First Offshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP)

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First Offshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP)

Niels G Mortensen, Morten Nielsen, Hans E Jørgensen
DTU Wind Energy

EWEA Offshore 2013
Frankfurt, Germany
• The data pack used for the offshore comparison was made available by Renewable Energy Systems Ltd. (RES); thanks to Mike Anderson and Tom Young.
• The 38 sets of results were submitted by 37 organisations from 13 countries; thanks to all of the teams for making the comparison and this presentation possible!
• Thanks to Tim Robinson and EWEA team for arranging the 2013 offshore CREYAP.
First offshore CREYAP results

- Introduction
- Case study wind farm
  - Wind farm and turbine data
  - Wind-climatological inputs
  - Topographical inputs
- Comparisons of results & methods
  - The prediction process
  - Long-term wind climate
  - Wind farm energy yields
  - Effect upon North Hoyle
  - Export system constraint
- Summary and conclusions
- Appendices
  - Team results and statistics
Gwynt y Môr wind farm

- 160 wind turbines (576 MW)
  - Rated power: 3.6 MW
  - Hub height: 79.4 m
  - Rotor diameter: 107 m
  - Spacing: regular, 6-7 D
  - Air density: 1.23 kg m\(^{-3}\)

- Site meteorological mast
  - Wind speed @ 85 m
  - Std. deviation @ 85 m
  - Wind direction @ 82 m
  - Air temperature @ 20 m
  - Barometric pressure @ 20 m

- Site topographical data
  - Participants choice
Wind-climatological inputs

Site meteorological mast
- 2.6 years of 10-min mean data

MERRA reanalysis data
- 11.4 years of hourly mean data
Data analysis & presentation

Data material
• Result spreadsheets from 38 teams

Data analysis
• Quality control and reformatting
• Consistent calculations (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)
Steps in the energy yield prediction process

- Reference yield
  - Flow modelling
    - Wake modelling
  - Vertical extrapolation
    - Site wind climate
    - Site wind observation
      - Long-term adjustment

- Gross yield
  - Loss estimation
  - Uncertainty estimation
  - Net yield $P_{50}$
  - Project economy
    - Net yield $P_{90}$
    - Potential yield
Comparison of air density $\rho$ @ hub height

Data points used = 36 (of 38)

Mean air density = 1.226 kgm$^{-3}$
Standard deviation = 0.007 kgm$^{-3}$
Coefficient of variation = 0.6%
Range = 1.201 to 1.240 kgm$^{-3}$ (3%)

AEP sensitivity $\sim$ 0.5% for 1% in $\rho$
Turbine sites: mean potential AEP [GWhy$^{-1}$]
Predicted wind farm wake losses

Data points used = 38 (of 38)

Mean wake loss = 14.3%
Standard deviation = 5.2%
Coefficient of variation = 37%
Range = 6.9% to 37%
Comparison of wake models

![Box plot showing wind farm wake loss for different models. The x-axis labels include WASP Park (11), WindPRO Park (8), WindFarmer EV (6), OpenWind (3), Ensemble (3), Fuga + CFD (3), Misc. (4), and All models (38). The y-axis represents wind farm wake loss in percentage.](image-url)
Turbine sites: coefficient of variation of AEP [%]
Statistics of predicted per-turbine energy yields

Box Whisker Plot
- outliers
- upper fence
- 75% quantile
- 25% quantile
- lower fence

Turbine ID vs. Potential yield [GWh]
Effect of wake decay parameter $k$ in PARK

Comparison with Fuga (linearized CFD) suggests

- $k=0.03$ for wake effects at Gwynt y Môr (case study)
- $k=0.04$ for North Hoyle when including effect of Gwynt y Môr
- $k=0.075$ for North Hoyle before construction of Gwynt y Môr

Probably no universal optimal offshore wake decay parameter!
Net energy yield of wind farm, $P_{90}$

- Data points used = 37 (of 38)
- Mean net $P_{90}$ yield = 1609 GWh$^{-1}$
- Standard deviation = 139 GWh$^{-1}$
- Coefficient of variation = 8.7%
- Range = 1123 to 1862 GWh$^{-1}$
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!
## Wind farm key figures

