Limitations in reduction of wind power intermittency with storage technologies

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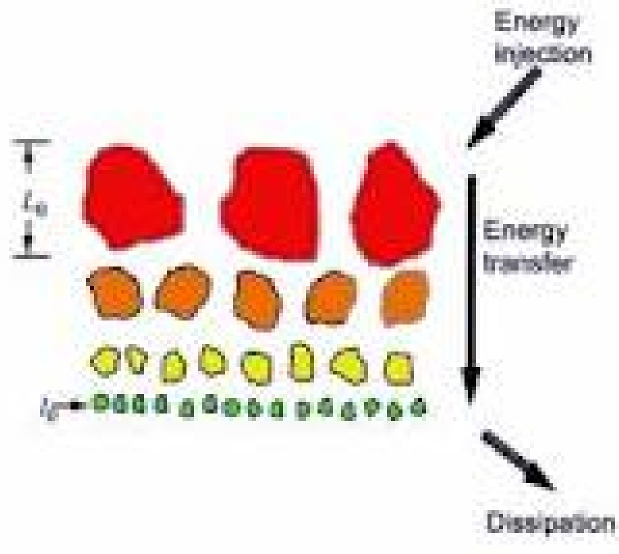
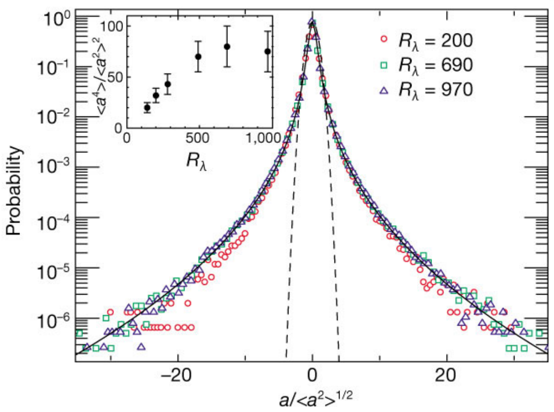
Turbulence

- *"Turbulence is the greatest unsolved problem of classical physics."* R. Feynman
- Self-similar structure leads to broad range of scales involved
- Anomalous fluctuations: enhanced probability of rare events
- Conventional large deviation theory does not apply: fluctuations are weakly suppressed by spatial/temporal averaging
- Universality: statistics in inertial range is the same for all turbulent flows





La Porta et.al., *Nature* **409**, 1017 (2001)

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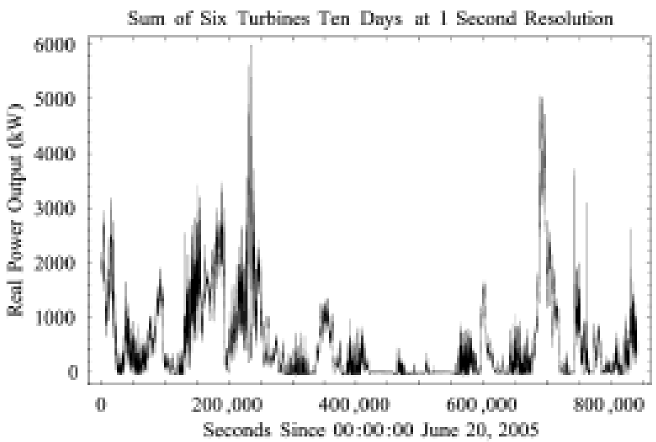
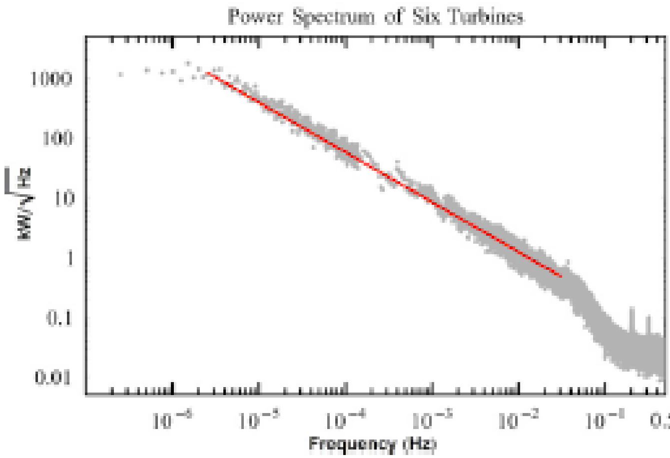
Wind intermittency

