Offshore CREYAP Part 2 – final results

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Acknowledgements

• DONG Energy Wind Power A/S for Barrow data
• Dong Energy, Iberdrola and Crown Estate for Shell Flats wind data and other information.
• 22 teams from 8 countries; thanks for making the comparison and presentation possible!
• EWEA team for arranging the 2015 Offshore CREYAP Part 2, thanks to Tim Robinson et al.
Comparison of Resource and Energy Yield Assessment Procedures

EWEA CREYAP concept
• Industry benchmark
• In-house training and R&D
• Identification of R&D issues

Three issues today
• Wakes and wake modelling
• Yield assessment uncertainties
• Modelled vs observed yields

CREYAP history
• Onshore Part 1, Bruxelles 2011
  – Scotland W, 28 MW, 37 teams
• Onshore Part 2, Dublin 2013
  – Scotland E, 29 MW, 60 teams
• Offshore Part 1, Frankfurt 2013
  – Gwynt y Môr, 576 MW, 37 teams
• Offshore Part 2, Helsinki 2015
  – Barrow, 90 MW, 22 teams

Summary
• 156 submissions from 27 countries
Barrow Offshore Wind Farm

- 30 V90 wind turbines (90 MW)
  - Rated power: 3.0 MW
  - Hub height: 75 m MSL
  - Rotor diameter: 90 m
  - 4 staggered rows, $5.5 \times 8.5 \, D$
  - Air density: $1.23 \, \text{kg} \, \text{m}^{-3}$
  - SCADA: 2008-02 to 2009-01

- Site meteorological masts
  - One 80-m and 50-m mast
  - Wind speed and direction
  - Temperature and pressure
  - Data: 2011-07 to 2012-08

- Auxiliary data
  - MERRA reanalysis 1998-2013
  - Topographical data by choice
Steps in the energy yield prediction process

- Site wind observation
- Site wind climate (Long-term adjustment)
- Reference yield
  - Vertical extrapolation
  - Flow modelling
- Gross yield
  - Horizontal extrapolation
  - Wake modelling
- Potential yield
- $P_x$ yield (Uncertainty modelling)
- Net yield (Loss estimation)

Steps:
1. Site wind observation
2. Site wind climate (Long-term adjustment)
3. Reference yield
   - Vertical extrapolation
   - Flow modelling
4. Gross yield
   - Horizontal extrapolation
   - Wake modelling
5. Potential yield
6. $P_x$ yield (Uncertainty modelling)
7. Net yield (Loss estimation)
Estimated turbine mean yield and wake effect (10 y)
Predicted wind farm wake losses

Data points used = 23 (of 23)

Mean wake loss = 7.9%
Standard deviation = 1.3%
Coefficient of variation = 16%
Range = 5.5 to 10.4%
Comparison of wake models
Wake models used

- windPRO Park (N.O. Jensen) (5)
  - $k = 0.04$, offshore settings, ...
- WAsP Park (4)
  - $k = \{0.03, 0.04, 0.05, 0.075\}$
- CFD-type (3)
  - OpenFoam CFDwake, CFD+linear, WindSim WM-1
- Ainslie Eddy Viscosity (3)
  - Quarton, + linearised CFD, +equivalent roughness
- WindFarmer Eddy Viscosity (2)
  - LWF correction, LWF
- FUGA (3)
  - Neutral, stable, unstable
- Other models (3)
  - OpenWind DAWM, Jensen-type+deep array+eff. turbulence, EV
Predicted turbine site wake loss
Estimated turbine yields – coefficient of variation
Predicted turbine site wake losses

![Graph showing predicted turbine site wake losses.](image)
Sensitivity to WAsP and Fuga input parameters

- Variable input parameters explain spread in wake loss predictions
- Impossible to select universal parameters which will match WAsP and Fuga results for all turbine positions
## Wake modelling uncertainty (CREYAP 1-4)

