Selling Random Energy

Kameshwar Poolla
UC Berkeley

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Co-conspirators

- Eilyan Bitar [Berkeley]
- Ram Rajagopal [Stanford]
- Pramod Khargonekar [Florida]
- Pravin Varaiya [Berkeley]

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Outline

1 Introduction

2 Problem Formulation

3 Analytical Results

4 Empirical Studies

5 Future Directions
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 ≈ 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

\[ w(t), \text{wind} \]
\[ C(t), \text{contract} \]

**forward market**
\( (t = -24 \text{ hrs}) \)

**power**
\( (t = 0) \)

**delivery interval**

**deviation penalty:** \( q \)

\( w(t), \text{wind} \)
\( C(t), \text{contract} \)

**ex-ante:** single forward market
**ex-post:** penalty for contract deviations

Remarks:
- Offered contracts are piecewise constant on 1 hr blocks
- No energy storage \( \Rightarrow \) no price arbitrage opportunities \( \Rightarrow \) contract sizing decouples between intervals
Simple Pricing Model

Prices ($ per MW-hour)

\[ p = \text{ex-ante clearing price in forward market} \]
\[ q = \text{ex-post shortfall penalty price} \]

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

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

\[
\Sigma_-(C, w) = \int_{t_0}^{t_f} [C - w(t)]^+ \, dt
\]

\[
\Sigma_+(C, w) = \int_{t_0}^{t_f} [w(t) - C]^+ \, dt
\]

These are random variables
So we’re interested in their expected values
Many variants
ex: sell spilled wind in AS markets, penalty for overproduction
Taking expectation with respect to $w$,\[ J(C) = \mathbb{E} \Pi(C, w) \]
\[ S_-(C) = \mathbb{E} \Sigma_-(C, w) \]
\[ S_+(C) = \mathbb{E} \Sigma_+(C, w) \]

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)
  - 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 et 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
**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*

\[ C^* = F^{-1}(\gamma) \quad \text{where} \quad \gamma = p/q \]
**Theorem**

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

\[
J(C^*) = J^* = qT \int_0^\gamma F^{-1}(w)dw
\]

\[
S_-(C^*) = S_- = T \int_0^\gamma [C^* - F^{-1}(w)] dw
\]

\[
S_+(C^*) = S_+ = T \int_\gamma^1 [F^{-1}(w) - C^*] dw
\]
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 $\approx 0$
- optimal expected profit $\approx 0$
- sell no wind – too much financial risk for deviation

Small penalty $q$, price/penalty ratio $\gamma \approx 1$
- offered optimal contract $\approx 1 = \text{nameplate}$
- optimal expected profit $= pT\mathbb{E}[W]$
- sell all wind – no financial risk for deviation

Price/penalty ratio $\gamma$ controls prob of meeting contract, curtailment, variability taken

Result is simple application of Newsboy problem
The Role of Information

\[ F(w) = \gamma = 0.5 \]

\[ A_1, A_2, C^* \]

ex: 24 hour ahead forecast
The Role of Information

![Graph showing the role of information with areas A1, A2, A3, and C* labeled. The graph illustrates a function F(w) with w (MW generation/capacity) on the x-axis and F(w) on the y-axis, with γ = 0.5.]

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 \( \sigma \)

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**

<table>
<thead>
<tr>
<th>$\epsilon$</th>
<th>risk level (LOLP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>contract offered by WPP</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>deficit at time $t = [C - w]^+$</td>
</tr>
<tr>
<td>$R(C, \epsilon)$</td>
<td>reserve margin</td>
</tr>
</tbody>
</table>

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

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** $\phi(\Delta, R)$

![Diagram showing deviation penalty function $\phi(\Delta, R)$ with $\Delta$ on the x-axis and $\phi(\Delta, R)$ on the y-axis.](image-url)
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

\[ C_R^* = F^{-1}(\gamma_R) \quad \text{where} \quad \gamma_R = (p - q_c)/q_e \]
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

$$J_L(C) = \mathbb{E} \int_{t_0}^{t_f} \left( prC - \phi(C - w(t), L) \right) dt$$

- Profit
- Imbalance energy payment
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

$$\left. \frac{dJ^*}{dL} \right|_{L=0} = \left( 1 - \frac{q_L}{q} \right) p T$$
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:
\[ 0 \leq e(t) \leq \bar{e} \]
\[ 0 \leq P_{\text{in}}(t) \leq \bar{P}_{\text{in}} \]
\[ 0 \leq P_{\text{ext}}(t) \leq \bar{P}_{\text{ext}} \]

Dynamics and constraints are linear
Consider storage system [small capacity $\epsilon$, not lossy]

$w(t)$

$\xi$: # of events where $w(t)$ crosses $C$ from above

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

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

- \( w(t), \text{wind} \)
- \( C(t), \text{contract} \)

\[
\begin{align*}
C_1 & \geq C_2 & \geq C_3 & \cdots & \geq C_N \\
\gamma_1 & \geq \gamma_2 & \geq \gamma_3 & \cdots & \geq \gamma_N \\
p_1 & \geq p_2 & \geq p_3 & \cdots & \geq p_N
\end{align*}
\]

- **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

![Graph showing wind power data over time][1]
Empirical Wind Power Model

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

Empirical CDFs for nine different hours

$\hat{F}_N(w, t)$
Optimal Forward Contracts

- Optimal contracts for $\gamma = [0.3 : 0.9]$
- Consistent with typical wind pattern
- Bigger penalty $\Rightarrow$ smaller contract
Optimal expected profit $J^*$ as a function of $\gamma$

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

Units: $$/ (q \cdot \text{nameplate capacity})$
Marginal Value of Storage - Empirical

Useful in sizing storage

17-20 MW-Hours/day per 1 MW hour of 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