- Intermittency of wind fluctuations:
  - Reasonably well understood for instant velocity distribution *P(v)*
  - Much less is known about short time variability
- Kolmogorov spectrum:
  - $P(f) = Cf^{-5/3}$
  - Valid in broad range of scales
  - Universal: details of the system do not matter

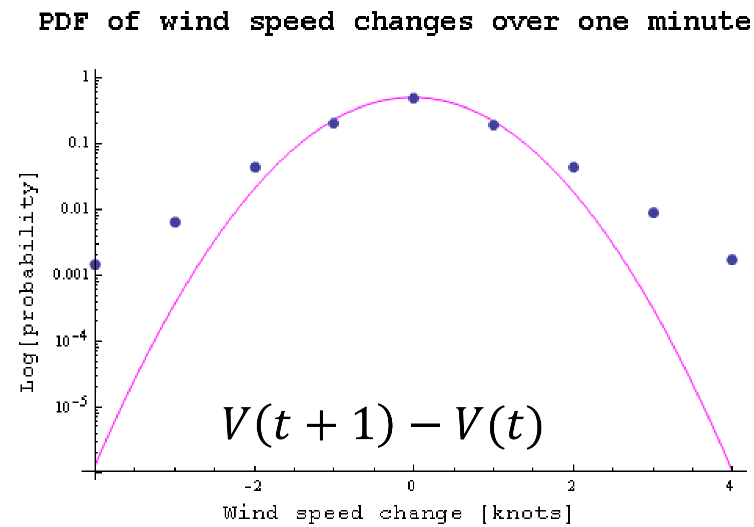


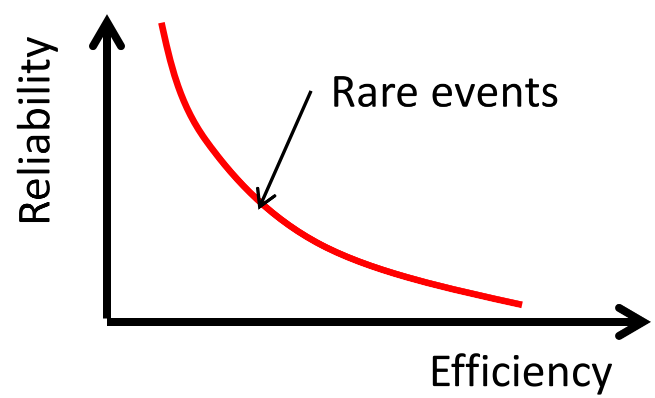


J. Apt, Journal of Power Sources 169 (2007) 369–37

Anomalous fluctuations

- Gaussian model underestimates the probability of rare velocity fluctuations: presumably once a year events happen once a week!
- Can we mitigate this intermittency with storage: real or virtual ?
- How can we quantify the reliability ?
- Universality can help, but only if the right questions are asked.





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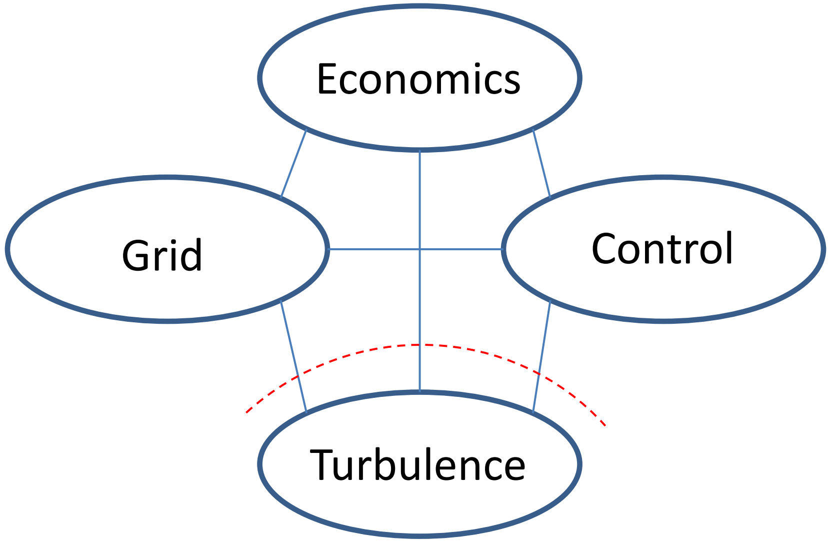
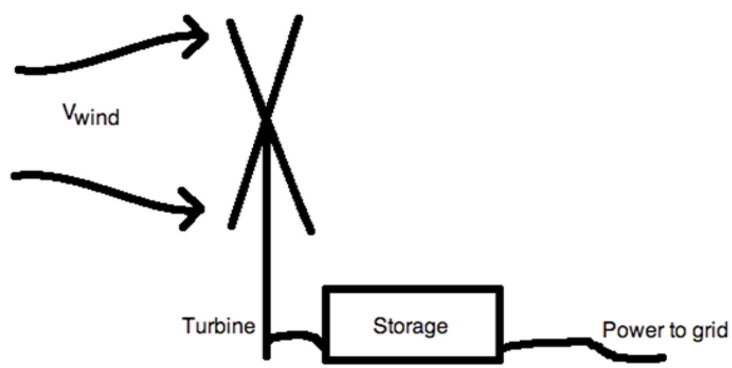
Mitigation of intermittency

