Selling Random Energy

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Co-conspirators

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... and thanks to many useful discussions with:
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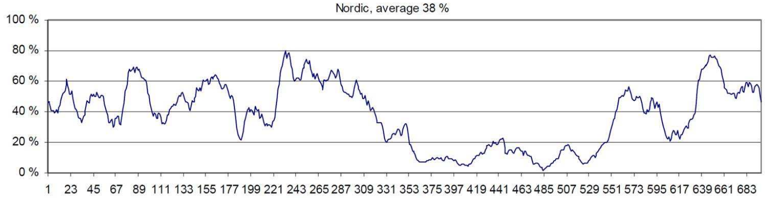
Outline

Wind Power Variability

Wind is variable source of energy:

- Non-dispatchable - cannot be controlled on demand
- Intermittent - exhibit large fluctuations
- Uncertain - difficult to forecast

This is *the* problem! Especially large ramp events



Hourly wind power data from Nordic grid, Feb. 2000 – P. Norgard et al.,2004

Wind Energy: *Status Quo*

Current penetration is modest, but aggressive future targets

- Wind energy is 25% of added capacity worldwide in 2009 (40% in US) – surpassing all other energy sources
- Cumulative wind capacity has doubled in the last 3 years – growth rate in China $\approx$ 100%

Almost all wind sold today uses extra-market mechanisms

- Germany – Renewable Energy Source Act
  TSO must buy all offered production at fixed prices
- CA – PIRP program
  end-of-month imbalance accounting + 30% constr subsidy

Dealing with Variability

Today:

- Variability absorbed by operating reserves
- All produced wind energy is taken, treated as negative load
- Integration costs are socialized

Tomorrow:

- Deep penetration levels, diversity offers limited help
- Too expensive to take all wind, must curtail
- Too much reserve capacity $\implies$ lose GHG reduction benefits

Today's approach won't work tomorrow

Dealing with Variability Tomorrow

At high penetration ($> 20\%$), wind power producer (WPP) will have to assume integration costs [ex: ERCOT]

Consequences:

1. WPPs participating in conventional markets [ex: GB, Spain]
2. WPPs responsible for reserve cost [ex: procure own reserves (BPA pilot), reserve cost sharing]
3. Firming strategies to mitigate financial risk [ex: Ibadrola]
   - energy storage, co-located thermal generation
   - aggregation services
4. Novel market systems
   - Intra-day [recourse] markets
   - Novel instruments [ex: interruptible contracts]

Problem Formulation

1. Wind Power Model
2. Market Model
3. Pricing Model
4. Contract Model
5. Contract Sizing Metrics

Wind Power Model

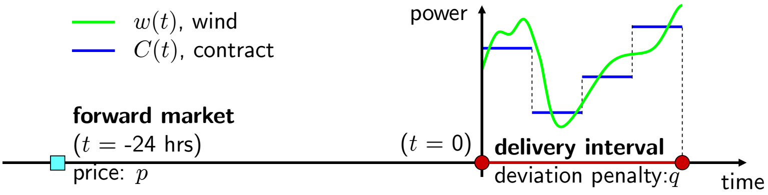
Wind power $w(t)$ is a stochastic process

- Marginal CDFs assumed known, $F(w,t) = \mathbb{P}\{w(t) \leq w\}$
- Normalized by nameplate capacity so $w(t) \in [0,1]$

Time-averaged distribution on interval $[t_0, t_f]$

$$F(w) = \frac{1}{T} \int_{t_0}^{t_f} F(w,t) dt$$

Simple Market Model



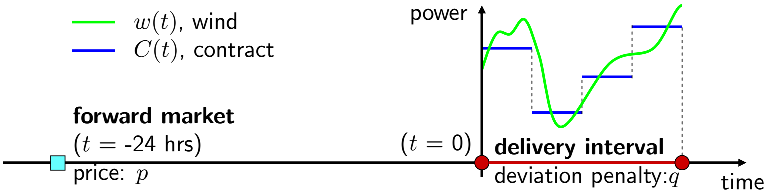
ex-ante: single forward market

ex-post: penalty for contract deviations

Remarks:

- Offered contracts are piecewise constant on 1 hr blocks
- No energy storage ⇒ no price arbitrage opportunities ⇒ contract sizing decouples between intervals

Simple Pricing Model



Prices ($ per MW-hour)

p = *ex-ante* clearing price in forward market

q = *ex-post* shortfall penalty price

Assumptions:

- Wind power producer (WPP) is a price taker
- Prices p and q are fixed and known
  [results easily extend to random prices uncorr with w]

Metrics of Interest

For a contract C offered on the interval $[t_0, t_f]$, we have

$$\begin{aligned} \text{profit acquired} \quad \Pi(C,w) &= \int_{t_0}^{t_f} pC - q\,[C - w(t)]^+\,dt \\ \text{energy shortfall} \quad \Sigma_-(C,w) &= \int_{t_0}^{t_f} [C - w(t)]^+\,dt \\ \text{energy curtailed} \quad \Sigma_+(C,w) &= \int_{t_0}^{t_f} [w(t) - C]^+\,dt \end{aligned}$$

These are random variables
So we're interested in their expected values
Many variants
ex: sell spilled wind in AS markets, penalty for overproduction

Optimal Contracts

Taking expectation with respect to w,

$$\begin{aligned} J(C) &= \mathbb{E}\ \Pi(C, w) \\ S_-(C) &= \mathbb{E}\ \Sigma_-(C, w) \\ S_+(C) &= \mathbb{E}\ \Sigma_+(C, w) \end{aligned}$$

Optimal contract maximizes expected profit:

$$C^* = \arg\max_{C \geq 0} J(C)$$

Objectives

Theoretical

- Studying effect of wind uncertainty on profitability
- Understanding the role of p and q
- Utility of local generation and storage

Empirical

- Calculating marginal values of storage, local-generation

Bigger picture

- Using studies to *design* penalty mechanisms to incentivize WPP to limit injected variability
- Dealing with variability at the system level

Related Work

- Botterud et al (2010)
- Morales et al (2010)
  - Uncertainty in prices using ARIMA models
  - AR models and wind power curves for wind production
  - LP based solution using scenarios for uncertainties
- Pinson et al (2007)
  - Asymmetric penalty structure, quantile formula for optimal bids
- Dent at al (2011)
  - Quantile formula for optimal bids

Main Results

1. Optimal contracts in a single forward market
2. Role of forecasts
3. Role of reserve margins
4. Role of local generation
5. Role of energy storage
6. Optimal contracts with recourse

Optimal Contracts: γ-quantile policy

Theorem

Define the time-averaged distribution

$$F(w) = \frac{1}{T} \int_{t_0}^{t_f} F(w,t)dt$$

The optimal contract C^* *is given by*

$$C^* = F^{-1}(\gamma) \qquad \text{where} \quad \gamma = p/q$$

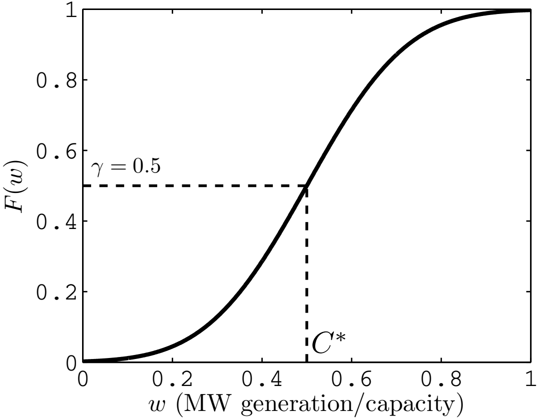
Optimal Contracts: Profit, Shortfall, & Curtailment

Theorem

The expected profit, shortfall, and curtailment corresponding to a contract C^* are:

$$\begin{aligned} J\left(C^*\right) &= J^* = & qT \int_0^{\gamma} F^{-1}(w) dw \\ S_-\left(C^*\right) &= S_-^* = & T \int_0^{\gamma} \left[C^* - F^{-1}(w)\right] dw \\ S_+\left(C^*\right) &= S_+^* = & T \int_{\gamma}^{1} \left[F^{-1}(w) - C^*\right] dw \end{aligned}$$

