Wind Integration by all Available Means

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August 10, 2010

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Wind Energy Background

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    - Production
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Wind Energy - Production

- 38 GW capacity added in 2009
    - 10 GW in US
    - 10 GW in EU
    - 13 GW in China
- Wind is 25% of the added capacity in 2009
    - $>$ every other energy source 40% of the total in USA
- Cumulative wind capacity has doubled in the last 3 years
    - Growth rate in China is 100%
- USA leads the world in total installed capacity at 35 GW

Plenty of wind capacity and more is coming

Wind Energy - Penetration

- Current penetration levels
  - 3.7% in EU
  - 2% in the USA
  - 19% in Denmark
  - 11% in Spain, Portugal
- Aggressive future goals [consumption not capacity]
  - 20 % from renewable sources by 2020 in EU
  - 12-14% from wind by 2020 in EU
  - 30 % from renewable sources by 2020 in Denmark
  - 20 % Wind Energy by 2030[1]

Current penetration modest, but aggressive future targets

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[1] US DOE technical feasibility report

Wind Integration - Current Policy

- Denmark: market price + subsidy
- Germany: Renewable Energy Source Act (RESA)
  TSO must buy all offered production at fixed prices
- Spain: A mix of minimum price and premium over market price which gradually decreases to zero
- UK: A new feed-in tariff of €0.23/kWh for small (¡ 5MW) wind projects
- CA: PIRP program – end-of-month imbalance accounting

Almost all wind sold today uses
extra-market mechanisms, subsidies, price guarantees

Wind Integration - Major Issues

- Transmission capacity
  - without added transmission, substantial curtailment of wind generation will be required at 20% penetration[2]
- Wind forecasting
- Role and benefit of storage
- Coordination of independent power producers, system operators, and regulatory agencies
- Operational impact of variability on the grid due
  - reserves, unit commitment
  - load-following, and real-time balancing
  - net green house gases benefit

Current operating experience offers little guidance on managing the added variability at deep penetration levels

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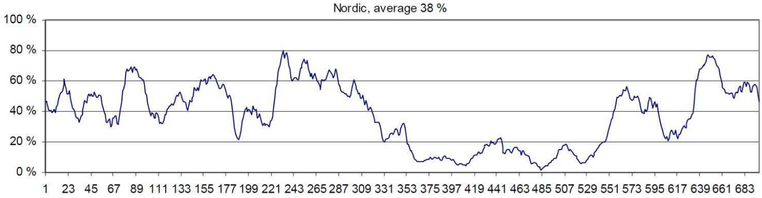
[2] DOE EWITS, 2010

Wind Power Variability

- hourly wind power data from Nordic grid, feb 2000[3]
- normalized to nameplate capacity
- not stationary!
- steady and gusty modes with ramp events



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[3] P. Norgard et al.,2004

Dealing with Variability

- All wind produced today is sold through extra-market mechanisms
- Variability absorbed in reserve margins
  - Operating Reserve to deal with forecasting error, outages
  - Regulation Reserve for automatic generation control
- Reserve margins are expensive

Wind integration requires increased reserve margins
Not economically feasible at deep penetration levels

Our Research Agenda

- Systems and control problems relevant to
  - integration of renewables
  - grid operation
- Uncertainty and variability
  - introduced by renewable generation and demand response
  - develop dynamic control and optimization algorithms to minimize operational impact
- Understand impact of distributed decisions made by various actors – producers, consumers, system operators – on system stability and performance
- Analysis and design of new market structures
- Simplified models and rigorous analysis that capture (and verify) behaviors predicted by large scale computational/statistical simulation studies

Problem Formulation

1. Markets
2. Pricing
3. Contract model
4. Contract sizing metrics
5. Objectives

Markets

- Current practice [CAISO]

  ex-ante: 2 successive markets [DA, RT]

  ex-post: settlement mechanism for imbalance pricing
- Future trend [NYISO]

