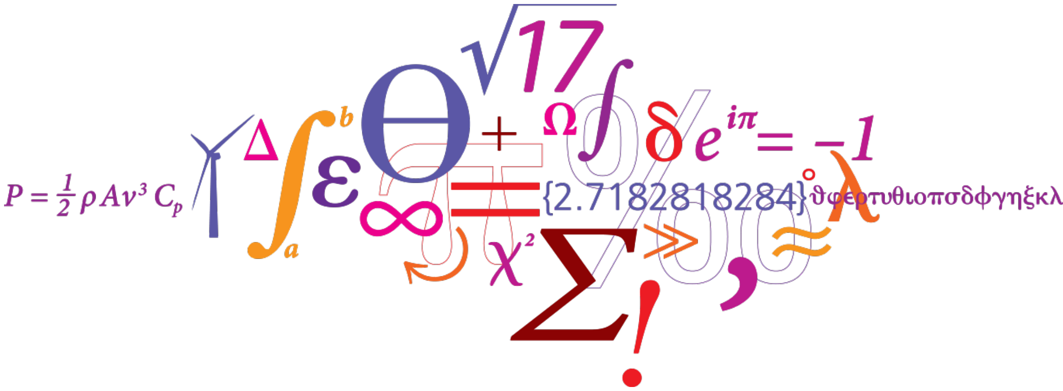
Offshore CREYAP Part 2 – final results

Niels G Mortensen, Morten Nielsen & Hans E Jørgensen

EWEA Resource Assessment 2015
Helsinki, Finland



DTU Wind Energy
Department of Wind Energy

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

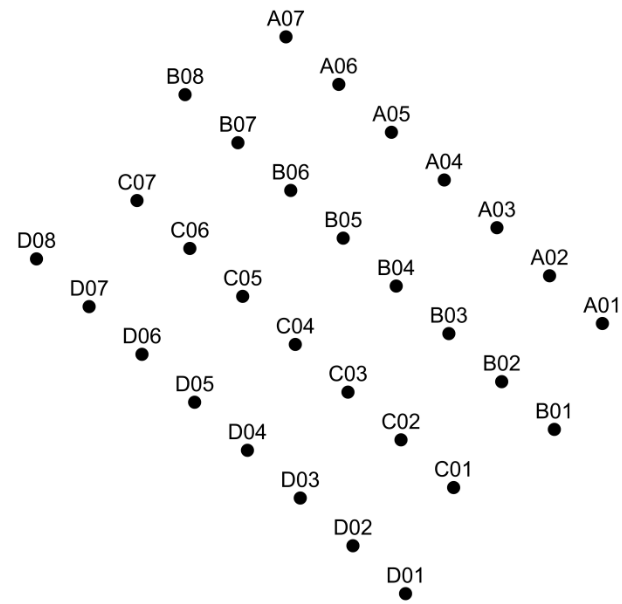
- Onshore Part 1, Bruxelles 2011
  - Scotland W, 28 MW, 37 teams
- Onshore Part 2, Dublin 2013
  - Scotland E, 29 MW, 60 teams
- Offshore Part 1, Frankfurt 2013
  - Gwynt y Môr, 576 MW, 37 teams
- Offshore Part 2, Helsinki 2015
  - Barrow, 90 MW, 22 teams