Graphical Interpretation of Optimal Policy



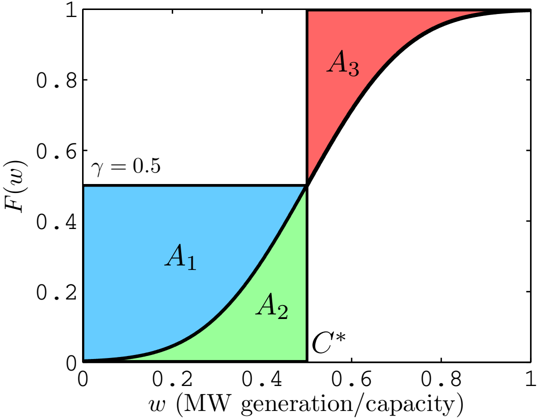
Price-Penalty Ratio

$$\gamma = \frac{p}{q}$$

Optimal Contract

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

Graphical Interpretation of Optimal Policy



Profit:

$J^* = qT\ A_1$

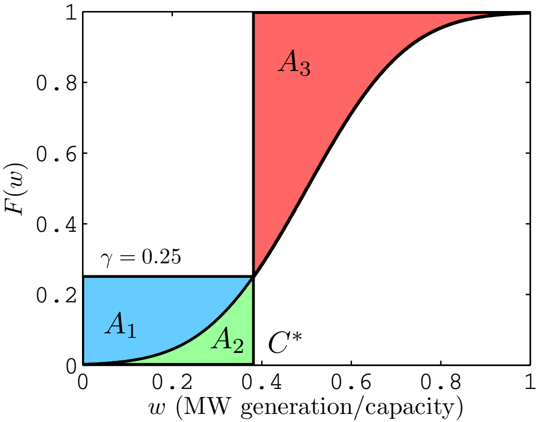
Shortfall:

$S_-^* = T\ A_2$

Curtailment:

$S_+^* = T\ A_3$

Graphical Interpretation of Optimal Policy



Profit:

$J^* = qT\ A_1$

Shortfall:

$S_-^* = T\ A_2$

Curtailment:

$S_+^* = T\ A_3$

Some Intuition ...

Large penalty q, price/penalty ratio $\gamma \approx 0$

- optimal contract ≈ 0
- optimal expected profit ≈ 0
- sell no wind – too much financial risk for deviation

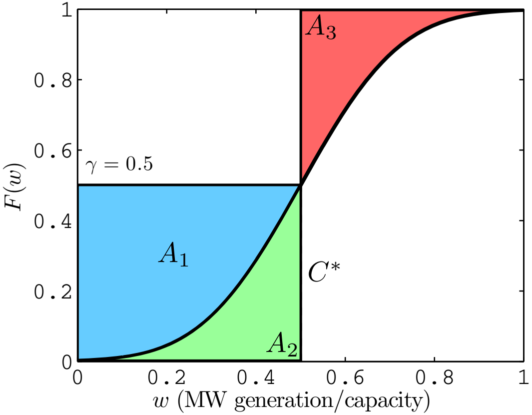
Small penalty q, price/penalty ratio $\gamma \approx 1$

- offered optimal contract $\approx 1 =$ nameplate
- optimal expected profit $= pT\mathbb{E}[W]$
- sell all wind – no financial risk for deviation

Price/penalty ratio γ controls prob of meeting contract, curtailment, variability taken

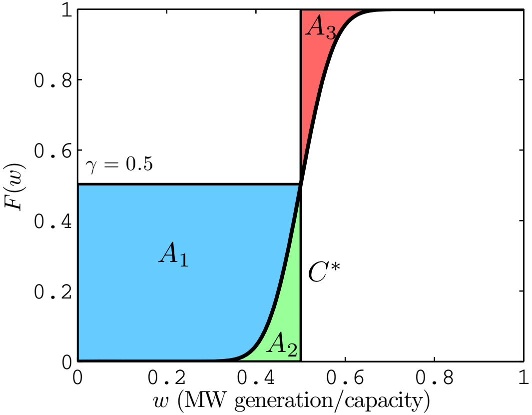
Result is simple application of Newsboy problem

