Wind Power Forecasting and Electricity Market Operations

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32\textsuperscript{nd} IAEE Int. Conf., June 22\textsuperscript{th} 2009, San Francisco, CA, USA
Outline

- Wind power in the United States
- Wind Power Forecasting
- Electricity Market Operations with Wind Power
- Concluding Remarks
Introduction: Wind Penetration in Selected Countries

U.S. recently became the world leader in wind power with over 8 GW installed in 2008 and 25 GW total installed capacity (AWEA, Feb 09)

Source: Berkeley Lab estimates based on data from BTM Consult and elsewhere
Wind Penetration in US States (Capacity and Generation)

% Generation by State

Source: AWEA 2009
US Wind Power Capacity is Growing Quickly

Source: AWEA 2009
U.S. DOE’s 20% Wind Energy by 2030 Report

- Explores “a modeled energy scenario in which wind provides 20% of U.S. electricity by 2030”

- Describes opportunities and challenges in several areas
  - Turbine Technology
  - Manufacturing, materials, and jobs
  - Transmission and integration
  - Siting and environmental effects
  - Markets

- Enhanced wind forecasting and better integration into system operation is one of the key challenges
  - This is also emphasized by NERC in a recent report (NERC, 2009)
Argonne Project: “Development and Deployment of an Advanced Wind Forecasting Technique”

Goal: To contribute to efficient large-scale integration of wind power by developing improved wind forecasting methods and better integration of advanced wind power forecasts into system and plant operations.

Collaborators: INESC Porto – Institute for Systems and Computer Engineering of Porto, Portugal
Vladimiro Miranda, Cláudio Monteiro, Ricardo Bessa

Industry Partners: Midwest ISO (MISO) and Horizon Wind Energy

Argonne Team: Audun Botterud, Jianhui Wang, Guenter Conzelmann

Sponsor: DOE-EERE (Wind and Hydropower Technologies Program)

The project consists of two main parts:
- Wind power forecasting
  - Review and assess existing methodologies
  - Develop and test new and improved algorithms

- Integration of forecasts into operations (power system and power plants)
  - Review and assess current practices
  - Propose and test new and improved approaches, methods and criteria
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Wind Forecasts are the Result of Combination of Models and Diverse Set of Input Data

NWP Output Data → Weather Data → Off-site Met Data → Site Power Gen & Met Data

Physical Models

Statistical Models

Forecast Results
Wind Power Forecasts: How Good are They?

Eyeballing: Looks pretty good

Mean absolute error is 9.3%

But devil is in the details (ramps)

Source: Iberdrola Renewables, 2009
Several Sources of Forecast Errors

- Error depends on several factors
  - Prediction horizon
  - Time of the year
  - Terrain complexity
  - Model inputs and model types
  - Spatial smoothing effect
  - Level of predicted power

Error sources:

- Error in meteorological forecasts
- Errors in wind-to-power conversion process
- Errors in SCADA information (wind power and met data)

What are the consequences for economics and security?
### Uncertainty in Wind Power Forecasts

#### Uncertainty Representation

<table>
<thead>
<tr>
<th>Probabilistic</th>
<th>Quantiles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interval Forecasts</td>
</tr>
<tr>
<td></td>
<td>Probability Mass Function</td>
</tr>
<tr>
<td></td>
<td>Probability Density Function</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk Indices</th>
<th>Meteo Risk Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prediction Risk Index</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenarios of Generation</th>
<th>Scenarios with temporal dependency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenarios with spatial/temporal dependency</td>
</tr>
</tbody>
</table>

#### Interval forecast

#### Scenarios
Outline

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# Wind Power and Market Operation in selected US Markets