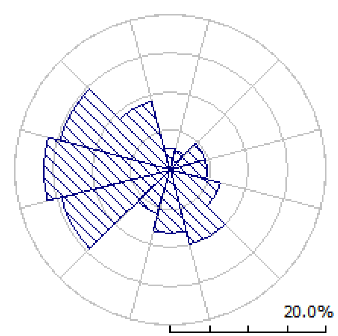
Summary

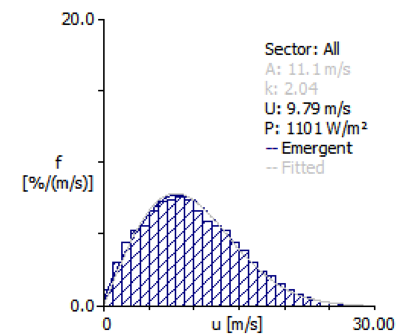
- 156 submissions from 27 countries

Barrow Offshore Wind Farm

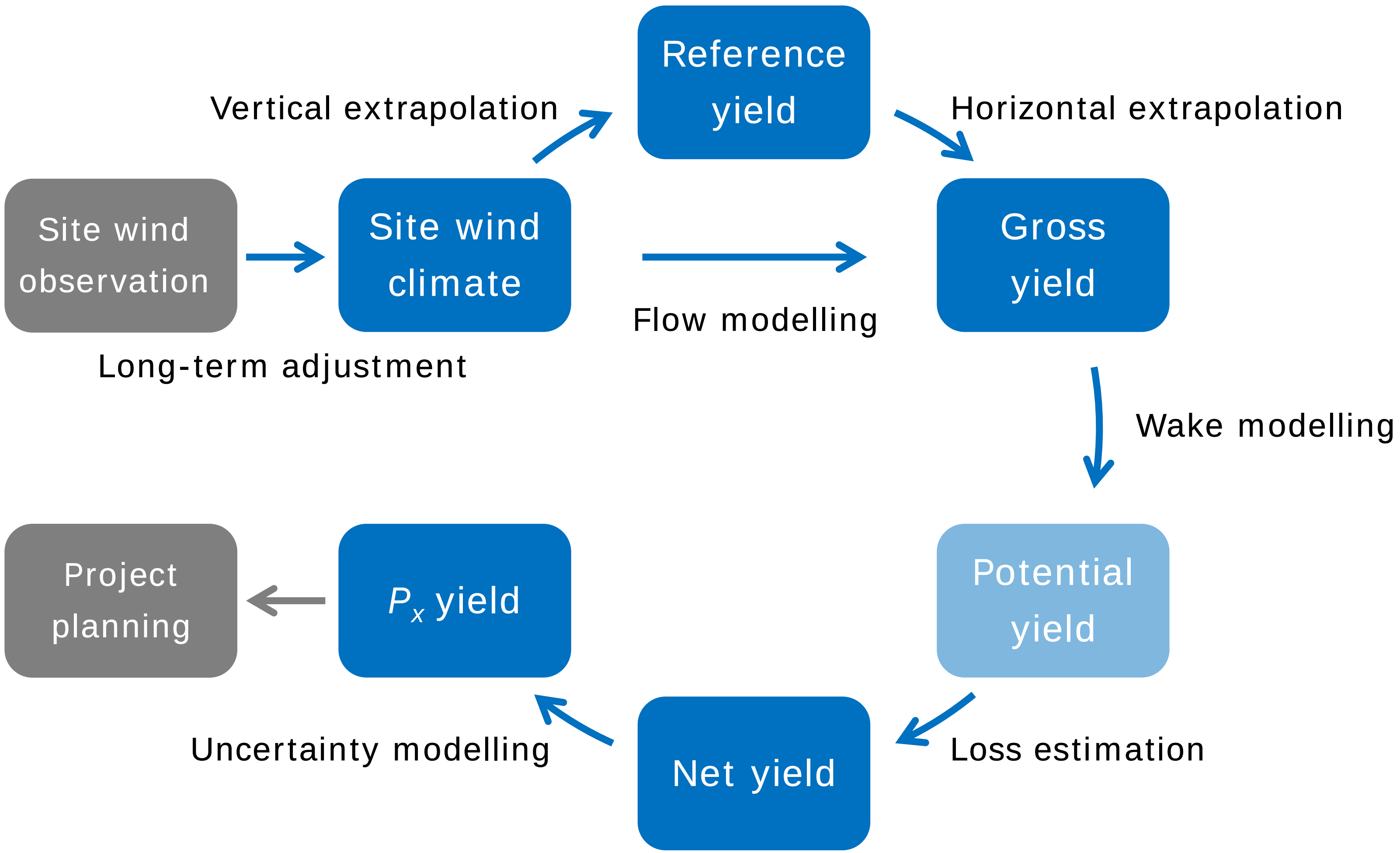
- 30 V90 wind turbines (90 MW)
  - Rated power: 3.0 MW
  - Hub height: 75 m MSL
  - Rotor diameter: 90 m
  - 4 staggered rows, $5.5 \times 8.5\ D$
  - Air density: 1.23 kg m^{-3}
  - SCADA: 2008-02 to 2009-01
- Site meteorological masts
  - One 80-m and 50-m mast
  - Wind speed and direction
  - Temperature and pressure
  - Data: 2011-07 to 2012-08
- Auxiliary data
  - MERRA reanalysis 1998-2013
  - Topographical data by choice



