Price Responsive Demand for Operating Reserves in Co-Optimized Electricity Markets with Wind Power

Zhi Zhou, Audun Botterud

Decision and Information Sciences Division
Argonne National Laboratory
zzhou@anl.gov, abotterud@anl.gov

Federal Energy Regulatory Commission, Washington DC, June 25 2013
Outline

- Background and Motivation
  - Scarcity pricing in electricity markets
  - Wind power uncertainty in market operations

- Analytical approach
  - Wind power forecast uncertainty
  - Demand curve for operating reserves
  - Market operations: commitment and dispatch

- Case study of IL power system
  - Assumptions
  - Costs, prices, revenue

- Concluding Remarks
Prices and Investments in the Electricity Market

In a perfect market:
- Scarcity rent covers investment costs for the optimal mix of new generation
- Investments should come in time to meet demand

Potential problems for adequate generation investments:
- Limited demand response, price caps and poor scarcity pricing ("missing money"), high investment risks difficult to hedge, market power

How does a large-scale wind power expansion influence investments?
- Resource variability and ramping, forecast uncertainty, low marginal costs

Source: Botterud 2003
Electricity Prices in MISO node 2006 and 2012

- Historical day-ahead prices for ALTW.FOXLK1 node in Lakefield, MN

<table>
<thead>
<tr>
<th>Price</th>
<th>2006</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average [$/MWh]</td>
<td>46.1</td>
<td>21.3</td>
</tr>
<tr>
<td>Rel. St.Dev. [%]</td>
<td>64.0</td>
<td>92.3</td>
</tr>
</tbody>
</table>

Wind power increases the need for adequate scarcity pricing
A demand curve for operating reserves can address forecast uncertainty in short-term operations and improved scarcity pricing for long-term resource adequacy.
Outline

- Background and Motivation
  - Scarcity pricing in electricity markets
  - Wind power uncertainty in market operations

- Analytical approach
  - Wind power forecast uncertainty
  - Demand curve for operating reserves
  - Market operations: commitment and dispatch

- Case study of IL power system
  - Assumptions
  - Costs, prices, revenue

- Concluding Remarks
Probabilistic Forecasting - Kernel Density Estimation

- Conditional wind power probabilistic forecasting

\[ f_P(p_{t+k} \mid X = x_{t+k|t}) = \frac{f_{P,X}(p_{t+k}, x_{t+k|t})}{f_X(x_{t+k|t})} \]

- Joint or multivariate density function of \( p \) and \( x \)

- Marginal density of \( x \)

- Kernel density estimation (KDE)
  - Advantages
    - Forecasts the full probability density function
    - Nonparametric
  - Example

\[ \hat{f}_X(x) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{h_i} \cdot K \left( \frac{x - X_i}{h} \right) \]

\[ K(x) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{\sqrt{2\pi}} \cdot e^{-\frac{(x-X_i)^2}{2\cdot h^2}} \]
Probabilistic Forecasting - Quantile-Copula Estimator

**Copula Definition**

\[ F_{XY}(x, y) = C(F_X(x), F_Y(y)) \]

A multivariate distribution function separated in:

- marginal functions
- dependency structure between the marginals modeled by a copula

**Copula Density Function**

\[ f(x, y) = \frac{\partial^2}{\partial u \cdot \partial v} \cdot C(u, v) = f_X(x) \cdot f_Y(y) \cdot c(u, v) \]

**KDE Estimator**

\[ \hat{f}(y|X = x) = \frac{f_X(x) \cdot f_Y(y) \cdot c(u,v)}{f_X(x)} = f_Y(y) \cdot c(u,v) \]

\[ \hat{f}_Y(y) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{h_i} \cdot K \left( \frac{y - Y_i}{h_y} \right) \]

\[ \hat{f}(y|X = x) = \frac{1}{N \cdot h_y} \cdot \sum_{i=1}^{N} K_y \left( \frac{y - Y_i}{h_y} \right) \cdot \frac{1}{N} \cdot \sum_{i=1}^{N} K_u \left( \frac{F_X^e(u) - F_X^e(U_i)}{h_u} \right) \cdot K_v \left( \frac{F_X^e(v) - F_X^e(V_i)}{h_v} \right) \]

**Empirical Cumulative Distribution**

\[ U_i = F_X^e(X_i) \text{ and } V_i = F_Y^e(Y_i) \]

\[ F^E(t) = \frac{1}{N} \cdot \sum_{i=1}^{N} I(x_i \leq t) \]

[Bessa et al. 2012]
Demand Curve for Operating Reserves – Overview

- Basic idea
  - Consider the uncertainties from load and supply (thermal and wind)
  - Estimate the risk of supply shortage for system
  - Link the expected cost of this risk to the price to pay for reserves (Hogan, 2005)

- Uncertainty sources:
  - Wind power: probabilistic forecast
  - Load: forecasting error
  - Thermal units: forced outage rates
From Generation Margin to Demand Curve

Generation Margin Distribution

LOLP: Loss of load probability
VOLL: Value of loss load

Price(reserve) = LOLP(reserve, gen.margin) * VOLL
Simulating Electricity Market Operations

DA: Day-ahead
RAC: Reliability Assessment Commitment
RT: Real Time
UC: Unit Commitment
ED: Economic Dispatch

![Diagram of electricity market operations](image-url)
Outline

- Background and Motivation
  - Scarcity pricing in electricity markets
  - Wind power uncertainty in market operations