  Additional intra-day recourse markets between DA and RT

  Will likely be realized by aggregators

Pricing Model

Single *ex-ante forward market* with *ex-post imbalance penalty* for scheduled contract deviations

p : clearing price ($ per MW-hour) in forward market [DA]

q : penalty price ($ per MW-hour)

Assumptions:

1. Wind power producer (WPP) is a price taker in forward market (marginal cost of production ≈ 0)
2. Prices p and q are fixed and known (can be relaxed)

Remarks

1. WPP has no recourse
2. WPP sells energy at price p
3. WPP pays deviation penalty at price q for contract deficits
4. Penalty price q can be generalized to a class of convex functions to capture other costs (ex: local generation)
5. Prices can interpreted as *shadow prices* for a chance constrained formulation.
6. Results can be generalized to p concave and q convex in deviation $\delta = C - w$

Contract Model

Contract structure:

- Conventional contract model $[C, t_0, t_f]$
- Contracts in practice [setpoint and ramp constraints]
- Novel contract structure [risk limiting]

Profit $$\Pi(C, w) = \int_{t_0}^{t_f} pC - q\left[C - w(t)\right]^+ dt$$

Contract Sizing Metrics

Profit
$$\Pi(C,w) = \int_{t_0}^{t_f} pC - q\,[C - w(t)]^+ \, dt$$

Expected Profit
$$J(C) = \mathbb{E}_w \, \Pi(C,w)$$

Risk-Sensitive Profit
$$J(C,\theta) = \mathbb{E}_w \, \Pi(C,w) - \theta \mathrm{var}_w \left(\Pi(C,w)\right)$$

Expected Curtailment
$$S(C) = \mathbb{E}_w \int_{t_0}^{t_f} [w(t) - C]^+ \, dt$$

Objectives

- Theoretical
  - Framework for optimal contract sizing
  - Understanding the role of p and q
- Empirical
  - Studying marginal values of information, storage, local-generation
  - Studying effect of wind uncertainty
- Bigger picture
  - Using studies to *design* q to incentivize WPP to limit injected variability
  - Dealing with variability at the system level

Related Work

- Bathurtst et al (2002)
- Pinson et al (2007)
- Matevoysyan and Soder (2006)
- Morales et al (2010)

Day ahead, hourly, and balancing markets
Asymmetrical imbalance prices and profits
Incorporate risk of profit variability
Uncertainty in prices using ARIMA models
AR models and wind power curves for wind production
Linear programming based solution using scenarios for various uncertainties created using a tree structure

Main Results

1. Optimal contracts in DA markets
2. The role of observations
3. Marginal utility of forecasts
4. Marginal utility of local generation
5. Marginal utility of of storage
6. Optimal dispatch with intra-day markets

Optimal Contract Sizing

CDF of $w(t)$: $F(w,t)$

Contract interval: $[0,T]$

Define

$$F(w) = \frac{1}{T}\int_0^T F(w,t)dt, \quad \gamma := \frac{p}{q}$$

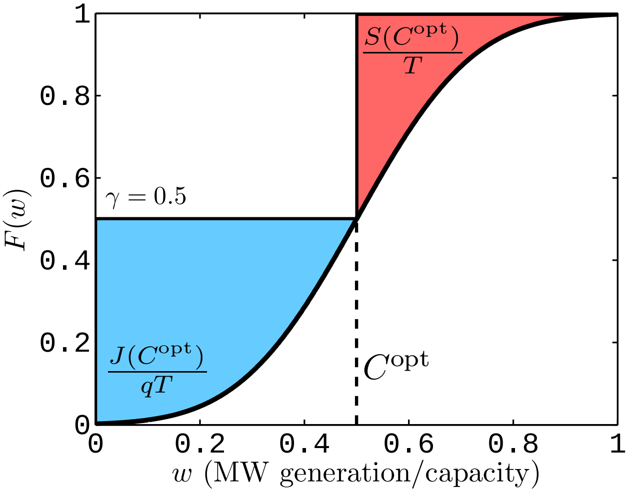
Theorem

$$C^{\textsf{opt}} = F^{-1}(\gamma)$$

$$J\left(C^{\textsf{opt}}\right) = qT\int_0^\gamma F^{-1}(w)dw \;\; =: \;\; J^{\text{opt}}$$

$$S\left(C^{\textsf{opt}}\right) = T\int_\gamma^1 \left[F^{-1}(w) - F^{-1}(\gamma)\right] dw \;\; =: \;\; S^{\text{opt}}$$

Optimal Contract Sizing



The Role of Information: Model

Condsider the following model for wind power at a single time point.