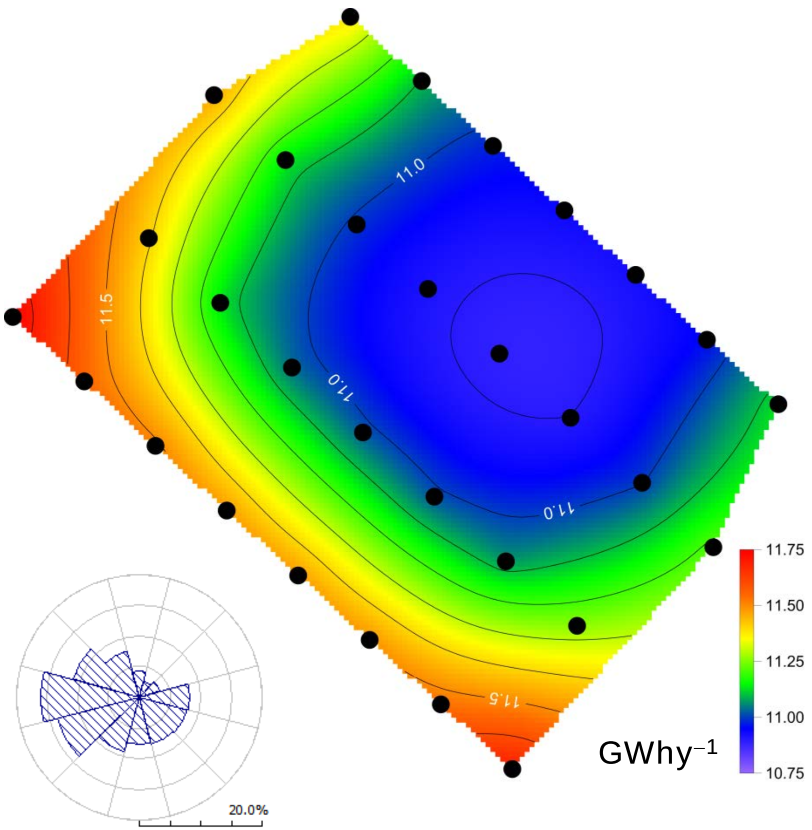


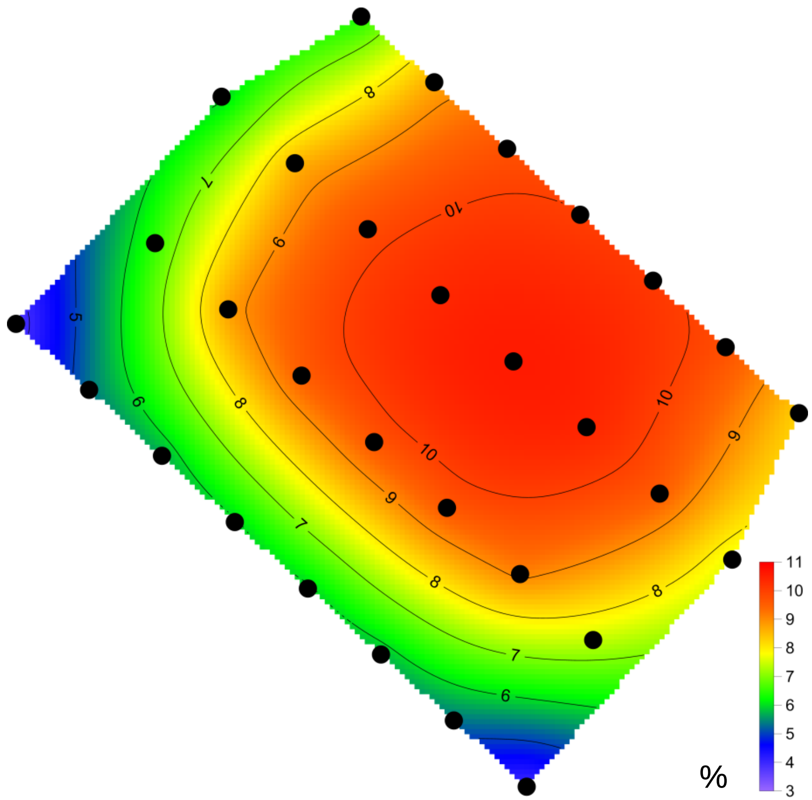


Steps in the energy yield prediction process

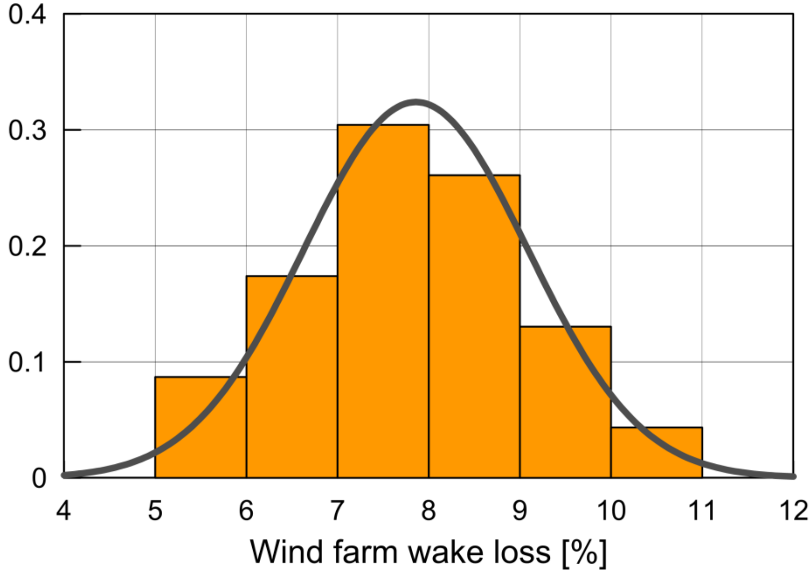


