EERA DTOC wake results offshore

Hasager, Charlotte Bay; Hansen, Kurt Schaldemose; Réthoré, Pierre-Elouan; Volker, Patrick; Palomares, Ana; Prospathopoulos, John; Chaviaropoulos, Takis; Sieros, Giorgos; Schepers, Gerard; Ott, Søren

Publication date:
2014

Citation (APA):
EERA DTOC wake results offshore

Charlotte Bay Hasager, Kurt Schaldemose Hansen, Pierre-Elouan Réthoré, Patrick Volker, Ana Palomares, John Prospathopoulos, Takis Chaviaropoulos, Giorgos Sieros, Gerard Schepers, Søren Ott, Alfredo Peña, Elena Cantero, Jose Palma, Sara Pryor, Rebecca Bartheimie, Alexis Mouche, Gregor Giebel, Merete Badger, Sergio Lozano, Pedro Fernandes Correia, Ole Rathmann, Tuhfe Göçmen, Tom Young, Javier Rodrigo, Peter Hauge Madsen, E. Maguire
Content

- EERA DTOC project in brief
- Wake results at Lillgrund offshore wind farm
- Wake results at Horns Rev 1 offshore wind farm

European Energy Research Alliance: EERA

Design Tool for Offshore wind farm Clusters: DTOC
EERA DTOC project partners

- DTU Wind Energy (former Risø)
- Fraunhofer IWES
- CENER
- ECN
- EWEA
- SINTEF
- ForWind
- CRES
- CIEMAT
- University of Porto
- University of Strathclyde
- Indiana University

- CLS
- Statkraft
- Iberdrola Renovables
- Statoil
- Overspeed
- BARD
- Hexicon
- Carbon Trust
- E.On
- RES

Plus acknowledgment for collaboration with Vattenfall and DONG energy
EERA DTOC vision

• A robust, efficient, easy to use and flexible tool created to facilitate the optimised design of individual and clusters of offshore wind farms.

• A keystone of this optimisation is the precise prediction of the future long term wind farm energy yield and its associated uncertainty.
EERA DTOC concept

Meteorological data / Cluster layout / Turbine data

Grid data

Wake models

Grid models

Yield models

System services
Energy yield

Optimised Cluster Design
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
Lillgrunds available measurements

- 65 m mast
- Data: wind speed, turbulence, wind direction, air temperature
- Period: 2003 to 2006 and 2008 to 2010 (before wind farm installation with high quality and after medium quality)

- SCADA data 10 minute statistics (mean values and stddev from each wind turbine).
- Signals: power, pitch, rpm, nacelle wind speed and position
- Period: 2008 to 2012.
63 simulation results have been provided from the 10 participants.
1 Flow case, 3.3 D spacing

Lillgrund-SectorDeficit; spacing=3.3D; wdir=120±2.5°; ws=9±0.5 m/s
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 percentage for different scenarios with 4.3D spacing.]
4 Flow case

Park efficiency for 0 – 360º inflow at 9 m/s & $\Delta = 3^\circ$.

Inflow conditions:
- Wind direction (derived)
- Wind speed (derived)
4 Flow case – park efficiency

Normalized \( \Delta \text{AEP} \) (\( V_{\text{hub}} = 9 \pm 0.5 \text{ m/s} \))
Summary on Lillgrund wake benchmark

- 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;
Horns Rev 1 offshore wind farm

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

Data are courtesy of DONG energy and Vattenfall

Table 1: Wake models participating in EERA-DTOC Horns Rev benchmark.

<table>
<thead>
<tr>
<th>Model</th>
<th>Affiliation</th>
<th>Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCADA(BA)</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:pire@dtu.dk">pire@dtu.dk</a></td>
</tr>
<tr>
<td>NOJ(BA)</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:pire@dtu.dk">pire@dtu.dk</a></td>
</tr>
<tr>
<td>FUGA</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:pire@dtu.dk">pire@dtu.dk</a></td>
</tr>
<tr>
<td>GCL(BA)</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:pire@dtu.dk">pire@dtu.dk</a></td>
</tr>
<tr>
<td>DWM/HAWC2</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:fjul@dtu.dk">fjul@dtu.dk</a></td>
</tr>
<tr>
<td>CRESflowNS</td>
<td>CRES</td>
<td><a href="mailto:jprosp@fluid.mech.ntua.gr">jprosp@fluid.mech.ntua.gr</a></td>
</tr>
<tr>
<td>WASP/NOJ</td>
<td>Indiana University</td>
<td><a href="mailto:rbarthel@indiana.edu">rbarthel@indiana.edu</a></td>
</tr>
<tr>
<td>RANS</td>
<td>PORTO University</td>
<td><a href="mailto:jpalma@fe.up.pt">jpalma@fe.up.pt</a></td>
</tr>
<tr>
<td>FarmFlow</td>
<td>ECN Wind Energy</td>
<td><a href="mailto:schepers@ecn.nl">schepers@ecn.nl</a></td>
</tr>
<tr>
<td>Ainslie</td>
<td>RES-LTD</td>
<td>Tom <a href="mailto:Young@res-ltd.com">Young@res-ltd.com</a></td>
</tr>
<tr>
<td>NOJ/Penä</td>
<td>DTU Wind Energy</td>
<td><a href="mailto:ald@dtu.dk">ald@dtu.dk</a></td>
</tr>
<tr>
<td>GCL(GU)</td>
<td>CENER</td>
<td><a href="mailto:jsrodrigo@cener.com">jsrodrigo@cener.com</a></td>
</tr>
</tbody>
</table>