The Role of Information



ex: 24 hour ahead forecast

The Role of Information



ex: 4 hour ahead forecast

Good Forecasts are Valuable

Better information $\Rightarrow$ larger profit

ex: $W \sim$ uniform

$$J^* = \underbrace{pT\mathbb{E}[W]}_{\text{perfect forecast}} - \underbrace{pT\sigma\sqrt{3}(1-\gamma)}_{\text{loss due to forecast errors}}$$

loss due to forecast errors is linear in std dev σ

General case:
Can quantify value of information using deviation measures

The Role of Reserve Margins

$$Reserve\ Cost = Capacity\ Cost + Energy\ Cost$$

- Status quo: added cost of reserve margins for wind is socialized
- With increased penetration, WPPs will assume the cost
  ex: BPA-Iberdrola-Constellation project
- Current reserve calculation is deterministic (worst-case)
- Too conservative for wind – reduction in net GHG benefit

Risk-limiting calculation of reserves a natural alternative

Risk-limiting Reserve Margins

Idea: WPP procures reserve margin to cover largest deficit with probability $\geq 1 - \epsilon$

Reserve Calculation

ϵ	risk level (LOLP)
C	contract offered by WPP
Δ	deficit at time t $= [C - w]^+$
$R(C, \epsilon)$	reserve margin

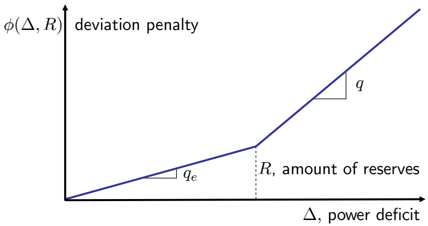
$$R(C, \epsilon) = \min_{R \geq 0} R \quad \text{s.t.} \quad \mathbb{P}\{R \leq \Delta\} \leq \epsilon$$

Reserve margin $R(C, \epsilon)$ covers largest deficit with prob $> 1 - \epsilon$

Reserve Margin Pricing

- Capacity price q_c
  ex ante capacity payment for keeping reserve on call
- Energy Price q_e
  ex post energy payment for deficits $< R(C, \epsilon)$

Augmented penalty fn
Deficit $\Delta = [C - w]^+$
Deviation Penalty $\phi(\Delta, R)$



Optimal Contracts with Reserve Costs

Theorem

The required reserve capacity is

$$R(C,\epsilon) = \left[C - \min_t F^{-1}(\epsilon, t)\right]$$

The optimal contract C_R^* is

$$C_R^* = F^{-1}(\gamma_R) \qquad \textit{where} \quad \gamma_R = (p - q_c)/q_e$$

Role of Local Generation

- Can be used to firm wind power
- Large capital costs $\Rightarrow$ need for cost/benefit analysis
- What is profit gain from investment in small local generation?

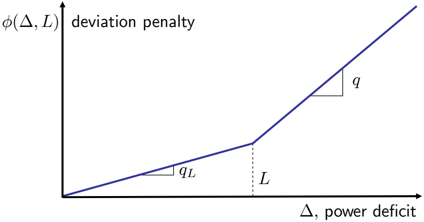
Marginal values are critical for systems planning!

Local Generation

WPP has small co-located power generation plant

Augmented penalty fn

- Capacity L
- Operational Cost q_L



Expected profit criterion with local generation

$$J_L(C) = \mathbb{E} \int_{t_0}^{t_f} \underbrace{pC}_{\text{revenue}} - \underbrace{\phi\left(C - w(t),\ L\right)}_{\text{imbalance energy payment}} \; dt$$

Marginal Value of Local Generation

Theorem

The optimal contract C *solves*

$$p = q_L F(C) + (q - q_L) F(C - L)$$

The marginal value of local generation at the origin is

$$\left.\frac{dJ^*}{dL}\right|_{L=0} = \left(1 - \frac{q_L}{q}\right) pT$$

Energy Storage

WPP has co-located energy storage facility

Questions:

- *ex ante* Optimal contract with local storage?
- *ex post* Optimal storage operation policy?
- Impact of storage capacity [capital cost] on profit?