Estimated turbine mean yield and wake effect (10 y)





Predicted wind farm wake losses



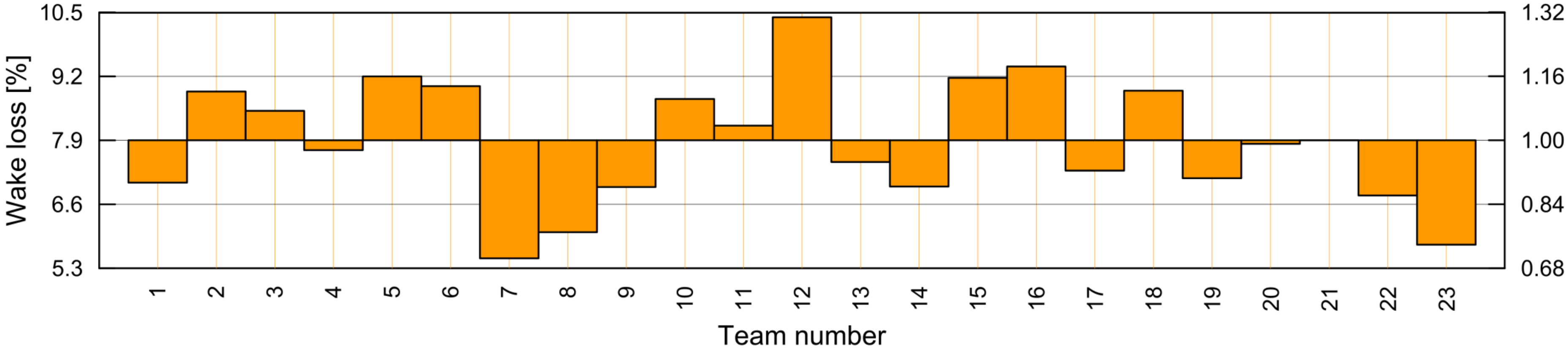
Data points used = 23 (of 23)

