Statistical Analysis of the Effects of Geographic Diversity on Wind Plant Integration

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Outline

• Motivation
• Geographic Diversity
• Methodology
• Case Studies
• Conclusions
Motivation

• Wind generation in US: >25,000 MW
• Research interest increases: 3450 articles in IEEE Xplore database as of Sept. 2009
• Federal Production Tax Credit (PTC) renewed
• State Renewable Portfolio Standards (RPS)
  ▪ 30 states
  ▪ WA: 15% by 2020
Motivation

• What are the operational consequences of high levels of wind power penetration?
• Must understand the wind resource as characterized by
  - **Uncertainty**: inability to perfectly forecast weather
  - **Variability**: changing of the wind resource across operational time scales
Motivation

• Uncertainty and variability are influenced by
  ▪ Penetration level
  ▪ Geographic diversity
  ▪ Transmission constraints
Geographic Diversity

• Types of geographic diversity
  ▪ Spatial
  ▪ Topographical
Geographic Diversity

• Wind plants in close proximity in homogeneous terrain likely exhibit strong correlation in their power output
Geographic Diversity

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Geographic Diversity

- As distance increases, the linear correlation between the power output decreases.
Geographic Diversity

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Geographic Diversity

Increasing Operational Timescale

Geographic Diversity

• Terrain influences geographic diversity

• Examples
  - Shore lines: sea breezes caused by land/water temperature differentials
  - Mountain valleys or gorges: flow channeling
  - Mountain tops/down slope: mountain wave events (Chinook winds)
Geographic Diversity

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Wind Resources in the U.S.
Geographic Diversity: Theoretical Basis

- Consider wind plant \( n \) in an \( N \)-wind plant system
- Normalized power output of wind plant \( \tilde{P}_n \)

\[ \tilde{P}_n = g_n \tilde{v}_n \]

- \( \tilde{v}_n \): representative wind speed at the wind plant
- \( g_n \): wind plant power curve
Geographic Diversity: Theoretical Basis

- Example distribution
  - 1 year hourly (8760)
  - GE 1.5 XLS wind turbine
- Contains information on uncertainty
Geographic Diversity: Theoretical Basis

• Case of no geographic diversity
• If we have identical $N$ wind plants with the assumption $\tilde{\nu}_1 = \cdots = \tilde{\nu}_n = \cdots = \tilde{\nu}_N$
• Histogram remains the same (after normalization)
Geographic Diversity: Theoretical Basis

• Now assume that the wind speeds at each plant are independent random variables for each hour.
• How does the histogram change as the number of independent wind plants are added?
Geographic Diversity

\[ N = 10 \]
Geographic Diversity: Theoretical Basis

- Since $\tilde{\nu}_n$ are independent, $\tilde{P}_n$ will also be independent.
- Aggregate power distribution $\tilde{P}_{agg}$ is found from:

$$f(\tilde{P}_{agg}) = f\left(\frac{\tilde{P}_1}{N}\right) \ast \ldots \ast f\left(\frac{\tilde{P}_n}{N}\right) \ast \ldots \ast f\left(\frac{\tilde{P}_N}{N}\right)$$
Geographic Diversity: Theoretical Basis

- Central Limit Theorem applies
  - As $N \Rightarrow \infty$
    
    $$f(\bar{x}) \approx \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\bar{x} - \mu)^2}{2\sigma^2}}$$

- Variance changes as
  
  $$\sigma_{agg}^2 = \frac{1}{N^2} \sum_{n=1}^{N} \sigma_n^2$$
Geographic Diversity: Theoretical Basis

![Diagram showing power (MW) over time (hr) with labels for regulation: seconds-minutes and load-following: minutes-hours.]