<table>
<thead>
<tr>
<th></th>
<th>MISO</th>
<th>NYISO</th>
<th>PJM</th>
<th>ERCOT</th>
<th>CAISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Cap. [MW]</td>
<td>4,000</td>
<td>1275</td>
<td>2050</td>
<td>8000</td>
<td>2500</td>
</tr>
<tr>
<td>Peak load [MW]</td>
<td>109,157 (7/31-06)</td>
<td>33,939 (8/2-06)</td>
<td>144,644 (8/2-06)</td>
<td>62,339 (8/17-06)</td>
<td>50,270 (7/24-06)</td>
</tr>
<tr>
<td>Centralized unit commit.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Congestion management</td>
<td>LMP</td>
<td>LMP</td>
<td>LMP</td>
<td>Zonal</td>
<td>LMP</td>
</tr>
<tr>
<td>Co-opt. of energy and reserves</td>
<td>Yes (DA and RT)</td>
<td>Yes (DA and RT)</td>
<td>Yes, but limited</td>
<td>No</td>
<td>Yes (DA and RT)</td>
</tr>
<tr>
<td>Dispatch frequency</td>
<td>5 min</td>
<td>5 min</td>
<td>5 min</td>
<td>15 min</td>
<td>5 min</td>
</tr>
<tr>
<td>Wind power forecasting</td>
<td>Yes</td>
<td>Yes</td>
<td>Being introduced</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
**Typical Market Operations Timeline (based on MISO)**

**Day ahead:**
- Prepare and submit DA bids
- Clear DA market using SCUC/SCED
- Post-DA RAC using SCUC
- Post results (DA energy and reserves)

**Operating day:**
- Prepare and submit RT bids
- Intraday RAC using SCUC
- Clear RT market using SCED (every 5 min)
- Operating hour
- Post results (RT energy and reserves)

**Role for wind forecasting**

**Abbreviations:**
- DA – day ahead
- RT – real time
- SCUC – security constr. unit commitment
- SCED – security constr. economic dispatch
- RAC – reliability ass. commitment
California ISO: Centralized forecasting system as part of “Participating Intermittent Resource Program” (PIRP, introduced in 2003)
  – Participants bid according to forecast in hour-ahead market
  – Net imbalances settled at monthly average price

NYISO: Using forecasts for system operations since June 2008
  – Integrated into commitment and dispatch routines
  – Upcoming: Mandatory real-time bidding by wind power; must follow dispatch instructions

ERCOT: Centralized forecasting system introduced ahead of schedule in 2008, after critical wind power event
  – Day-ahead resource planning (20 percentile)
  – Wind power capacity and forecast error considered in calculation of reserve requirements (regulation and non-spinning)

Midwest ISO: Centralized forecasting system introduced in 2008
  – Transmission outages coordination, peak load analysis, ramping analysis
  – Being introduced in reliability assessment and unit commitment
Deterministic vs. Stochastic Approach to Operation and Reliability

- How to deal with increased uncertainty in system operation?
  - Load uncertainty, generator outages, and wind uncertainty

- Reserve requirements and deterministic unit commitment
  - Traditional approach used in industry
  - Reserve requirements based on minimum reliability level (NERC)
  - Deterministic optimization problem with reliability constraints
  - Solution may deviate from economic optimum
  - Need to revisit current reliability criteria

- Stochastic unit commitment
  - Explicit representation of uncertainty in problem formulation
  - Minimization of expected costs
  - Requires consistent and robust representation of uncertainty
  - May become computationally too intensive
  - Increasing relevance due to additional uncertainty from wind power
Stochastic Unit Commitment to Address Wind Power Uncertainty

- Simple formulation using wind power forecast scenarios ($s$) w/probabilities ($prob_s$):

$$\text{Min} \sum_{s=1}^{S} \text{prob}_s \times \left\{ \sum_{k=1}^{K} \sum_{j=1}^{J} c^p_j(k) + \sum_{k=1}^{K} C_{ens} \times \text{ens}_s(k) \right\} + \sum_{k=1}^{K} \sum_{j=1}^{J} [c^w_j(k) + c^d_j(k)]$$

$$\sum_{i=1}^{I} p_{w_i}^s(k) + \sum_{j=1}^{J} p_{t_j}^s(k) = D(k) - \text{ens}_s(k) \quad \forall k, \forall s$$

$$\sum_{j=1}^{J} [p_{t_j}^s(k) - p_{t_j}^s(k)] \geq R(k) \quad \forall k, \forall s$$

$$p_{w_i}^s(k) + c_{w_i}^s(k) = PW_{w_i}^{f,s}(k) \quad \forall i, \forall s, \forall k$$

$$p_{t_j}^s(k) \in \pi_j^s(k) \quad \forall j, \forall k, \forall s$$

- Objective function (min cost)