- Complex interdisciplinary problem: interplay of constraints from grid (contingency), economics (costs), control (stability, predictability).
- Turbulence simulations for every specific grid: not realistic
- Data analysis has limited applications in the analysis of rare events for reliability
- We need to reduce the model: Encapsulate all the nonlinear hydrodynamics in some statistical characteristics relevant for the grid





Model

- Model:
  - Single 2 MW turbine with peak following speed control
  - NOAA ASOS wind data: 1 min resolution
- Variations on 5-30 min time-scale:
  - Inter-dispatch to ED timescale
  - Inside inertial range of turbulence (universal)
- Assume perfect forecast:
  - Sets the limits on achievable
  - Does not tell how to achieve it

Parameter	Value
Maximum rated power	2 MW
Blade Radius	35 m
Coefficient of performance	0.48
Cut in speed	3.5 m/s
Air density	1.225 kg/m^3

$$P_{in} = \frac{1}{2}\pi R_{blade}^2 \rho_{air} c_p v_{wind}^3$$

$$v_{min} < v_{wind} < v_{max}$$

Mathematical model

$$P_{out}(t) = P_{in}(t) + u(t-1) - u(t)$$

$t = 1\,..\,T$: time (with 1 min resolution)
$P_{in}(t)$: input power (from wind turbine model)
$u(t)$: stored energy
$P_{out}(t)$: output power

$$\min_{u} \| P_{out}(t) - \overline{P_{out}} \|_2 \;\; s.t.$$

$0 \leq u(t) \leq S$: Storage capacity
$\|P_{out} - P_{in}\|_\infty \leq R$: Ramping rate
$\|P_{out} - P_{in}\|_1 \leq C\,T$: Lifetime (number of cycles)

Convex!