W	r.v., wind power
Y	r.v., correlated to W ($\sim$ observation of W)

with $\mathbb{E}[W - Y] = 0$.

Key point: $\text{var}(W|Y) \leq \text{var}(W)$

The Role of Information

Define

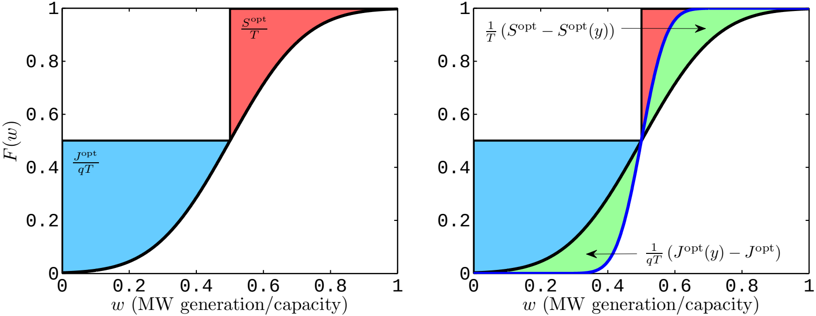
$$\begin{aligned} J^{\text{opt}}(y) &= qT\int_0^\gamma F^{-1}(w|y)dw \\ S^{\text{opt}}(y) &= T\int_\gamma^1 \left[F^{-1}(w|y) - F^{-1}(\gamma|y)\right] dw \end{aligned}$$

where, $F(w|y) \ := \ \mathbb{P}(W \leq w \mid Y = y)$.

Theorem

$$\mathbb{E}\left[\ J^{\text{opt}}(Y)\ \right] \ \geq \ J^{\text{opt}}$$

The Role of Information: Graphical Interpretation



Marginal Utility of Information

Again, consider a single time point contract

Theorem

Let Y be a r.v. correlated to W
Let $g(Y)$ be an unbiased estimator of W
Define $E = W - g(Y)$ and let cov $(E) = \sigma^2$
Then, the expected profit is

$$\text{(a)}\ \ f(e)\ \text{uniform} \qquad \mathbb{E}[J^{\text{opt}}(Y)] = p\mathbb{E}[W] - 0.707p\sigma(1-\gamma)$$

$$\text{(b)}\ \ f(e)\ \text{normal} \qquad \mathbb{E}[J^{\text{opt}}(Y)] = p\mathbb{E}[W] - \sqrt{3}p\sigma(1-\gamma)$$

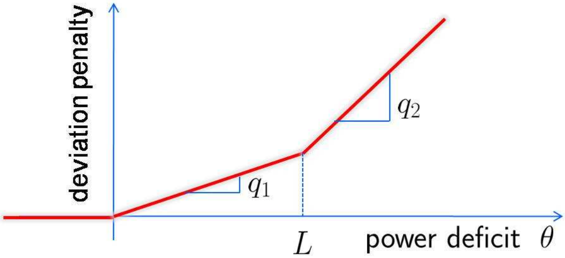
Remark: expected profit with perfect forecasting is $p\mathbb{E}[W]$

Expected profit is linear in standard deviation

Local Generation

- Idea: Local generation can be modeled by augmenting penalty price profile.
- Fast acting CCGT

  operational price q_1 (\$/MW)
  power capacity L (MW)
  capital costs not considered



Marginal Utility of Local Generation

Theorem

- *Optimal contract is the solution of:*

$$p = q_2 F(C) + (q_2 - q_1) L \left[f(C - L) - \frac{F(C) - F(C - L)}{L} \right]$$

