Benchmarking of Lillgrund offshore wind farm scale wake models

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Outline

• Motivation;
• Participants;
• Wind farm location, layout and challenges;
• Wake models;
• Benchmark flow cases;
• Results;
• Conclusion;
• Acknowledgement.
Motivation

• The wake modeling part of the EERA - DTOC (Design Tool for Offshore wind farm Clusters) project is to improve the fundamental understanding of wind turbine wakes and modeling.

• Many different types of wind farm wake models that have been developed during the last three decades.

• Two benchmark campaigns have been organized on the existing wind farm wake models available within the project.

• First benchmark deals with regular 8 x 10 turbines layout and medium internal spacing (7 – 10 D);

• The present benchmark represents an irregular layout of 8 wind turbines - with small internal spacing (3.3 – 4.3 - 7 D).
Participants

- E. Maguire, Vattenfall AB;
- P.-E. Rethoré, DTU Wind Energy;
- S. Ott, DTU Wind Energy;
- T. Göçmen, DTU Wind Energy;
- A. Penã, DTU Wind Energy;
- J. Prospathopoulos, CRES, Greece;
- G. Scheepers, ECN, The Netherlands;
- T. Young, RES-LTD, United Kingdom;
- J. Rodrigo, CENER, Spain.
Site Description:

• The Lillgrund offshore wind farm is located in Öresund, the body of water between Malmö, Sweden and Copenhagen, Denmark.

• Owner: Vattenfall AB – 100%

• The farm consists of 48 Siemens SWT-2.3-93 wind turbines, each producing a rated power of 2.3 MW with a rotor diameter of 93 m and a hub height of 65 m.

• The turbines are arranged in a dense array with separation of 3.3 rotor diameters (D) within a row and 4.3 D between the rows.
Lillgrund offshore wind farm, located between Sweden & Denmark
Location of Lillgrund offshore wind farm.
Layout of the Lillgrund offshore wind farm (Dahlberg, 2009).

8 Rows of turbines: NE => SW
8 Columns of turbines: SE => NW

2 ”missing” turbines

<table>
<thead>
<tr>
<th>SWP</th>
<th>2.3 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>92.6m</td>
</tr>
<tr>
<td>Swept area:</td>
<td>6735 m²</td>
</tr>
<tr>
<td>Rotor speed, dynamic operation range:</td>
<td>7.5-16 rpm</td>
</tr>
<tr>
<td>Hub height:</td>
<td>65 m</td>
</tr>
</tbody>
</table>
Lillgrund; Available measurements.

- 65 m mast (wind speed, turbulence, wind direction, air temperature), period: 2003 – 2006 (before WF installation, with high quality)


Wind Farm wake models used in the benchmark

1. **SCADA** is the processed wind farm data to be compared with the wind farm wake models;
2. **FUGA** is a linearized actuator disc eddy-viscosity CFD model for offshore wind farm wake developed by DTU;
3. **CRESflowNS** is an elliptic k-ε actuator disc CFD model tailored for offshore wake simulation developed by CRES;
4. **FarmFlow** is a parabolized k-ε actuator disc CFD model tailored for offshore wake simulation developed by ECN;
5. **GCL** is the G.C. Larsen eddy-viscosity wake model v2009 developed by DTU;
6. **NOJ** is the original N.O Jensen model;
7. **AD/Ainslie** is an eddy-viscosity wake model developed by RES-LTD.
1. Flow case

Power deficit along a row of turbines - 3.3D & 4.3 D spacing at 9 m/s;
2. Flow case

Power deficit along a row of turbines - 3.3D & 4.3 D spacing – with "missing" wind turbines at 9 m/s;
3. Flow case

1. Maximum power deficit – as function of turbulence intensity (TI) for a pair of turbines with 3.3D & 4.3 D spacing respectively;

   DEMO: $\Delta = 5^\circ$; $V_{hub} = 9$ m/s; spacing $X D$
4. Flow case

Park efficiency for 0 – 360° inflow at 9 m/s & Δ=3°.

Inflow conditions:
- Wind direction (derived)
- Wind speed (derived)
### Benchmark matrix

<table>
<thead>
<tr>
<th>EERA-DTOC</th>
<th>Complete rows</th>
<th>Missing turbine(s)</th>
<th>Turbulence</th>
<th>Park</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Row:3-120deg</td>
<td>Row:B-222deg</td>
<td>Row:5-120deg</td>
<td>Row:D-222deg</td>
</tr>
<tr>
<td>DTU</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CRES</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECN</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
<td>RES-LTD</td>
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<tr>
<td>CENER</td>
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<td></td>
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<tr>
<td>sum</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

63 simulation results have been provided from the 10 participants.
Basic definitions

- **Speed deficit**: $\mu_{\text{speed}} = 1 - \frac{<U_{\text{wake}}>}{<U_{\text{free}}>}$

- **Power deficit**: $\mu_{\text{power}} = 1 - \frac{<P_{\text{wake}}>}{<P_{\text{free}}>}$
  \[0 \leq \mu_{\text{power}} \leq 1\]

**Power deficit as function of inflow direction**

- **Maximum deficit**

- **95% confidence level**
1 Flow case, 3.3 D spacing

![Graphs showing power deficit vs spacing for different wind directions and speeds.](image-url)
1 Flow case, 3.3 D spacing

![Graphs showing flow case results for different spacings and wind speeds.](image-url)
2 Flow case, 3.3 D spacing with "missing turbines"

Decreased deficit - due to speed recovery
3 Flow case – turbulence dependence

Lillgrund-Turbulence; spacing 4.3D; wdir=222±2.5°; ws=9±0.5 m/s

![Graph showing power deficit vs turbulence for different models with 4.3D spacing highlighted.](image)
4 Flow case – park efficiency

Normalized $\Delta$AEP ($V_{hub} = 9 \pm 0.5$ m/s)}
Conclusion

• Good agreement between wake model results and measurements;
• All models were able to predict the increased deficit between closely spaced turbines;
• The speed recovery was well reproduced;
• Linear relation between deficit and turbulence was well reproduced;
• Park power deficit for 0 - 360° inflow was well reproduced within 4-5% at 9 m/s;
Acknowledgments

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We acknowledge Vattenfall AB for having access to the SCADA data from the Lillgrund offshore wind farm.

Thank you for your attention