Solution depends on sample: random process with universal distribution

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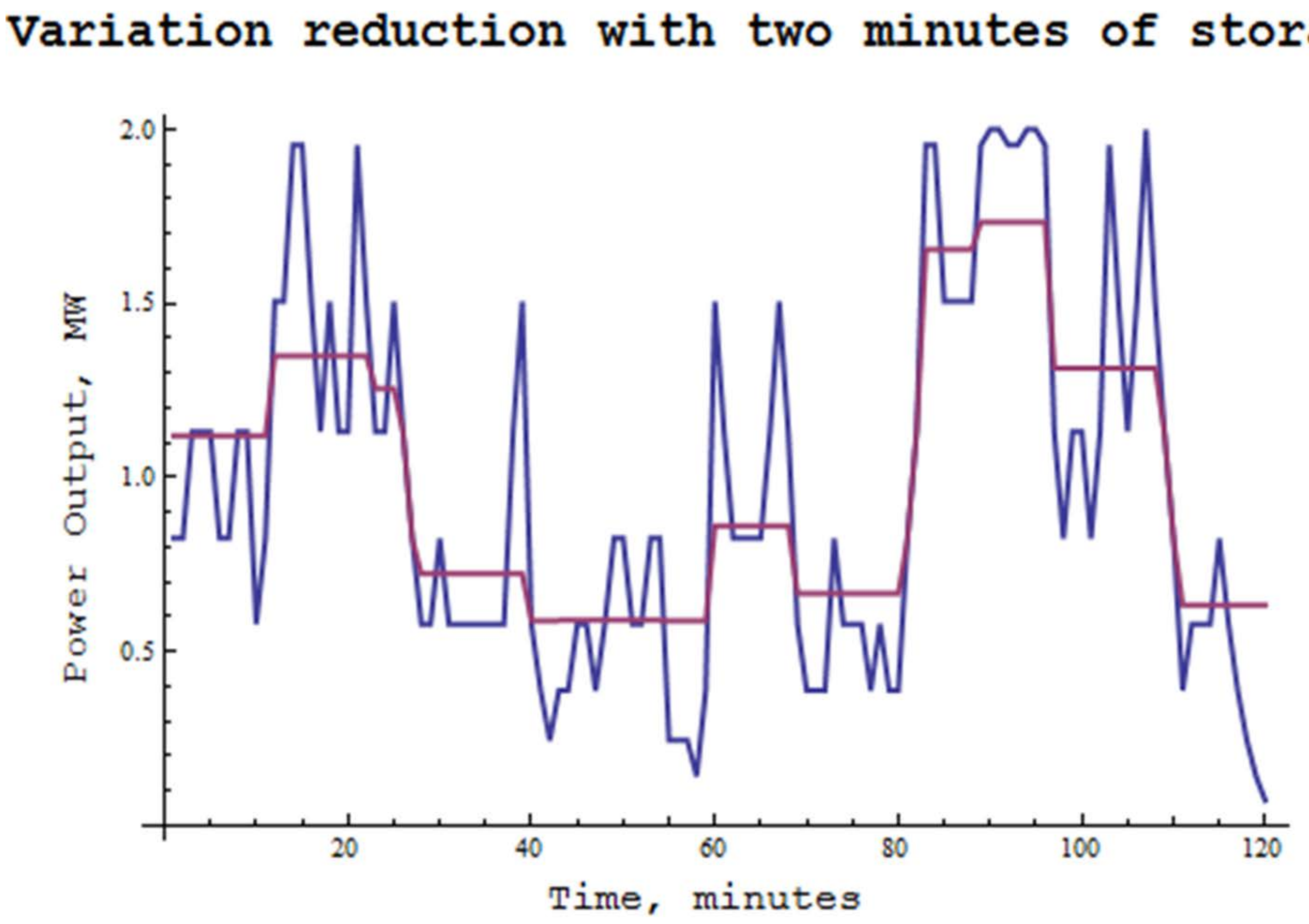
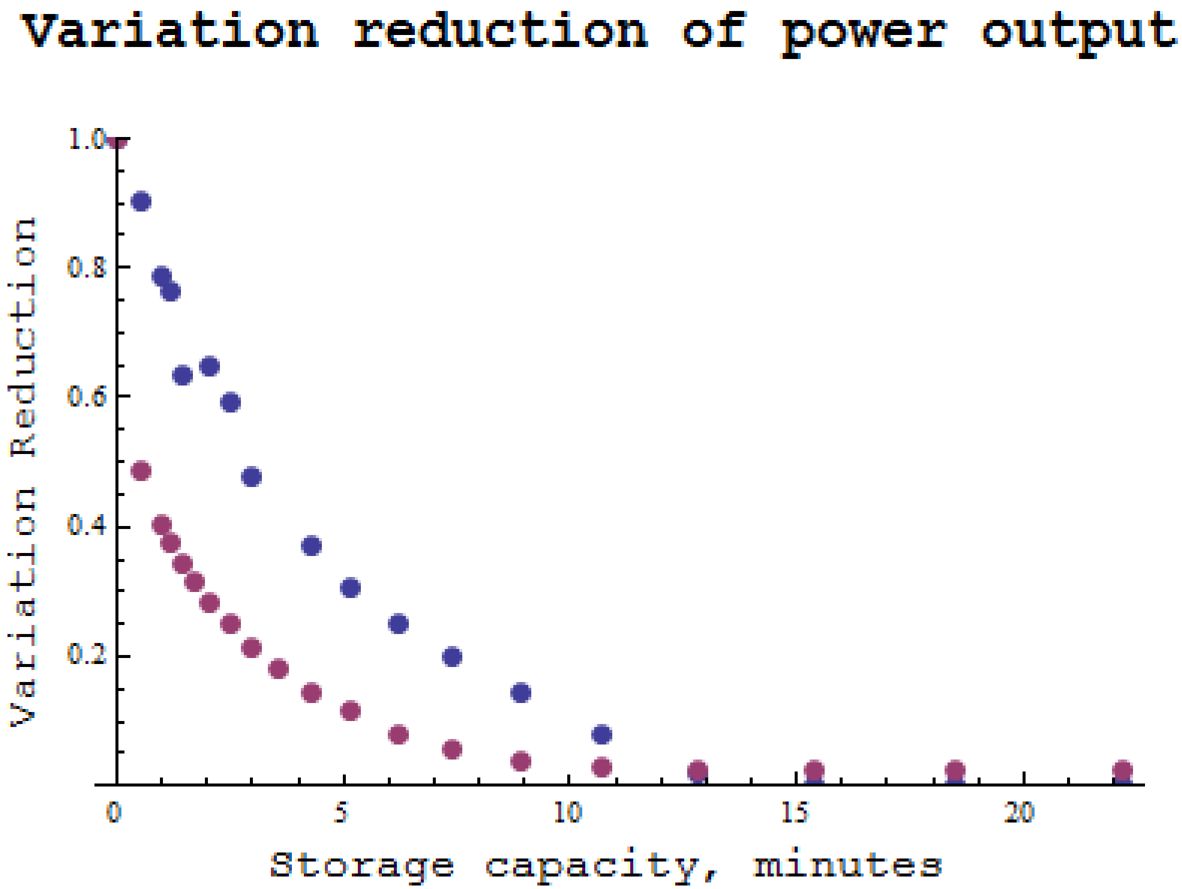
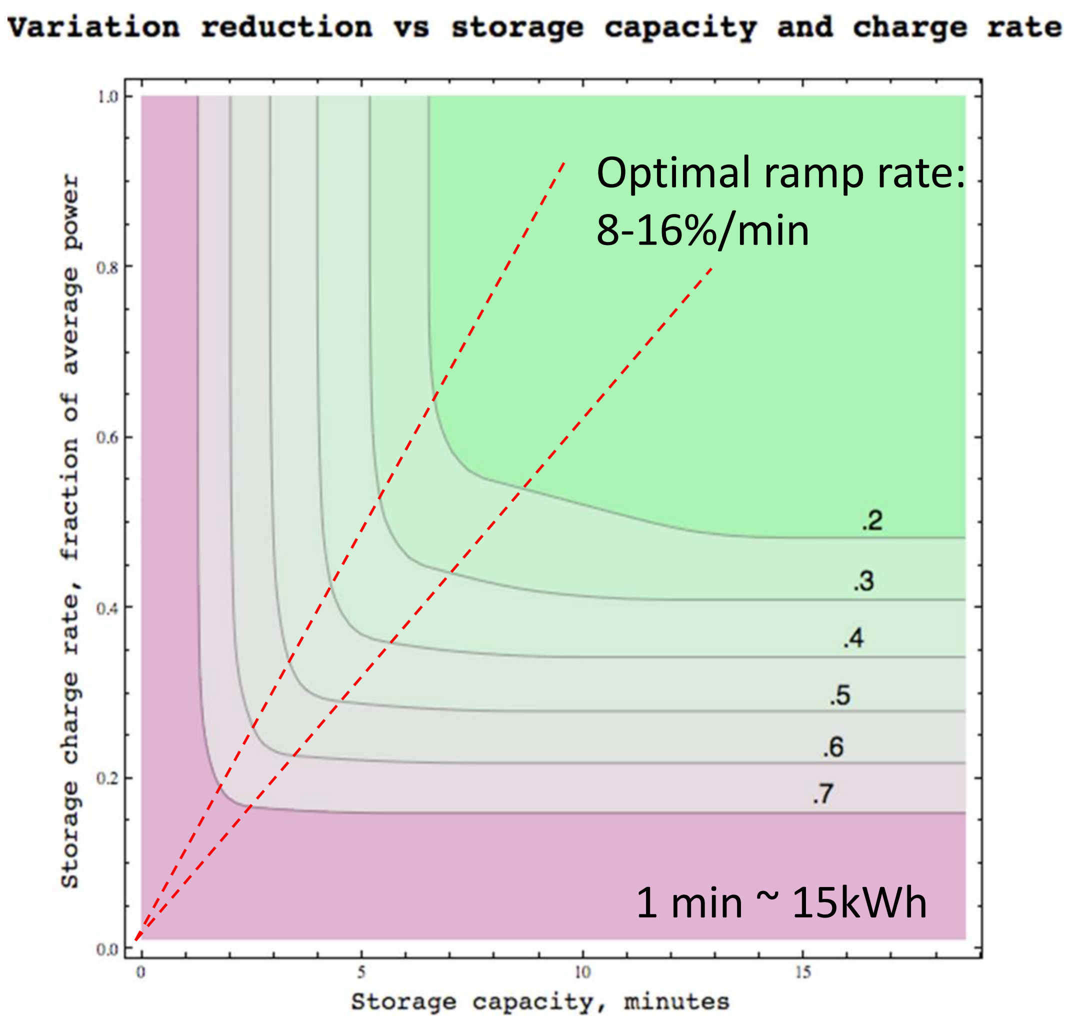
Results: optimal solution



