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 × 8.5 $D$
  - Air density: 1.23 kg 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

- Reference yield
- Gross yield
- Potential yield
- Net yield

- Site wind observation
- Site wind climate
- Flow modelling
- Horizontal extrapolation
- Vertical extrapolation
- Long-term adjustment
- Project planning
- $P_x$ yield
- Uncertainty modelling
- Loss estimation
- Wake modelling
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 CFDbake, 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

![Box plot showing predicted turbine site wake loss with different labels for turbines A01 to D08. The y-axis represents wake loss in percentage, and the x-axis shows turbine labels. The box plot includes error bars indicating variability.](image-url)
Estimated turbine yields – coefficient of variation
Predicted turbine site wake losses

![Graph showing predicted turbine site wake losses](image-url)
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 × 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 yr$^{-1}$
Standard deviation = 9.4 GWh yr$^{-1}$
Coefficient of variation = 3.1%
Range = 282 to 317 GWh yr$^{-1}$
## 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</td>
<td>GWh</td>
<td>366</td>
<td>8.9</td>
<td>338</td>
<td>377</td>
</tr>
<tr>
<td>Wake loss</td>
<td>%</td>
<td>7.9</td>
<td>1.3</td>
<td>5.5</td>
<td>10.4</td>
</tr>
<tr>
<td>Potential yield</td>
<td>GWh</td>
<td>334</td>
<td>10.3</td>
<td>311</td>
<td>350</td>
</tr>
<tr>
<td>Technical losses</td>
<td>%</td>
<td>9.3</td>
<td>0.1</td>
<td>9.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Net yield $P_{50}$</td>
<td>GWh</td>
<td>303</td>
<td>9.4</td>
<td>282</td>
<td>317</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>%</td>
<td>9.7</td>
<td>2.3</td>
<td>6.1</td>
<td>13.7</td>
</tr>
<tr>
<td>Net yield $P_{90}$</td>
<td>GWh</td>
<td>267</td>
<td>12.1</td>
<td>245</td>
<td>282</td>
</tr>
</tbody>
</table>

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

Coefficients of Variation [%]

- Offshore CREYAP exercises Part II+I
  - Barrow, 30 WTG, 90 MW (2015)

Steps:
- Long-term adjustment
- Yield calculation
- Flow modelling
- Wake modelling
- Loss estimation
- Uncertainty estimation
- Net yield, P50
- Net yield, P90
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 $\text{GWh}^{-1}$
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 ($P_{50}$) − $1.282 \times$ [uncertainty estimate]

Cross-check of $P_{90}$: $\frac{3}{4}$ of the teams agree with DTU, but $\frac{1}{4}$ 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 \( \sim 3\% \) 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
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 $P_{90} = P_{50} – 1.282 \times \text{[uncertainty estimate]}$
   • 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 m\(s^{-1}\)
Standard deviation = 0.14 m\(s^{-1}\)
Coefficient of variation = 1.5%
Range = 9.43 to 9.76 m\(s^{-1}\)
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 \text{ ms}^{-1}
Standard deviation = 0.10 \text{ ms}^{-1}
Coefficient of variation = 1.1\%
Range = 8.90 to 9.39 \text{ 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>Barrow (1 y)</th>
<th>Mean</th>
<th>σ</th>
<th>CV*</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential yield</td>
<td>GWh</td>
<td>389</td>
<td>7.0</td>
<td>1.8</td>
<td>373</td>
</tr>
<tr>
<td>Wake loss</td>
<td>%</td>
<td>7.5</td>
<td>1.1</td>
<td>14.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Gross energy yield</td>
<td>GWh</td>
<td>357</td>
<td>10.7</td>
<td>3.0</td>
<td>331</td>
</tr>
<tr>
<td>Technical losses</td>
<td>%</td>
<td>9.3</td>
<td>0.1</td>
<td>1.0</td>
<td>9.2</td>
</tr>
<tr>
<td>Net energy yield $P_{50}$</td>
<td>GWh</td>
<td>324</td>
<td>9.6</td>
<td>3.0</td>
<td>300</td>
</tr>
<tr>
<td>Measured</td>
<td>GWh</td>
<td>308</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td>%</td>
<td>5.2</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 GWhy$^{-1}$
Standard deviation = 10.7 GWhy$^{-1}$
Coefficient of variation = 3.0%
Range = 331 to 378 GWhy$^{-1}$
Reference yield of wind farm

Data points used = 22 (of 22)

Mean reference yield = 368 GWhy$^{-1}$
Standard deviation = 6.4 GWhy$^{-1}$
Coefficient of variation = 1.7%
Range = 347 to 377 GWhy$^{-1}$
Gross yield of wind farm

Data points used = 22 (of 22)

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

Data points used = 20 (of 22)

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

Wind turbine potential energy yield [GWh/yr]
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
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