- **Power (MW)**
- **Time (hr)**
- **scheduling: day**
- **regulation: seconds-minutes**
- **load-following: minutes-hours**

- Power (MW)
- Time (hr)
- Scheduling: day
- Regulation: seconds-minutes
- Load-following: minutes-hours
Geographic Diversity: Theoretical Basis

- Variations

\[ \Delta \tilde{P}_{agg}[h] = \tilde{P}_{agg}[h + k] - \tilde{P}_{agg}[h] \]

- \( \Delta \tilde{P}_{agg} \): variation
- \( \tilde{P}_{agg} \): power output at hour \( h \)
- \( k \): variation period
Geographic Diversity: Theoretical Basis

• Consider 1-hour variation period
• Empirical histogram contains information on variability
• Influence of independence of wind speeds has an analogous influence on distribution of variability
Methodology

- Parametric evaluation:
  - Examine statistical moments
- Non-parametric evaluation:
  - Compare PDFs (empirical histograms) to known distributions
Methodology: Uncertainty

- Observations
  - Bounded between 0 and 1
  - Diverse shapes as $N$ increases
  - Asymmetric for most levels of geographic diversity
Methodology: Uncertainty

- Beta Distribution:

\[ f(\tilde{x}) = \frac{\tilde{x}^{\alpha-1} \times (1 - \tilde{x})^{\beta-1}}{B(\alpha, \beta)} \]

\[ B(\alpha, \beta) = \int_0^1 \tilde{x}^{\alpha-1} \times (1 - \tilde{x})^{\beta-1} \, d\tilde{x} \]

\[ \alpha: 0.5 \]
\[ \beta: 2 \]
Methodology: Uncertainty

• Qualitative interpretation of parameters:
  ▪ $\alpha < 1$ increasing density toward 0
  ▪ $\alpha > 1$ decreasing density toward 0
  ▪ $\beta < 1$ increasing density toward 1
  ▪ $\beta > 1$ decreasing density toward 1

• Convenient calculation of capacity factor

$$\mu_{agg} = \frac{\alpha}{\alpha + \beta}$$
Methodology: Uncertainty

\[ N = 1 \]

\[ \alpha: 0.27 \]
\[ \beta: 0.46 \]
\[ \sigma^2_{agg}: 0.13 \]
Methodology: Uncertainty

\[ N = 10 \]

\[ \alpha: 5.38 \]

\[ \beta: 10.75 \]

\[ \sigma^2_{agg}: 0.013 \]
Methodology: Variability

- Laplace (double exponential) distribution:
  \[ f(\tilde{x}) = \frac{1}{2b} e^{-\frac{|\tilde{x}-a|}{b}} \]

- Statistical moments of observation interpretation
  - Variance: spread of values
  - Skewness (\(\gamma_1\)): asymmetry
    - Positive: large increases in power
    - Negative: large decreases in power
  - Kurtosis (\(\gamma_2\)): peakedness, thickness of tails
    - >3, leptokurtic—greater peak, thicker tails than Normal distribution
Methodology: Variability

- Variance: 0.0128
- Skewness ($\gamma_1$): -0.112
- Kurtosis ($\gamma_2$): 5.64
Case Studies

- How does the statistical signatures of uncertainty and variability change with penetration?
- How would long-distance transmission affect the uncertainty and variability?
Case Studies: Approach

• Consider two distant systems with rapid capacity additions over a two year period
• Perform year-to-year comparisons
• Consider a hypothetical connection between the two systems
Case Studies: Data Considerations

• Published data from:
  ▪ Bonneville Power Administration (BPA)
  ▪ Electric Reliability Council of Texas (ERCOT)

• Data Range:
  ▪ January 1, 2007 to December 31, 2008*
  ▪ Hourly granularity

• Limitations of data
  ▪ Curtailment not reported
  ▪ Transmission constraints
  ▪ Wind turbine outages
  ▪ Losses
Case Study: BPA

- Capacity increased by 220 percent
  - 722 MW to 1599 MW
- 15 wind plants
Case Study: BPA

- Year-to-year comparison of uncertainty
- Similar distributions
- Variance increased in 2008

\[ \alpha: 0.47 \]
\[ \beta: 1.13 \]
\[ \sigma^2_{agg}: 0.084 \]