Results: variation reduction



Results: Capacity vs Rated power



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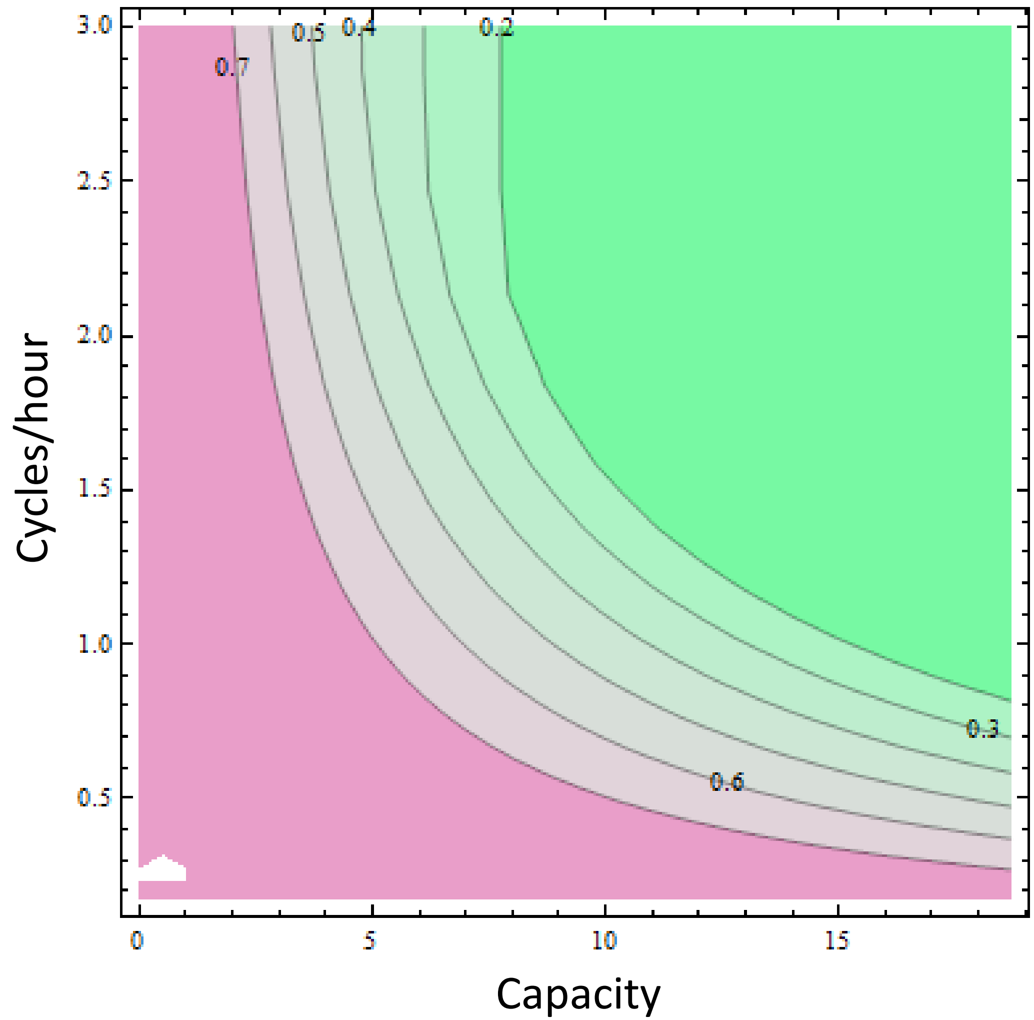
Results: Capacity vs Lifetime