Mean wake loss = 7.9%

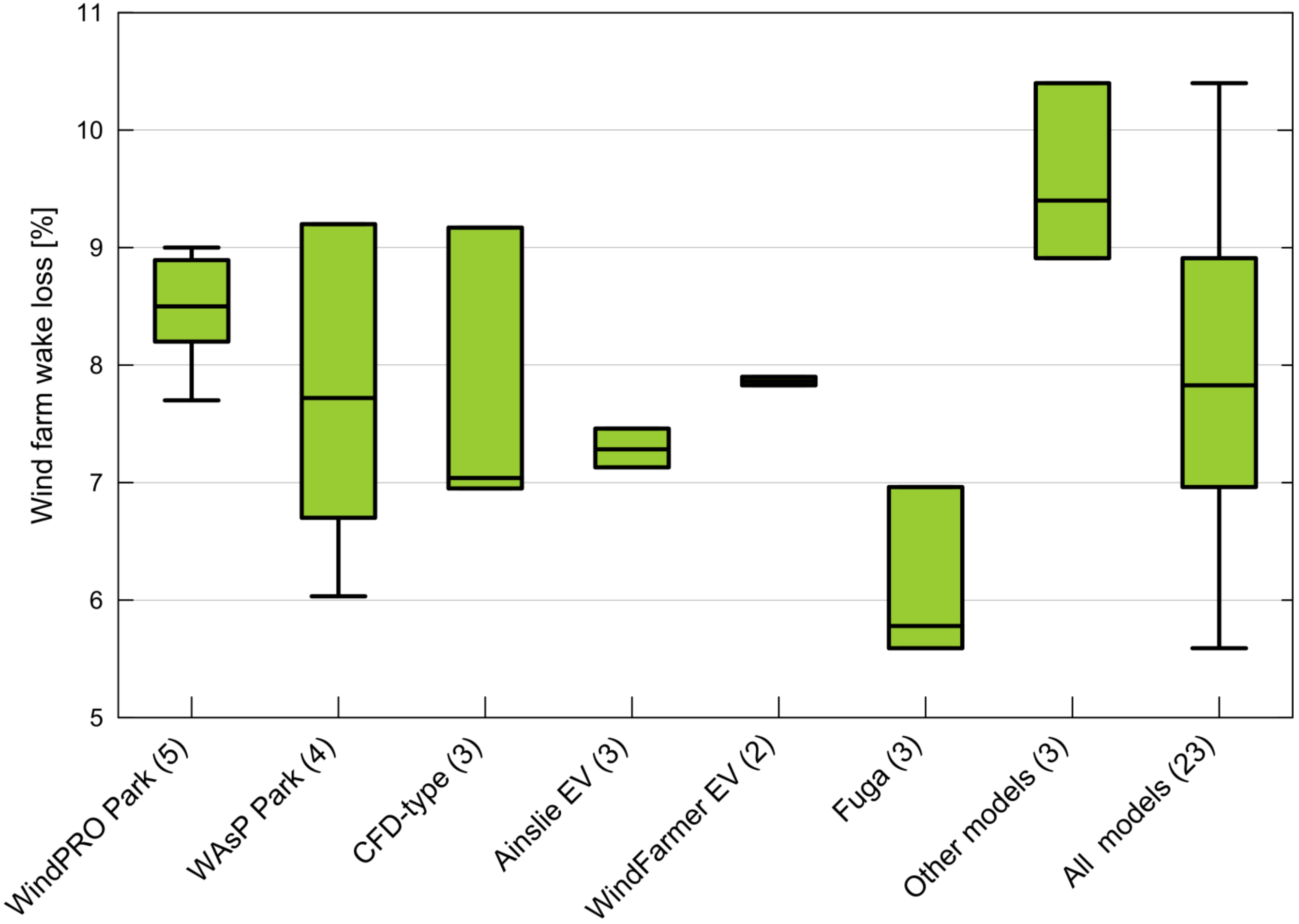
Standard deviation = 1.3%

Coefficient of variation = 16%

Range = 5.5 to 10.4%



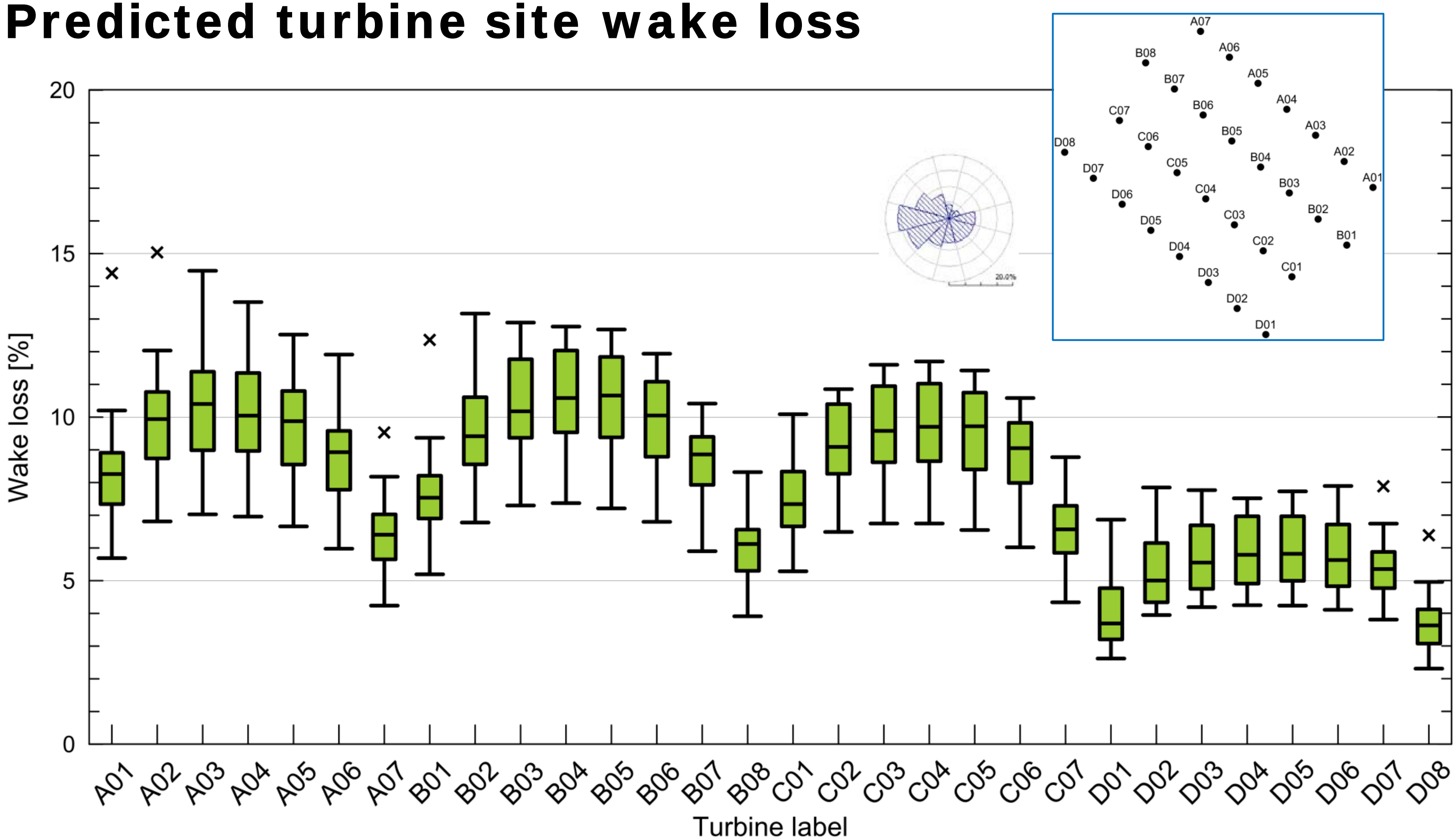
Comparison of wake models