<table>
<thead>
<tr>
<th>Wind farm</th>
<th>Size</th>
<th>Layout</th>
<th>Wake loss</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore Hilly</td>
<td>28 MW 14 WTG</td>
<td>Irregular 3.7-4.8 $D$</td>
<td>6.1%</td>
<td>13%</td>
</tr>
<tr>
<td>Onshore Complex</td>
<td>29 MW 22 WTG</td>
<td>Irregular 4-5 $D$</td>
<td>10.3%</td>
<td>18%</td>
</tr>
<tr>
<td>Offshore Gwynt y Môr</td>
<td>576 MW 160 WTG</td>
<td>Regular 6-7 $D$</td>
<td>14.3%</td>
<td>37%</td>
</tr>
<tr>
<td>Offshore Barrow</td>
<td>90 MW 30 WTG</td>
<td>4 staggered 5.5 $\times$ 8.5 $D$</td>
<td>7.9%</td>
<td>16%</td>
</tr>
<tr>
<td>10 offshore* DONG 2015</td>
<td>90-630 MW 30-175 WTG</td>
<td>various</td>
<td>n/a</td>
<td>16%</td>
</tr>
</tbody>
</table>

* N.G. Nygaard, EWEA Offshore 2015
Net energy yield of wind farm, $P_{50}$ (10 y)

Data points used = 22 (of 22)

Mean net yield = 303 GWh$^{-1}$
Standard deviation = 9.4 GWh$^{-1}$
Coefficient of variation = 3.1%
Range = 282 to 317 GWh$^{-1}$
Wind farm key figures (10-y estimates)

<table>
<thead>
<tr>
<th>Barrow (10 y)</th>
<th>Mean</th>
<th>σ</th>
<th>CV*</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross yield GWh</td>
<td>366</td>
<td>8.9</td>
<td>2.4</td>
<td>338</td>
<td>377</td>
</tr>
<tr>
<td>Wake loss %</td>
<td>7.9</td>
<td>1.3</td>
<td>16.0</td>
<td>5.5</td>
<td>10.4</td>
</tr>
<tr>
<td>Potential yield GWh</td>
<td>334</td>
<td>10.3</td>
<td>3.1</td>
<td>311</td>
<td>350</td>
</tr>
<tr>
<td>Technical losses %</td>
<td>9.3</td>
<td>0.1</td>
<td>1.0</td>
<td>9.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Net yield $P_{50}$ GWh</td>
<td>303</td>
<td>9.4</td>
<td>3.1</td>
<td>282</td>
<td>317</td>
</tr>
<tr>
<td>Uncertainty %</td>
<td>9.7</td>
<td>2.3</td>
<td>23.4</td>
<td>6.1</td>
<td>13.7</td>
</tr>
<tr>
<td>Net yield $P_{90}$ GWh</td>
<td>267</td>
<td>12.1</td>
<td>4.4</td>
<td>245</td>
<td>282</td>
</tr>
</tbody>
</table>

* Coefficient of Variation in per cent
Spread for different steps in the prediction process

- Offshore CREYAP exercises Part II+I
  - Barrow, 30 WTG, 90 MW (2015)
Comparison of predicted to observed $P_{50}$ (1 year)

Data points used = 20 (of 22)

Mean predicted $P_{50} = 324 \text{ GWh}^{-1}$
Standard deviation = $9.6 \text{ GWh}^{-1}$
Coefficient of variation = $3.0\%$
Range = 300 to 343 GWh$^{-1}$
Prediction bias = $+4\%$
Quality assurance of submitted spreadsheets

Cross-check of $P_{50}$: team results compared to DTU calculation from team values.