<table>
<thead>
<tr>
<th>Gwynt y Môr</th>
<th>Mean</th>
<th>σ</th>
<th>CV*</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference yield</td>
<td>GWh</td>
<td>2414</td>
<td>67</td>
<td>2.8</td>
<td>2287</td>
</tr>
<tr>
<td>Topographic effects</td>
<td>%</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Gross energy yield</td>
<td>GWh</td>
<td>2394</td>
<td>89</td>
<td>3.7</td>
<td>2178</td>
</tr>
<tr>
<td>Wake loss</td>
<td>%</td>
<td>14</td>
<td>5.3</td>
<td>37</td>
<td>6.9</td>
</tr>
<tr>
<td>Potential yield</td>
<td>GWh</td>
<td>2052</td>
<td>138</td>
<td>6.7</td>
<td>1444</td>
</tr>
<tr>
<td>Technical losses</td>
<td>%</td>
<td>9.6</td>
<td>0.7</td>
<td>7.8</td>
<td>7.5</td>
</tr>
<tr>
<td>Net energy yield $P_{50}$</td>
<td>GWh</td>
<td>1856</td>
<td>130</td>
<td>7.0</td>
<td>1296</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>%</td>
<td>10</td>
<td>3.1</td>
<td>29</td>
<td>6.2</td>
</tr>
<tr>
<td>Net energy yield $P_{90}$</td>
<td>GWh</td>
<td>1609</td>
<td>139</td>
<td>8.7</td>
<td>1123</td>
</tr>
</tbody>
</table>

* Coefficient of Variation in per cent.

| Net energy yield $P_{90}$            | GWh  | 1609 | 139 | 8.7   | 1123  | 1862  |

| Gross AEP inferred by DTU. |

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First EWEA Offshore CREYAP 21 Nov 2013
Spread for different steps in the prediction process

<table>
<thead>
<tr>
<th>Step</th>
<th>Coefficient of Variation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH air density</td>
<td>0.5</td>
</tr>
<tr>
<td>LT wind @ 85 m</td>
<td>0.5</td>
</tr>
<tr>
<td>Reference yield</td>
<td>2.0</td>
</tr>
<tr>
<td>Gross yield</td>
<td>3.0</td>
</tr>
<tr>
<td>Potential yield</td>
<td>6.0</td>
</tr>
<tr>
<td>Net yield, P50</td>
<td>7.5</td>
</tr>
<tr>
<td>Net yield, P90</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Steps in the prediction process:
- Vertical extrapolation & yield calculation
- Flow modelling
- Wake modelling
- Loss estimation
- Uncertainty estimation
Wind farm efficiency of North Hoyle @ 10 ms$^{-1}$

After Gwynt y Môr
Before Gwynt y Môr

Power efficiency [%] vs. Direction [Degree]
Effect of Gwynt y Môr upon North Hoyle

Data points used = 35 (of 38)

Mean loss of AEP = 2.3 %
Standard deviation = 1.6 %
Coefficient of variation = 69%
Range = 0.3 to 6.8%
Loss due to 500-MW Export System Constraint

Data points used = 33 (of 38)

Mean loss of AEP = 4.0 %
Standard deviation = 2.6 %
Coefficient of variation = 64%
Range = 0.1 to 13%
Summary and conclusions

• Definition and usage of terms and concepts uncertain, e.g. *gross yield*
  – Adopt standards, guidelines, best practice (IEC, IEA, Measnet, ...)
  – Energy yield calculations must be unambiguous (*P*<sub>90</sub>, loss factors, ...)

• Seemingly simple tasks introduce quite a bit of spread
  – Air density calculation, reference yield, long-term correlation, ...

• Wake modelling for Gwynt y Môr
  – Mean wake effect = 14.3%, standard deviation = 5.2% (CV = 37%)
  – Wake modelling uncertainty increases with depth into wind farm

• Overall spread of *P*<sub>90</sub> predictions (~9%) quite similar to CREYAP I & II – and to the estimated uncertainty (~10%); but different steps may be different.

• Effect of Gwynt y Môr upon North Hoyle is clear, but a bit uncertain
  – Mean effect 2.3%, std. deviation 1.6% (CV = 69%), 0.3 to 6.8%

• Loss due to 500-MW Export System Constraint is clear, but a bit uncertain
  – Mean effect 4.0%, std. deviation 2.6% (CV = 64%), 0.1 to 13%
Thank you for your attention!
Who submitted results?

- 37 organisations (38 teams) from 13 countries submitted results
  - Belgium, China, Denmark, Finland, Germany, India, Italy, Japan, Norway, Poland, Spain, United Kingdom, USA

- Names of organisations
Gwynt y Môr wind farm setting
Gwynt y Môr wind farm setting
Comparisons of results and methods \{definitions\}

1. LT wind @ 85 m (mast) = Measured wind ± [long-term adjustment]
   - comparison of long-term adjustment methods

2. LT wind @ 79 m (hub height) = LT wind @ 85 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 ($P_{90}$) = Net AEP ($P_{50}$) − $1.282 \times$ [uncertainty estimate]
   - comparison of uncertainty estimates

7. Comparison to teams average AEP − spread and bias
Comparisons of results and methods {notes}

- Comparison of long-term correlation methods
  - MCP using site and MERRA data, no adjustment factors given by teams