Can be treated as:
finite-horizon constrained stochastic optimal control problem

Energy Storage Model

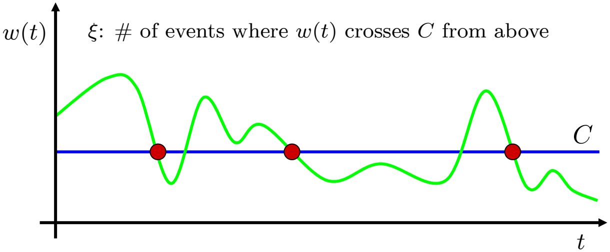
Model: $$\dot{e}(t) = \alpha e(t) + \eta_{\text{in}} P_{\text{in}}(t) - \frac{1}{\eta_{\text{ext}}} P_{\text{ext}}(t)$$

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

Dynamics and constraints are linear

Marginal Value of Energy Storage (Intuition)

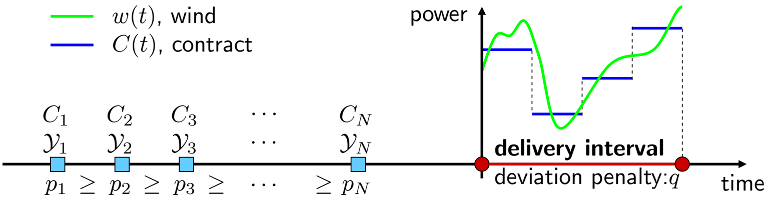
Consider storage system [small capacity ϵ, not lossy]



- ξ equivalent to number of energy arbitrage opportunities
- Each arbitrage opportunity gives savings $= q\epsilon$

$$\text{Marginal value of storage} = q\,\frac{\eta_{\text{in}}}{\eta_{\text{ext}}}\,\mathbb{E}[\xi]$$

Intra-day Markets



- *ex-ante*: In market n, offer contract C_n at price p_n
- *ex-post*: Imbalance deviation penalty from cumulative contract $C = \sum_{k=1}^{N} C_k$

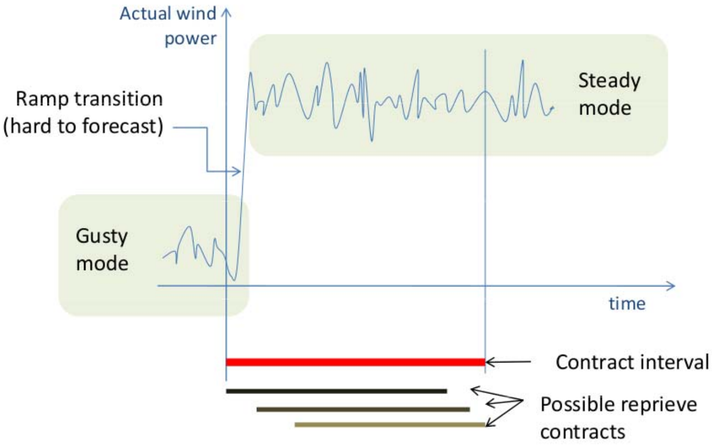
Trade-off: decreasing prices , increasing information
Solution: stochastic dynamic programming

Interruptible Power Contracts

Dealing with ramp events

- WPP offers contract with reprieve
- Reprieve must be managed by ISO
- Is this effective? pricing?

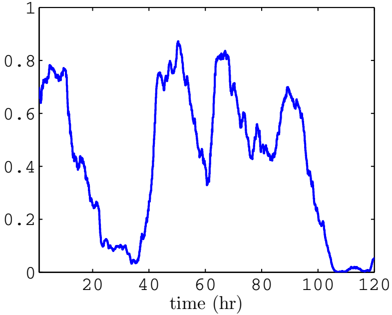
Interruptible Power Contracts ...