- Net AEP ($P_{90}$) = Net AEP ($P_{50}$) − 1.282 × [uncertainty estimate]

Cross-check of $P_{90}$: ¾ of the teams agree with DTU, but ¼ get a different result!
# Sensitivity analyses for Barrow

<table>
<thead>
<tr>
<th>Offshore datums and transition piece</th>
<th>Input change</th>
<th>AEP change in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Met. mast height</td>
<td>MSL $\rightarrow$ HAT</td>
<td>+0.9</td>
</tr>
<tr>
<td>• Wind turbine hub height</td>
<td>MSL = HAT − 5 m</td>
<td>−1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modelling parameter (examples)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Wake decay parameter $k$ in Park</td>
<td>0.01 in $k$</td>
<td>0.7</td>
</tr>
<tr>
<td>• Stability settings in FUGA</td>
<td>1/1000 in 1/L</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind climatology</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Calibration of anemometer</td>
<td>1% in $U$</td>
<td>1.3</td>
</tr>
<tr>
<td>• Long-term correlation</td>
<td>1% in $U$</td>
<td>1.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power production estimation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Air density estimation</td>
<td>1% in $\rho$</td>
<td>0.6</td>
</tr>
<tr>
<td>• Power curve / turbine specification</td>
<td>several</td>
<td>???</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observed production statistics</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Independent calculations</td>
<td></td>
<td>1.3</td>
</tr>
</tbody>
</table>
Summary and conclusions

- Long-term adjustment (applied twice)
  - Average effect = 5.7%, spread = 1.2%

- Wake modelling
  - Average wind farm wake effect = 7.9%, spread = 16%
  - Wake modelling spread increases with depth into wind farm
  - Wake model, version, and settings should all be specified

- Modelled vs observed 1-y yields
  - Estimated = 104% of observed, spread = 3%
  - Uncertainty of predictions within TPWind vision
  - Measured yield has an uncertainty too

- CREYAP results seem to improve over time
  - No or fewer outliers in present study
  - Uncertainty ~ 3% for net yield ($P_{50}$)
  - But uncertainty calculations still not good enough...
Future work

• Summary and reporting on first four CREYAP exercises
  – Hilly, moderately complex and offshore covered so far
  – Abstract submitted for EWEA 2015

• Future CREYAP exercises
  – Wind resource and energy yield assessment
  – Steep or forested terrain, tall turbines, ...
  – Wind conditions and site suitability

• Comments, suggestions and ideas
  – EWEA: Lorenzo Morselli Lorenzo.Morselli@ewea.org
  – DTU: Niels G Mortensen nimo@dtu.dk

• And, as allways...
  – High-quality wind farm data in high demand for future studies!
Thank you for your attention!
Who submitted results?

- 20 organisations (22 teams) from 8 countries submitted results
  - Belgium, Denmark, Germany, India, Norway, Spain, UK, US

- Names of organisations
Barrow offshore wind farm setting

© RSK Environment Ltd (RSK)
Barrow offshore wind farm setting
Data analysis & presentation

Data material
• Result spreadsheets from 22 teams

Data analysis
• Quality control and reformatting
• Consistent calculations (errors, loss factors)
• Calculation of missing numbers – but no comprehensive reanalysis!

Data presentation
• Comparison of methods and models
  – Non-parametric box-whisker plot
  – Statistics (median, quartiles, IQR)
• Overall distribution of all results
  – Normal distribution fitted to the results
  – Statistics (mean, standard deviation, coefficient of variation)
• Team results for each parameter (see appendix)
Offshore CREYAP II results in two parts

Long-term comparisons (10 y)
- Observed wind climate
- Observed turbulence
- Long-term adjustment
- Reference yield
- Gross yield
- Wake effects
- Net yield P50
- Uncertainty estimates
- Net yield P90
- Per-turbine results

- Team characteristics
- Methodology information

Predicted vs observed yields (1 y)
- Reference yield
- Potential yield
- Array efficiency
- Net P50 (losses given)

- SCADA calculation
  - Sum of WTG power readings
  - Curtailment correction
  - Availability correction to 100%
  - Two independent calculations
  - Checked with sub-station meter
Comparisons of results and methods  
\{definitions\}