- Comparison of vertical extrapolation methods
  - Wind shear exponent of 0.1 prescribed, no shear factors given by teams

- Comparison of flow models
  - Terrain effects not given by teams

- Comparison of wake models
  - Illustrated in presentation in several ways

- Comparison of technical losses estimates
  - Losses prescribed, except hysteresis effect which is illustrated below

- Comparison of uncertainty estimates
  - Uncertainty components are participants own choice; it has not been possible to brake this down for the presentation.
Long-term wind speed @ 85 m

Data points used = 37 (of 38)

Mean wind speed = 9.12 ms\(^{-1}\)
Standard deviation = 0.06 ms\(^{-1}\)
Coefficient of variation = 0.7%
Range = 8.98 to 9.24 ms\(^{-1}\)
Wind speed uncertainty @ 85 m

Data points used = 37 (of 38)

Mean uncertainty = 0.38 ms$^{-1}$
Standard deviation = 0.24 ms$^{-1}$
Coefficient of variation = 64%
Range = 0.09 to 1.21 ms$^{-1}$
Turbulence intensity @ 85 m

Data points used = 37 (of 38)

Mean turbulence intensity = 7.0%
Standard deviation = 0.9%
Coefficient of variation = 12.3%
Range = 6.0 to 9.7%
Turbine site mean wind speed [ms$^{-1}$]
Turbine site wind speed CV [%]
Mean air density @ 20 m

Data points used = 37 (of 38)

Mean air density = 1.232 kgm$^{-3}$
Standard deviation = 0.006 kgm$^{-3}$
Coefficient of variation = 0.5%
Range = 1.208 to 1.244 kgm$^{-3}$
Mean air density $\rho$ @ hub height

Data points used = 36 (of 38)

Mean air density = $1.226 \text{ kgm}^{-3}$
Standard deviation = $0.007 \text{ kgm}^{-3}$
Coefficient of variation = 0.6%
Range = 1.201 to 1.240 kgm$^{-3}$ (3%)

AEP sensitivity $\sim 0.5\%$ for 1$\%$ in $\rho$
Reference yield

Data points used = 36 (of 38)
Mean reference yield = 2414 GWhy\(^{-1}\)
Standard deviation = 67 GWhy\(^{-1}\)
Coefficient of variation = 2.8%
Range = 2287 to 2737 GWhy\(^{-1}\)
Comparison of flow models

It is not straightforward to compare the horizontal extrapolation methods quantitatively, but here is a list of the methods specified by the teams:

- WAsP – 24 teams, 2 through WindPRO interface
- WRF – 3 teams, 1 together with GLGH VMD
- Vortex – 2 teams
- Mesoscale – 2 teams, unspecified model
- SiteWind – 2 teams
- OpenWind – 1 team
- WindSim – 1 team
- CFD – 1 team, unspecified model
- Skiron – 1 team, mesoscale model
- Not available – 1 team
Gross yield

Data points used = 37 (of 38)
Mean reference yield = 2394 GWhy\(^{-1}\)
Standard deviation = 89 GWhy\(^{-1}\)
Coefficient of variation = 3.7%
Range = 2178 to 2737 GWhy\(^{-1}\)
Data points used = 36 (of 38)

Mean potential yield = 2052 GWh\(^{-1}\)
Standard deviation = 138 GWh\(^{-1}\)
Coefficient of variation = 6.7%
Range = 1444 to 2251 GWh\(^{-1}\)
Technical losses

Data points used = 37 (of 38)

Mean technical loss = 9.6%
Standard deviation = 0.7%
Coefficient of variation = 7.8%
Range = 7.5 to 13%
Hysteresis effect factor

Data points used = 37 (of 38)

Mean hysteresis effect = 0.991
Standard deviation = 0.007
Coefficient of variation = 0.7%
Range = 0.960 to 0.999
**Net energy yield of wind farm, $P_{50}$**

Data points used = 37 (of 38)

Mean net yield = 1856 GWh$^{-1}$
Standard deviation = 130 GWh$^{-1}$
Coefficient of variation = 7.0%
Range = 1296 to 2035 GWh$^{-1}$
Uncertainty estimates

Data points used = 36 (of 38)

Mean uncertainty = 10%
Standard deviation = 3.1%
Coefficient of variation = 29%
Range = 6.2 to 21%
Legend and references

Legend to graphs

- 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, x-axis covers teams 1-38. No team number indicates ‘result not submitted’.
- Box-whisker plots: whiskers defined by the lowest datum still within 1.5 IQR of the lower quartile (Q1), and the highest datum still within 1.5 IQR of the upper quartile (Q3).

For more information on CREYAP Pt. I and II (onshore)