- *For* L *small,* $C^{\text{opt}} \approx F^{-1}(\gamma)$, *where* $\gamma = \frac{p}{q_2}$.
- *Extra optimal expected profit*

$$\Delta J = (q_2 - q_1) \int_{C^{\text{opt}} - L}^{L} (C^{\text{opt}} - w) f(w) dw$$

- *Marginal utility of local generation capacity*

$$\frac{dJ^{\text{opt}}}{dL} = (q_2 - q_1) L f(C^{\text{opt}} - L)$$

Energy Storage Model

Dynamics: $\dot{e}(t) = \lambda e(t) + \eta_{\text{in}} P_{\text{in}}(t) - \frac{1}{\eta_{\text{ext}}} P_{\text{ext}}(t)$

Linear constraints

$$\begin{aligned} 0 \leq & \quad e(t) & \leq \overline{e} \\ 0 \leq & \quad P_{\text{in}}(t) & \leq \overline{P}_{\text{in}} \\ 0 \leq & \quad P_{\text{ext}}(t) & \leq \overline{P}_{\text{ext}} \end{aligned}$$

Parameters

$\lambda \in [0,1]$,	leakage coefficient
$\eta_* \in [0,1]$,	roundtrip efficiency

linear equality and inequality constraints
decision variables: $P_{\text{in}}(t)$, $P_{\text{ext}}(t)$

Optimal Use of Energy Storage

$J(C, w, P_{\text{in}}, P_{\text{ext}}) :=$ profit using storage policies $P_{\text{in}}, P_{\text{ext}}$

Theorem

- *optimal storage policy is causal in* $w(t)$

$$\begin{aligned} J(C, w) &= \inf_{P_{\text{in}}, P_{\text{ext}}:\textit{causal}} J(C, w, P_{\text{in}}, P_{\text{ext}}) \\ &= \inf_{P_{\text{in}}, P_{\text{ext}}:\textit{all}} J(C, w, P_{\text{in}}, P_{\text{ext}}) \end{aligned}$$

- $J(C, w)$ *can be found by solving a linear program*
- *optimal contract sizing is a convex program:*

$$C^{\text{opt}} = \arg\min_{C} \mathbb{E}_w J(C, w)$$

Marginal Utility of Storage

Assumptions

1. No rate constraints on energy injection/extraction.
2. Perfect efficiency.

Define

$\xi(C, w) :=$ number of times the wind power $w(t)$ crosses C from above, per unit time

Theorem

$$\left.\frac{dJ^{\text{opt}}}{d\overline{e}}\right|_{\overline{e}=0} = qT\,\mathbb{E}\left[\,\xi(C^{\text{opt}}, w)\right] \quad \textit{where } C^{\text{opt}} = F^{-1}(\gamma)$$

$$= pT(1-\gamma) \quad \textit{if } w(t) \textit{ is IID}$$

Marginal utility of storage is constant in $\overline{e}$
increases with variability of wind.

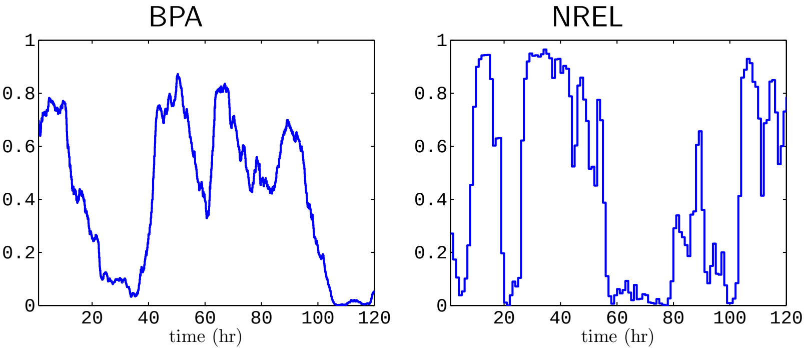
Recourse Markets

- Capacity reserves are purchased as new information becomes available in intra-day markets.
- Different reserve types corresponding to response times.

