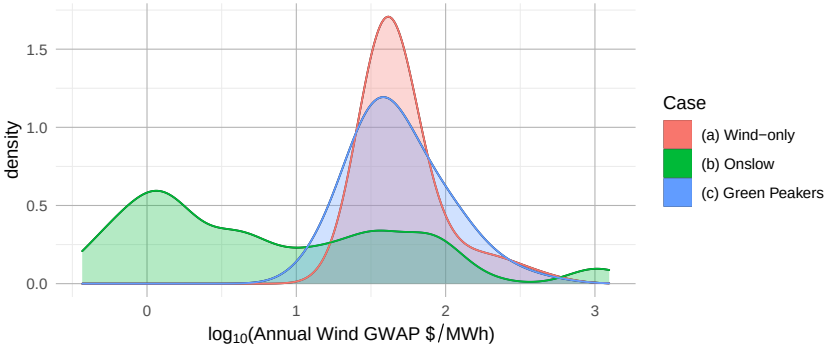

Figure: Smoothed distributions of annual GWAP for wind (transformed using $\log_{10}$).

Annual GWAP 1932-2020

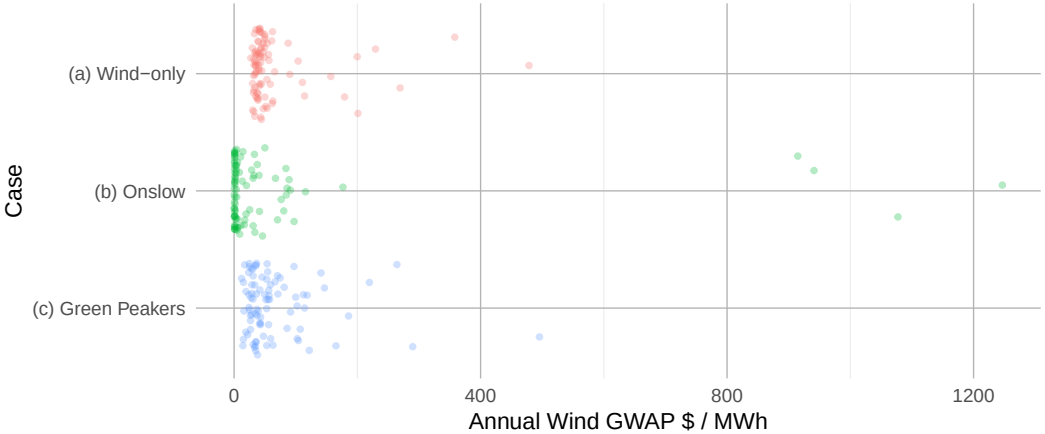

Figure: Annual GWAP for wind. Each dot shows a single year from the sequence of 89 years.

Storage and LWAP 2005-2008

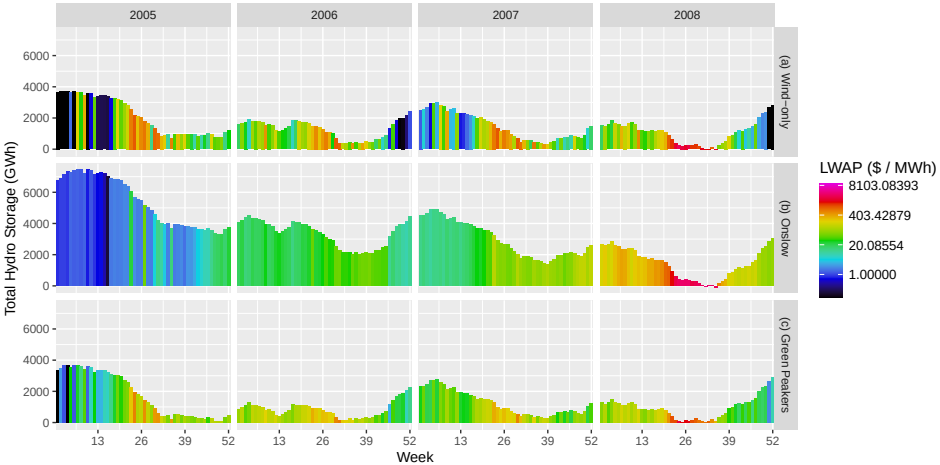

Figure: Storage and LWAP for each case from 2005 to 2008.

Prices for 2035 case studies

Metric	(a) Wind-only	(b) Onslow	(c) Green Peakers
TWAP	145.1	72.4	99.0
LWAP	181.0	75.8	116.0
Wind GWAP	65.0	67.1	65.7
Hydro GWAP	237.1	64.0	126.5
Peaker GWAP	NA	NA	590.6
Pump GWAP	NA	18.3	NA
Release GWAP	NA	67.6	NA

Table: Prices for each case study ($/MWh).

Onslow storage for maximum revenue

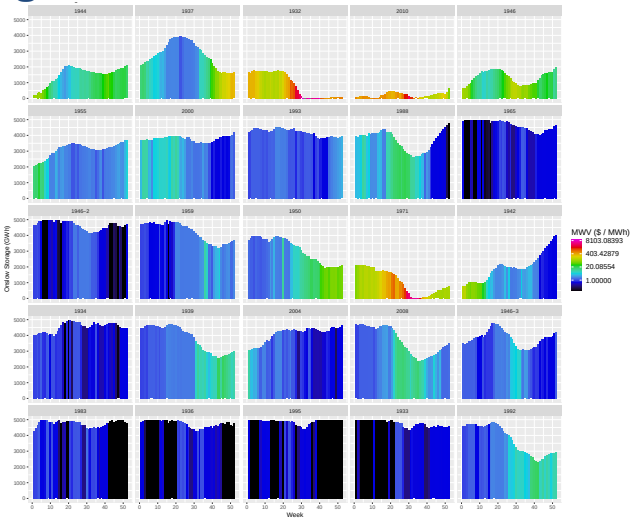

Figure: Onslow storage (GWh) and the corresponding marginal water value ($/MWh) over the most profitable sequences of hydrological years sampled.

The End

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