Analysis of the Reduced Wake Effect for Available Wind Power Calculation During Curtailment Including Validation Experiments
Outline of the Presentation

• Rationale
• Algorithm
• Experiments
• Validation results
• Conclusions

• Recommendations
• Questions
Rationale

• Grid balance

• Financial opportunity
Algorithm

![Diagram of Algorithm]

Wake – Curtailment Model

Wind conditions

- Normal $V_i$
- Curtailed $V_{ci}$

Power Curve

- $P_i$
- $P_{ci}$

Reduced Wake Effect

- $P_{RWEi}$

Available Power
- $P_{ci}$
- $APE_i$

Produced Power
- $P_i$

Reduced Wake Effect
- $APE_i$

Available Power $P_{AWF}$
Wake – Curtailment Model

\[ V_0 \times \text{Thrust Curve} \]

\[ c_i \rightarrow \text{Curtailment Model} \]

\[ T_{I_i} \rightarrow \text{Wake Model} \]

\[ d_{c_i,1} \rightarrow \text{Wake Mixing} \]

\[ u_i \rightarrow d_{c_i} \]

\[ d_{c_i+1} = \begin{cases} d_{c_i,1} & \text{for } i = 1 \\ 1 & \text{for } i = 2 \text{ to } i = N - 1 \end{cases} \]
Uncertainties

• Using the wake models
  – instantaneously
  – during curtailment
• Using power curve instantaneously
• The turbulence model
Curtailment Experiments

Wind farm Westermeerwind, The Netherlands

© 2016 GeoBasis-DE/BK (© 2009), Google
Curtailment Experiments

- **Turbine**
  - Siemens Wind Power
  - 3 MW
  - 108m diameter

- **Experiments**
  - Curtailing turbine #1 only
  - Wind direction along turbines
  - Different curtailment levels
Curtailment Experiments

\[ t_{\text{delay}} = \frac{\Delta x}{\frac{1}{2}(u_i(1 - 2a_i) + u_{i+1})} \]

Curtailment Experiments
Validation Results

[4] Larsen GC 2009 A simple stationary semi-analytical wake model *Riso National Laboratory for Sustainable Energy, Technical University of Denmark 1713*
Validation Results

![Validation Results Diagram](image_url)

- APE sum
- Measured
- Jensen
- Larsen

Average Available Power [kW]

<table>
<thead>
<tr>
<th>Experiment [#]</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APE sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jensen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larsen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Validation Results

![Validation Results Diagram](image-url)

- APE sum
- Jensen
- Larsen

Experiment [#]:
- 3
- 4
- 5
- 6
- 7
Conclusion

• Research boundaries
  – Straight row of turbines with aligned wind
  – Only sub-rated wind conditions
  – Only Jensen and Larsen wake models

• When curtailing #1
  – RWE #2 is 45% to 80%
  – RWE #3 is -5% to -40%
  – RWE #4+ is negligible
Conclusion

• Wake models fit measurements well
• Error reduction for #2
  – Gross 60% to 100%
  – Algorithm Larsen 10-40%
  – Algorithm Jensen 1% to 20%
• For whole row
  – Improvement less significant
Recommendations

• Other wake models
• Continuous calibration
• Measurements
• Transient Response
Analysis of the Reduced Wake Effect for Available Wind Power Calculation During Curtailment

Including Validation Experiments

M P C Bontekoning ¹  S Sanchez Perez-Moreno ¹
B C Ummels ²  M B Zaaijer ¹

¹ Delft University of Technology  ² Ventolines BV