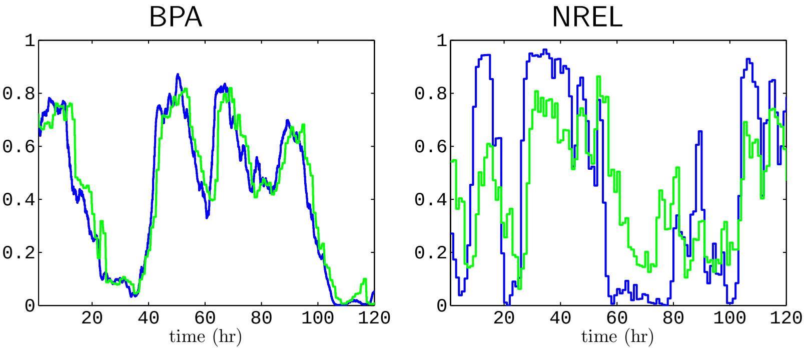
Wind Power Data Sets

- National Renewable Energy Lab (NREL)
  - Data generated from multiscale physical model
  - 1 hour average power sampling
  - 366 days
  - 24 hour ahead forecasts
- Bonneville Power Authority (BPA)
  - Measured aggregate wind power over BPA control area
  - 5 minute average power sampling
  - 639 days
  - 1 hour ahead forecasts

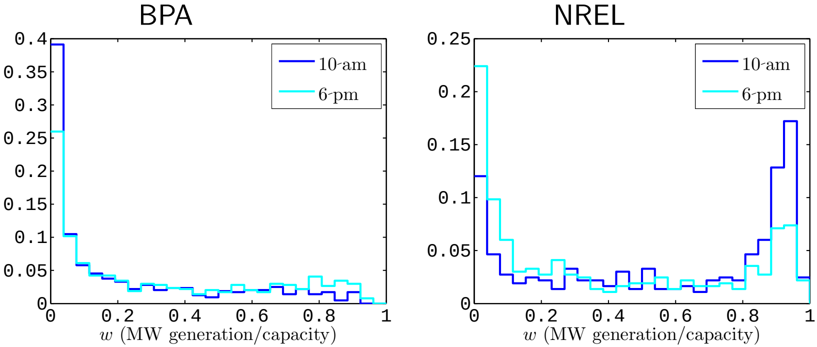
Wind Power (Measured)



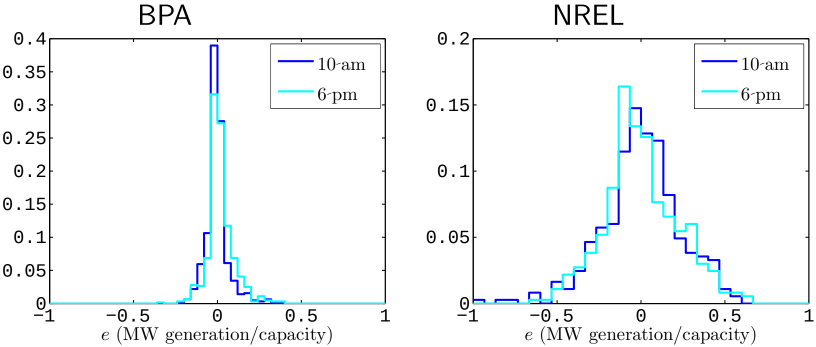
Wind Power (Measured, Forecast)



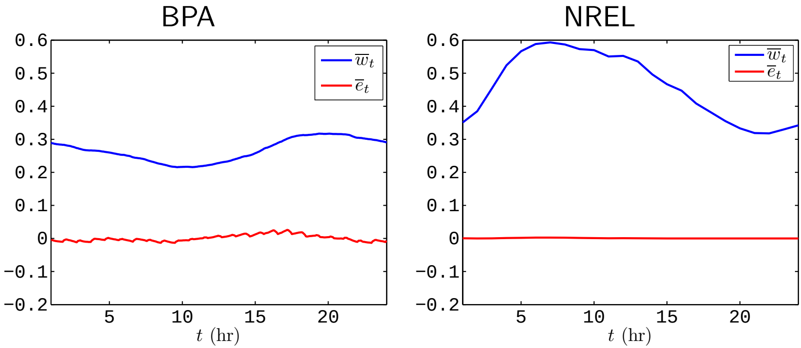
Empirical Wind Power Densities, $f(w,t)$