Kurt S. Hansen prepared the SCADA data and did the wake comparisons.
### Horns Rev 1 Wake Bench Results

<table>
<thead>
<tr>
<th>EERA-DTOC</th>
<th>Flow sector</th>
<th>Stratification</th>
<th>Turbulence</th>
<th>Spacing</th>
<th>Park efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>3.2</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>4.2</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASP (NOJ)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NOJ (BA)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>FarmFlow</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUGA</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCL (BA)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DWM/HAWC2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CRESflowNS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ainslie</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RANS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOJ/Penål</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>GCL (GU)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>sum</strong></td>
<td><strong>10</strong></td>
<td><strong>11</strong></td>
<td><strong>11</strong></td>
<td><strong>3</strong></td>
<td><strong>3</strong></td>
</tr>
</tbody>
</table>

1\textsuperscript{a} Amended GCL calibrated with CRESflowNS
Horns Rev 1 wake bench results

Example:
Power deficit along one row

Horns Rev, wdir=270 ± 15°, spacing=7D, ws=8 ± 0.5 m/s
7.2 Run 1: Wind direction $0^\circ \pm 2.5^\circ$, $5^\circ \pm 2.5^\circ$, $10^\circ \pm 2.5^\circ$, $15^\circ \pm 2.5^\circ$, $20^\circ \pm 2.5^\circ$, $25^\circ \pm 2.5^\circ$, $30^\circ \pm 2.5^\circ$, $35^\circ \pm 2.5^\circ$, $360^\circ \pm 2.5^\circ$.

Figure 13: Park power efficiency at 8 m/s inflow - as function of inflow direction.
Horns Rev 1 offshore wake photo study case

Courtesy: Vattenfall
Horns Rev 1 offshore wake photo study case
Horns Rev 1 offshore wake photo study case

Detached eddy simulation results showing vertical velocity

Vertical slice at z/D = 0.1
Vertical slice at z/D = 1.0
Vertical slice at z/D = 2.0
The special atmospheric conditions are characterized by a layer of cold humid
supersaturated air that re-condensates to fog in the wake of the turbines. The
process is fed by humid warm air up-drafted from below and adiabatic cooled
air down-drafted from above by the counter-rotating swirl generated by the
rotors.

The large-scale structure of the fog has an imprint of rotational spiraling bands
similar to wake flow characteristics deduced from CFD DES modeling.

Wind speed near cut-in.

Reference: Hasager, C.B., Rasmussen, L., Peña, A., Jensen, L.E., Réthoré, P.-
E., 2013, Wind farm wake: The Horns Rev photo case, Energies, 6(2), 696-716
Horns Rev 1 offshore wake photo study case

Courtesy: Vattenfall
WRF simulations with the EWP parametrization.

Homogeneous initial conditions, no forcing from the lateral boundaries and a zero heat flux at the lower boundary. The horizontal resolution was 1120m.

The normalized velocity at hub-height for three different vertical resolutions (28, 40 and 80 layers) against met mast (M6, M7) measurements. The normalized velocity is the ratio between the velocity from the wind farm simulations and the reference simulation without wind farm.

The model velocity is obtained by averaging 7 simulations, in which the flow angle ranged from 258.75 to 281.25 degrees.

The mast measurements were provided by Kurt S. Hansen (long-term time average over a flow angle ranging from 255 to 285 degrees).
Mesoscale coupled wake model results

P. J. H. Volker, J. Badger, A. N. Hahmann and S. Ott Implementation and Evaluation of a Wind Farm Parametrization in a Mesoscale Model, BLM in review
We acknowledge Vattenfall AB for having access to the SCADA data from the Lillgrund offshore wind farm and SCADA data from the Horns Rev 1 wind farm from DONG energy and Vattenfall.