- Analytical approach
  - Wind power forecast uncertainty
  - Demand curve for operating reserves
  - Market operations: commitment and dispatch

- Case study of IL power system
  - Assumptions
  - Costs, prices, revenue

- Concluding Remarks
Case Study Assumptions

- **210 thermal units: 41,380 MW**
  - Base, intermediate, peak units

- **Peak load: 37,419 MW**
  - 2006 load series from Illinois

- **Wind power: 14,000 MW**
  - 2006 wind series from 15 sites in Illinois (NREL EWITS dataset)
  - 20% of load

- **Simulation periods**
  (1) High load period (July); (2) Low load period (Oct)

- **Curtailment assumptions**
  - Value of Lost Load: $3500/MWh
  - Value of operating reserve shortfall: $1100/MWh
Demand for Operating Reserves is Dynamic

- Demand curve examples
  - Hourly demand curves for the sum of spinning and non-spinning reserves
  - Contributions to reserve demand for two selected hours:
**Average OR Demand in July**

- Total demand for reserves is higher in DA than in RAC and RT.
## Simulated Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Wind power forecast</th>
<th>Operating reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Generator contingency</td>
</tr>
<tr>
<td>PF</td>
<td>Perfect forecast</td>
<td>Perfect</td>
<td>1146 MW</td>
</tr>
<tr>
<td>FR</td>
<td>Fixed reserve</td>
<td>50 % quantile</td>
<td>1146 MW</td>
</tr>
<tr>
<td>DR</td>
<td>Dynamic reserve</td>
<td>50 % quantile</td>
<td>1146 MW</td>
</tr>
<tr>
<td>DC</td>
<td>Demand curve</td>
<td>50 % quantile</td>
<td></td>
</tr>
</tbody>
</table>
The demand curve tends to schedule more operating reserves
Implications for Energy and Reserves Prices

- Price duration curves for day-ahead market, month of July:

- A demand curve for operating reserves
  - Gives higher prices for energy and reserves in most hours, fewer extreme price spikes
  - Stabilizes revenue stream for thermal generators; can alleviate “missing money” problem
  - Better reflects wind power forecast uncertainty in prices
Average Daily Operating Reserves Prices

July DA Average Daily Energy Prices

July DA Average Daily Reserve Prices

Oct DA Average Daily Energy Prices

Oct DA Average Daily Reserve Prices
A demand curve for operating reserves stabilizes the revenue stream
### Overview of Total Operating Cost

- **High load period (July)**

<table>
<thead>
<tr>
<th>RT-Cost (M$)</th>
<th>PF</th>
<th>FR</th>
<th>DR</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>198.74</td>
<td>212.91</td>
<td>209.02</td>
<td>215.07</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>189.39</td>
<td>202.08</td>
<td>199.58</td>
<td>207.03</td>
</tr>
<tr>
<td><strong>Startup</strong></td>
<td>9.33</td>
<td>9.67</td>
<td>8.93</td>
<td>8.04</td>
</tr>
<tr>
<td><strong>Curtailment</strong></td>
<td>0.02</td>
<td>1.16</td>
<td>0.51</td>
<td>NA</td>
</tr>
</tbody>
</table>

- **Low load period (October)**

<table>
<thead>
<tr>
<th>RT-Cost (M$)</th>
<th>PF</th>
<th>FR</th>
<th>DR</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>96.46</td>
<td>117.68</td>
<td>115.71</td>
<td>110.67</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>89.63</td>
<td>106.31</td>
<td>107.93</td>
<td>102.30</td>
</tr>
<tr>
<td><strong>Startup</strong></td>
<td>6.83</td>
<td>8.57</td>
<td>7.58</td>
<td>8.37</td>
</tr>
<tr>
<td><strong>Curtailment</strong></td>
<td>0.00</td>
<td>2.80</td>
<td>0.20</td>
<td>NA</td>
</tr>
</tbody>
</table>
Outline

- Background and Motivation
  - Scarcity pricing in electricity markets
  - Wind power uncertainty in market operations

- Analytical approach
  - Wind power forecast uncertainty
  - Demand curve for operating reserves
  - Market operations: commitment and dispatch

- Case study of IL power system
  - Assumptions
  - Costs, prices, revenue

- Concluding Remarks
Conclusion and Future Work

- **A demand curve for operating reserves**
  - Provides prices that better reflect the marginal reliability of the system as a function of the reserve level, accounting for multiple uncertainties (load, outages, wind).
  - Contributes towards more efficient market operations through improved price signals for short-term operation and maintenance, and long-term system expansion.
  - Is a solution that is compatible with current market designs.
  - Tends to schedule more reserves than price-inelastic reserve requirements in case study.

- **Future work**
  - Introduce transmission network / locational operating reserve demand curves.
  - Reserve provision from wind power and demand.
  - Supply curves from ancillary service providers.
References and Acknowledgements

- References for more information

- Acknowledgements
  - INESC Porto for collaboration on probabilistic wind power forecasting.
  - DOE’s wind program for sponsoring this research.

Price Responsive Demand for Operating Reserves in Co-Optimized Electricity Markets with Wind Power

Zhi Zhou, Audun Botterud

Decision and Information Sciences Division
Argonne National Laboratory
zzhou@anl.gov, abotterud@anl.gov

Federal Energy Regulatory Commission, Washington DC, June 25 2013