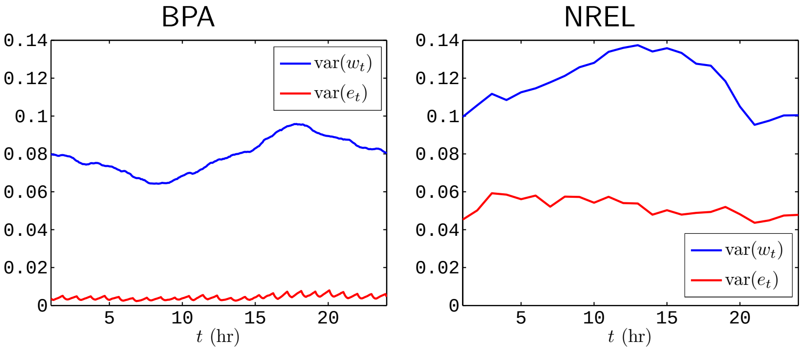
Empirical Forecast Error Densities, $f(e,t)$



Mean Statistics on Interval Marginals

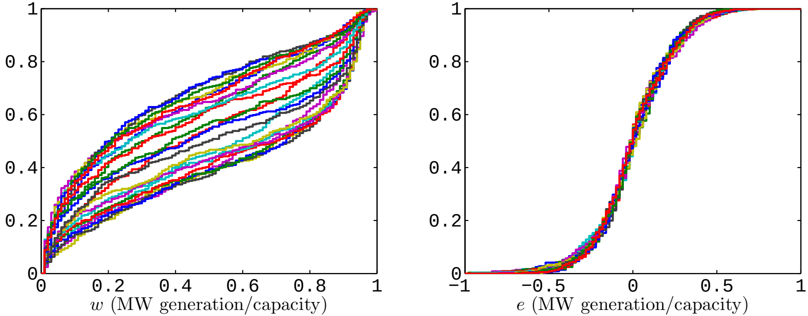


Variance Statistics on Interval Marginals



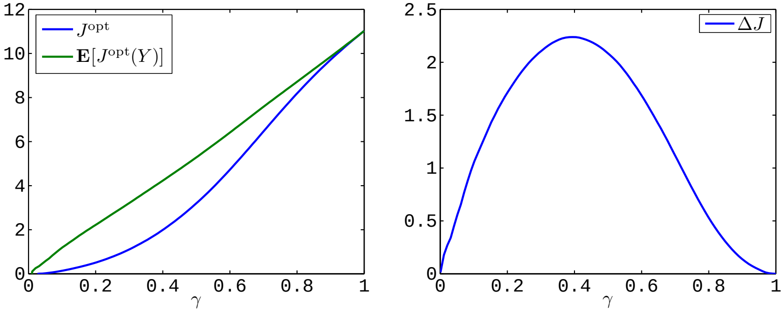
Marginal Distributions (NREL)

Forecasts reduce dispersion



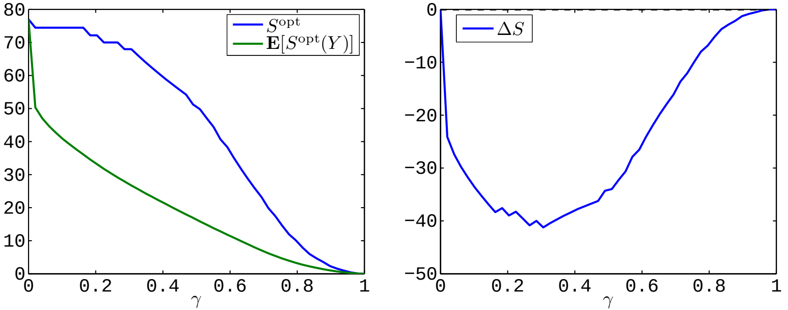
Effect of Information on Profit (NREL)