Wind Power Data

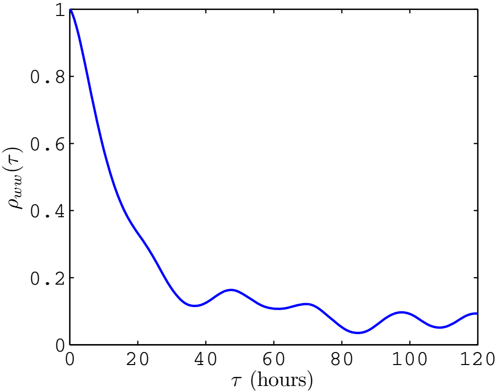
Bonneville Power Authority [BPA]

- Measured aggregate wind power over BPA control area
- Wind sampled every 5 minutes for 639 days



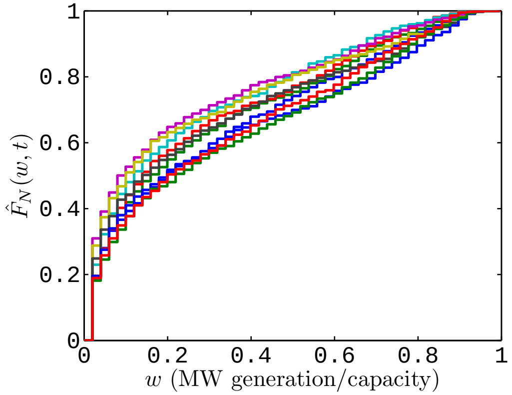
Empirical Wind Power Model

Empirical autocorrelation $\mathbb{E}\ w(t)w(t+\tau)$

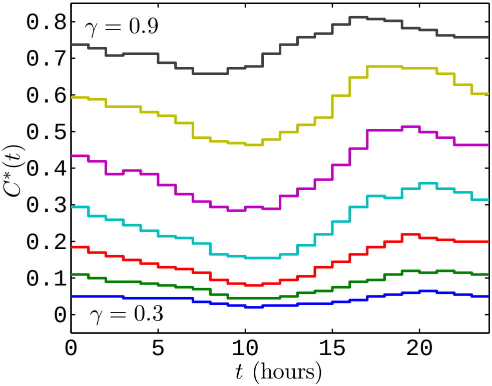


Empirical Distributions

Empirical CDFs for nine different hours



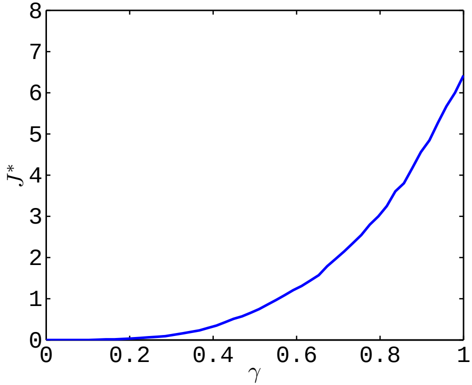
Optimal Forward Contracts



- Optimal contracts for $\gamma = [0.3 : 0.9]$
- Consistent with typical wind pattern
- Bigger penalty $\implies$ smaller contract

Optimal Expected Profit - Empirical

Optimal expected profit J^* as a function of γ

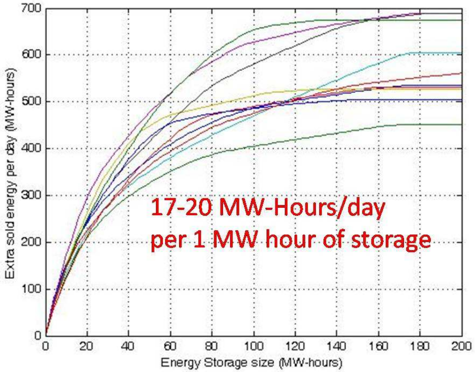


Typical numbers

- p=50 \$/MW-hour
- q=60 \$/MW-hour
- Capacity $=$ 160 MW
- ex: $\gamma = 5/6$
  $J^* \approx$ \$ 28K per day

Marginal Value of Storage - Empirical

Useful in sizing storage



Future Directions

- Alternative penalty mechanisms that support system flexibility
- Network aspects of wind integration
- Aggregation and profit sharing
- New markets systems: interruptible power contracts