- Energy balance

- Reserve requirements

- Wind generation

- Unit commitment constraints

- Promising results from Europe and US (e.g. Tuohy et al. 2009, Ruiz et al. 2009)

- How does a stochastic formulation change the operating reserve requirements?
MISO Wind Power and Minnesota Hub Prices, May 11-17, 2009

Wind power ramping events

Negative LMPs

Day Ahead price
Real Time price
Wind power
Wind Power Plants are Gradually Becoming More “Dispatchable”

- From individual wind turbines to wind plants

- Future wind plants are expected to incorporate measures into the design to allow them to appear as similar to a conventional plant as possible (GE 2008)
  - Reactive power contribution
  - Voltage regulation
  - Disturbance ride-through
  - Grid frequency response
  - Smoothing wind ramps
  - Controlled start-up/shut-down

- These developments will ease the integration into the power system and give the wind power producer more flexibility in market participation (energy and ancillary services)

- Availability of economical storage technology would make wind plants completely dispatchable: the cost of storage must be weighed against benefits
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Key Challenges for Wind Power Forecasting and Market Operation

- Improved wind power forecasting models
  - Forecasting ramping events
  - Generating wind power uncertainty forecasts
  - Data quality and availability (weather and plant availability data)
  - Frequency of forecasts (NWP models)

- Improved use of wind power forecasting into market operation
  - Integrate the wind power forecast into operating procedures and tools (reserve requirements, unit commitment and dispatch models)
  - Make efficient use of uncertainty information in wind power forecast in system operations
  - Market incentives for wind power: Wind power bidding, dispatch, curtailment, control (energy and ancillary services)
  - Wind power’s influence on market prices: Impact on overall incentives for operations and investment
Wind Power Forecasting: State of the Art 2009 (Report)

- Project report

- Contents
  - Introduction
  - Numerical weather prediction
  - Definition of the WPF problem
  - Literature Review
    - Incl. overview of existing forecasting models (Europe and US)
  - Uncertainty in WPF
  - Requirements and pre-requisites for WPF implementation
  - Wind power forecasting in power system operations
    - Includes overview of 5 US markets
  - Unit commitment with wind power uncertainty
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32nd IAEE Int. Conf., June 22th 2009, San Francisco, CA, USA
Geographical Footprint of Midwest ISO (MISO)

http://www.midwestiso.org/
Current Installed Wind Power Capacity (April 30th 2009)

United States - Current Installed Wind Power Capacity (MW)

Total: 28,635 MW
(As of 4/30/09)

Data from the Global Energy Concepts (DNV-GE) database.

Wind Power Capacity
Megawatts (MW)
1,000 - 8,300
100 - 1,000
20 - 100
1 - 20

U.S. Department of Energy
National Renewable Energy Laboratory

19-MAY-2009 1.1.23
Wind Resource Map for the United States

This map shows the annual average wind power estimates at a height of 50 meters. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
<td></td>
</tr>
<tr>
<td>4 Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
<td></td>
</tr>
<tr>
<td>5 Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.8 - 17.9</td>
<td></td>
</tr>
<tr>
<td>6 Outstanding</td>
<td>600 - 800</td>
<td>8.0 - 8.8</td>
<td>17.9 - 19.7</td>
<td></td>
</tr>
<tr>
<td>7 Superb</td>
<td>800 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.8</td>
<td></td>
</tr>
</tbody>
</table>

*Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory
MISO Wind Power and Cinergy (IN) Hub Prices, 5/11-5/17 2009
Different Forecasting Approaches are Used to Generate Wind Power Projections for Minutes up to Several Days Ahead

- **Physical models**
  - Numerical weather prediction (NWP) models simulate the evolution of the atmosphere over a 3D volume
  - Downscaled regional models with finer resolution
  - Power curve models for relationship between wind speed and power output

- **Statistical models**
  - Use empirical equations based on historical information on weather and wind production
  - Many different statistical approaches (regression, neural networks, fuzzy systems, etc.)

- **Forecast ensembles**
  - Use multiple model runs/approaches to develop composite forecast and estimate uncertainty
Example: The Danish Horns Rev Wind Farm is Providing Regulation (Frequency Response) and Balancing Response