1. LT wind @ \( X \) m (mast) = Measured wind ± [long-term adjustment]
   • comparison of long-term adjustment methods

2. LT wind @ \( Y \) m (hub height) = LT wind @ \( X \) m + [wind profile effects]
   • comparison of vertical extrapolation methods

3. Gross AEP = Reference AEP ± [terrain effects]
   • comparison of flow models

4. Potential AEP = Gross AEP – [wake losses]
   • comparison of wake models

5. Net AEP \( P_{50} \) = Potential AEP – [technical losses]
   • comparison of technical losses estimates

6. Net AEP \( P_{90} = P_{50} - 1.282 \times \) [uncertainty estimate]
   • comparison of uncertainty estimates

7. Comparison to teams average AEP – spread and bias
Comparisons of results and methods

- Long-term correlation methods
  - MCP on site and MERRA data, no adjustment factors given by teams

- Vertical extrapolation methods
  - Wind shear exponent not important here

- Flow modelling
  - Terrain effects not reported explicitly by teams

- Wake modelling
  - Illustrated in presentation in several ways

- Systematic technical losses estimates
  - Losses prescribed by exercise

- Uncertainty estimates/modelling
  - Uncertainty components in prescribed categories
Wind-climatological inputs

Site meteorological mast
• 1 y of 10-min data (2011-12)

MERRA reanalysis data
• 16 y of hourly data (1998-2013)
Observed wind speed @ 82 m

Data points used = 21 (of 22)

Mean wind speed = 9.59 ms$^{-1}$
Standard deviation = 0.14 ms$^{-1}$
Coefficient of variation = 1.5%
Range = 9.43 to 9.76 ms$^{-1}$
Long-term wind speed @ 82 m

Data points used = 21 (of 22)

Mean wind speed = 9.37 ms$^{-1}$
Standard deviation = 0.10 ms$^{-1}$
Coefficient of variation = 1.1%
Range = 9.10 to 9.54 ms$^{-1}$
Wind speed uncertainty @ 82 m

Data points used = 20 (of 22)

Mean uncertainty = 0.38 ms\(^{-1}\)
Standard deviation = 0.17 ms\(^{-1}\)
Coefficient of variation = 46%
Range = 0.04 to 0.61 ms\(^{-1}\)
Turbulence intensity @ 82 m

Data points used = 18 (of 22)

Mean turbulence intensity = 6.9%
Standard deviation = 0.6%
Coefficient of variation = 8.5%
Range = 6.0 to 8.1%
Long-term wind speed @ 75 m

Data points used = 21 (of 22)

Mean wind speed = 9.22 ms\(^{-1}\)
Standard deviation = 0.10 ms\(^{-1}\)
Coefficient of variation = 1.1%
Range = 8.90 to 9.39 ms\(^{-1}\)
Comparison of air density $\rho$ @ hub height

Data points used = 21 (of 22)

Mean air density = 1.233 kgm$^{-3}$
Standard deviation = 0.004 kgm$^{-3}$
Coefficient of variation = 0.3%
Range = 1.226 to 1.242 kgm$^{-3}$ (1%)
# Wind farm key figures – 1 year estimates

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>$\sigma$</th>
<th>CV*</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Potential yield</strong> (GWh)</td>
<td>389</td>
<td>7.0</td>
<td>1.8</td>
<td>373</td>
<td>399</td>
</tr>
<tr>
<td><strong>Wake loss</strong> (%)</td>
<td>7.5</td>
<td>1.1</td>
<td>14.8</td>
<td>5.2</td>
<td>9.2</td>
</tr>
<tr>
<td><strong>Gross energy yield</strong> (GWh)</td>
<td>357</td>
<td>10.7</td>
<td>3.0</td>
<td>331</td>
<td>378</td>
</tr>
<tr>
<td><strong>Technical losses</strong> (%)</td>
<td>9.3</td>
<td>0.1</td>
<td>1.0</td>
<td>9.2</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Net energy yield $P_{50}$</strong> (GWh)</td>
<td>324</td>
<td>9.6</td>
<td>3.0</td>
<td>300</td>
<td>343</td>
</tr>
<tr>
<td><strong>Measured</strong> (GWh)</td>
<td>308</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Difference</strong> (%)</td>
<td>5.2</td>
<td></td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Coefficient of Variation in per cent.
Reference yield of wind farm (1 y)