- Units of profit: $1/(p \cdot \mathrm{capacity} \cdot 24\mathrm{hr})$
- $\Delta J := \mathbb{E}[J^{\mathrm{opt}}(Y)] - J^{\mathrm{opt}}$

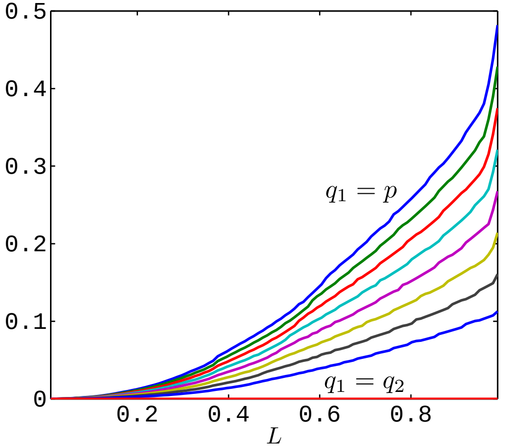


Effect of Information on Spillage (BPA)

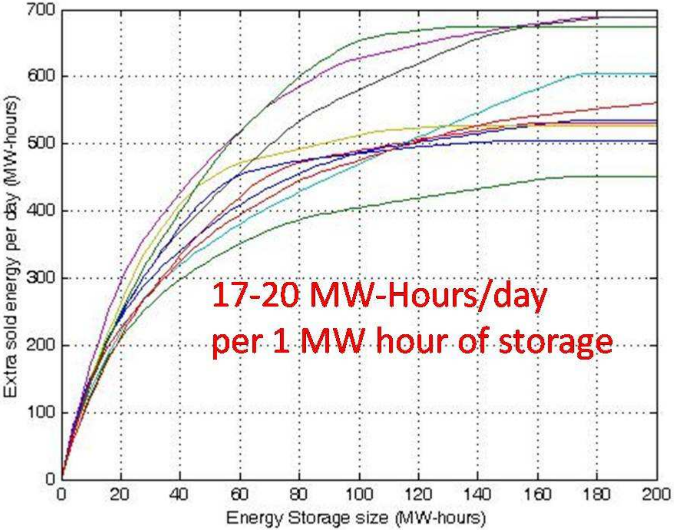
- Units of spillage: $1/(\text{capacity} \cdot 24\text{hr})$
- $\Delta S := \mathbb{E}[S^{\text{opt}}(Y)] - S^{\text{opt}}$



Marginal Value of Local Generation



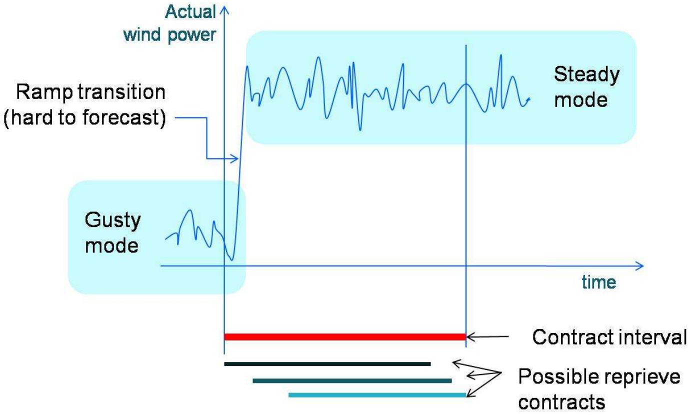
Marginal Value of Storage



17-20 MW-Hours/day

per 1 MW hour of storage

Contracts with Reprieve



Conclusions

- Conventional markets have evolved for dispatchable generation
- Not appropriate for wind
- Deviation penalty pricing is critical means of limiting injected variability
- Some wind must be spilled
- Network problem – how much variability can each player handle?
- How much wind penetration is possible?