BPA 2007

\[ \alpha: 0.51 \]
\[ \beta: 1.09 \]
\[ \sigma^2_{agg}: 0.088 \]

BPA 2008
Case Study: BPA

- Year-to-year comparison of variations
- 1-hour variation period
Case Study: BPA

• Statistical moments of the 1-hour variations

<table>
<thead>
<tr>
<th>Case</th>
<th>$\mu_{agg}$</th>
<th>$\sigma^2_{agg}$</th>
<th>$\gamma_{1,agg}$</th>
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• Skewness ($\gamma_1$):
  ▪ Positive in 2007, 2008
  ▪ Increased in 2008

• Kurtosis ($\gamma_2$):
  ▪ Leptokurtic in 2007, 2008
  ▪ Increase in 2008
BPA Balancing Authority Load & Total Wind Generation, Last 7 days
12Nov2008 - 19Nov2008 (last updated 18Nov2008 08:51:30)

Based on 5-min readings from the BPA SCADA system for points 45583, 79687
Balancing Authority Load in Red, Wind Generation in Blue; Installed Wind Capacity=1489 MW
BPA Technical Operations: Roy Ellis (rcellis@bpa.gov)
Case Study: ERCOT

- Capacity increased by 290 percent
  - 2790 MW to 8111 MW
- Approx. 50 wind plants
Case Study: ERCOT

- Year-to-year comparison
- Similar distributions
- Variance unchanged

\( \alpha: 0.81 \)
\( \beta: 2.42 \)
\( \sigma^2_{agg}: 0.043 \)

\( \alpha: 0.96 \)
\( \beta: 2.38 \)
\( \sigma^2_{agg}: 0.043 \)
Case Study: ERCOT

- Year-to-year comparison of variations
- 1-hour variation period
Case Study: ERCOT

- Statistical moments of the 1-hour variations

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- Skewness ($\gamma_1$):
  - Positive in 2007, 2008
  - Increased in 2008

- Kurtosis ($\gamma_2$):
  - Decrease in 2008
Case Study: Interconnected System

- Hypothetical connection of BPA and ERCOT during the data sets
- Approximately: 2500 km of transmission
Case Study: Interconnected System

- Significantly different from BPA or ERCOT

**Interconnected 2007**

\[ \alpha: 1.20 \]
\[ \beta: 3.36 \]
\[ \sigma^2_{agg}: 0.084 \]

**Interconnected 2008**

\[ \alpha: 1.40 \]
\[ \beta: 3.21 \]
\[ \sigma^2_{agg}: 0.088 \]
ERCOT 2007

\[ \alpha: 0.81 \]
\[ \beta: 2.42 \]
\[ \sigma^2_{agg}: 0.043 \]

Interconnected 2007

\[ \alpha: 1.20 \]
\[ \beta: 3.36 \]
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BPA 2007

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Case Study: Interconnected System

- Year-to-year comparison
## Summary of Variations

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<tr>
<td>Interconnected 2007</td>
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<td>0.0019</td>
<td>0.137</td>
<td>6.10</td>
</tr>
<tr>
<td>Interconnected 2008</td>
<td>0.0000064</td>
<td>0.0021</td>
<td>0.207</td>
<td>5.62</td>
</tr>
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Case Study: Interconnected System

- Check correlation (linear)
Conclusions

• Recent, substantive increases in wind capacity (penetration) in BPA and ERCOT did NOT significantly alter the statistical characteristics of uncertainty and variability

• Aggregate power of ERCOT wind plants have favorable characteristics when compared with BPA

• Interconnection had noticeable affect on uncertainty and variability

• Correlation likely caused by solar influences exist even in distant systems
Related Research

• Extending analysis to Midwest ISO and year 2009 data sets
• Goodness-of-fit analysis
• Variations across longer time scales
• Diurnal pattern analysis
• Benefits of geographic diversity
Questions?