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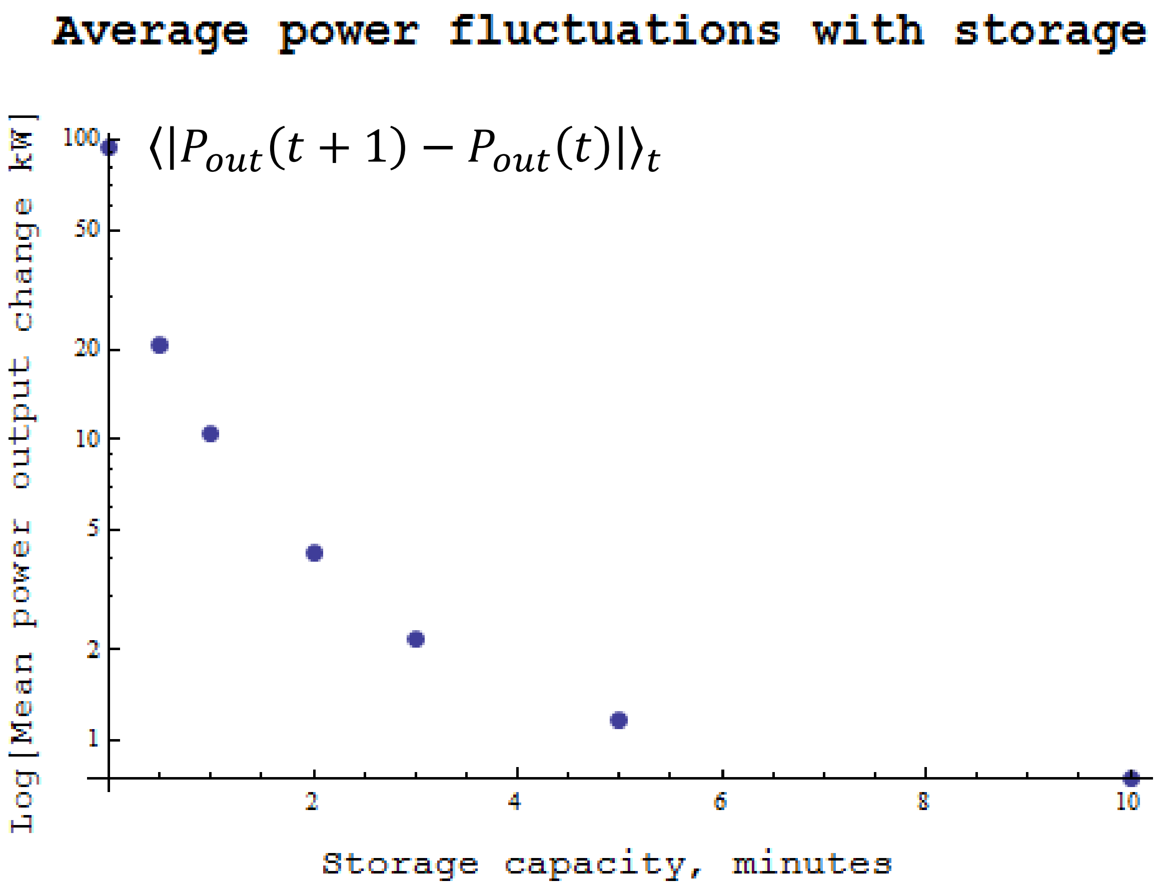
Results: short-term variability reduction



Future directions

- Better chosen objective function:

$$\int df\ H(f)|P_{out}(f)|^2$$

  Target specific frequency band (say 2-10 minutes for inter-dispatch variability)
- Role and value of wind predictability
- Actual control techniques
- More refined constraints: shifting loads, opportunity costs
- Dynamic wind curtailment: better solution for frequency control ?