Data points used = 20 (of 22)

Mean net yield = 389 GWh yr\(^{-1}\)
Standard deviation = 7.2 GWh yr\(^{-1}\)
Coefficient of variation = 1.8%
Range = 373 to 399 GWh yr\(^{-1}\)
Predicted wind farm wake losses (1 y)

Data points used = 21 (of 22)

Mean wake loss = 7.6%
Standard deviation = 1.2%
Coefficient of variation = 15%
Range = 5.2 to 9.5%
Potential yield of wind farm (1 y)

Data points used = 20 (of 22)

Mean net yield = 357 GWhyr$^{-1}$
Standard deviation = 10.7 GWhyr$^{-1}$
Coefficient of variation = 3.0%
Range = 331 to 378 GWhyr$^{-1}$
Reference yield of wind farm

Data points used = 22 (of 22)

Mean reference yield = 368 GWh yr\(^{-1}\)
Standard deviation = 6.4 GWh yr\(^{-1}\)
Coefficient of variation = 1.7%
Range = 347 to 377 GWh yr\(^{-1}\)
Gross yield of wind farm

Data points used = 22 (of 22)

Mean gross yield = 366 GWhy\(^{-1}\)
Standard deviation = 8.9 GWhy\(^{-1}\)
Coefficient of variation = 2.4%
Range = 338 to 377 GWhy\(^{-1}\)
Potential yield of wind farm

Data points used = 20 (of 22)

Mean potential yield = 334 GWh\(^{-1}\)
Standard deviation = 10.3 GWh\(^{-1}\)
Coefficient of variation = 3.1%
Range = 311 to 350 GWh\(^{-1}\)
Predicted turbine site energy yield

Wind turbine potential energy yield [GWyr⁻¹]
Uncertainty estimates

Data points used = 22 (of 22)

Mean uncertainty = 9.7%
Standard deviation = 2.3%
Coefficient of variation = 23%
Range = 6.1 to 14%
Uncertainty estimates by type

![Graph showing uncertainty estimates by type]
Net energy yield of wind farm, $P_{90}$

Data points used = 21 (of 22)

Mean net yield = 267 GWh$^{-1}$
Standard deviation = 12.2 GWh$^{-1}$
Coefficient of variation = 4.6%
Range = 245 to 282 GWh$^{-1}$
Profile of participants (the human factor)

What we know

• Number of persons in team
• Number of years in wind power industry
• Type of company
• Approximate number of wind farm projects
• Education as wind energy master or similar
• Continuing education courses in wind energy
• Courses in software tools and models used
• In-house training in wind and yield assessments
• Participation in previous CREYAP exercises

What we would like to show

• What are the main characteristics of the companies and teams?
• Do the team characteristics have a significant impact on the results?
• Which paths do the different teams follow in the prediction process?
• Different calculation practices and tools for production data statistics

Status of work

• No firm conclusions drawn yet
• Work continues and will be reported at a later stage
Legend to graphs

• Results distribution graphs
  – histograms + fitted normal distribution
  – statistics given next to graph

• Team result graphs
  – mean value is base value for histogram
  – y-axis covers a range of ±2 standard deviations
  – Absolute y-values (left) and relative (right)
  – x-axis covers teams 1-22
  – no team number indicates ‘result not submitted’

• Box-whisker plots
  – whiskers defined by lowest datum still within 1.5 IQR of the lower quartile (Q1), and highest datum still within 1.5 IQR of the upper quartile (Q3).
  – Extreme values shown with symbols
References


Offshore