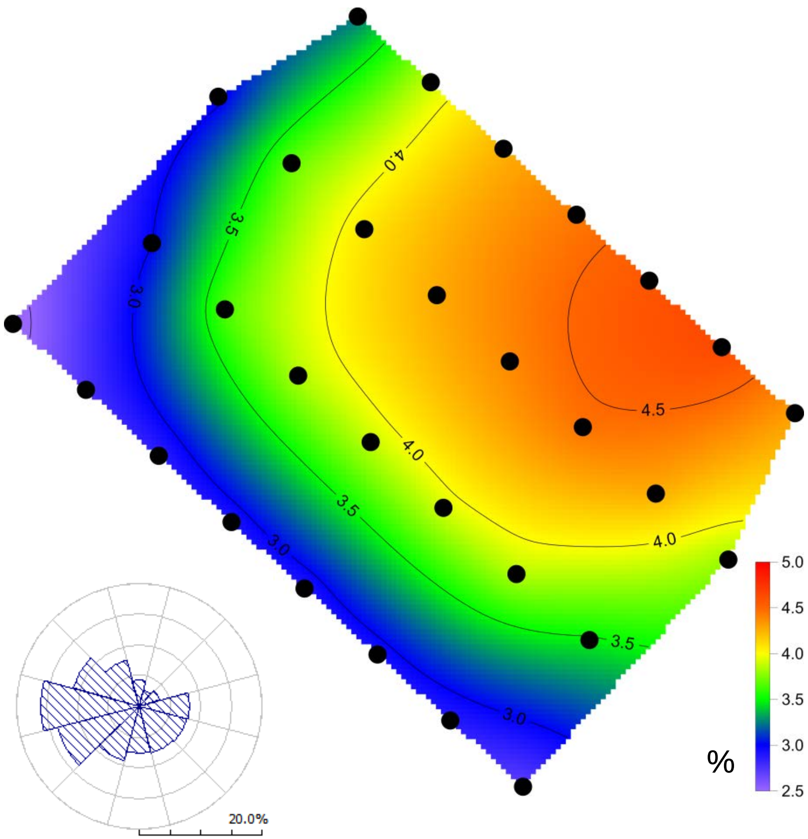
Wake models used

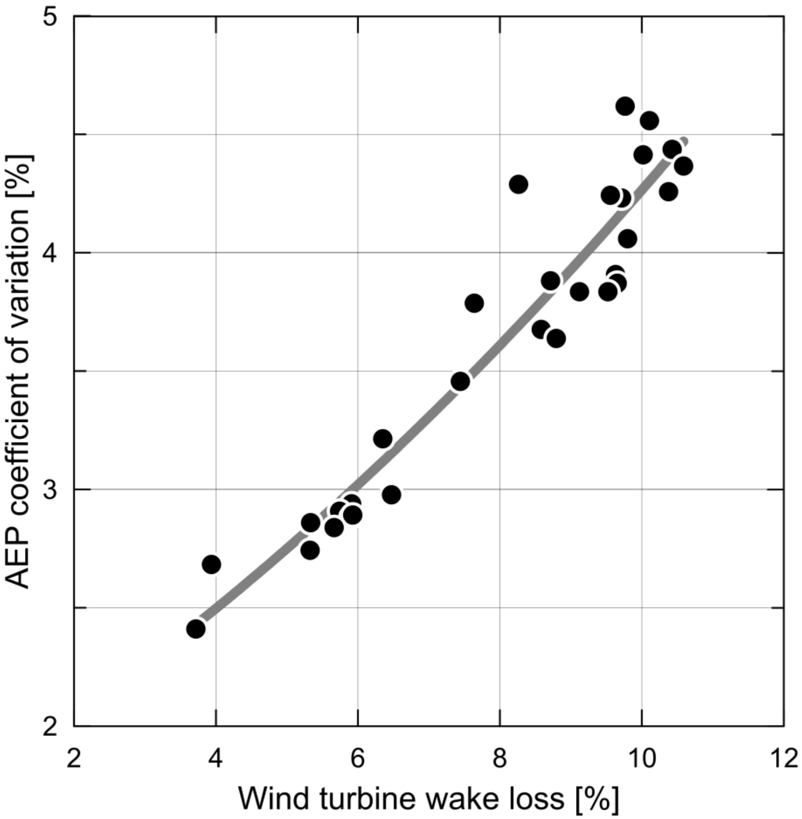
- windPRO Park (N.O. Jensen) (5)
  - k = 0.04, offshore settings, ...
- WAsP Park (4)
  - $k = \{0.03, 0.04, 0.05, 0.075\}$
- CFD-type (3)
  - OpenFoam CFDwake, CFD+linear, WindSim WM-1
- Ainslie Eddy Viscosity (3)
  - Quarton, + linearised CFD, +equivalent roughness
- WindFarmer Eddy Viscosity (2)
  - 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

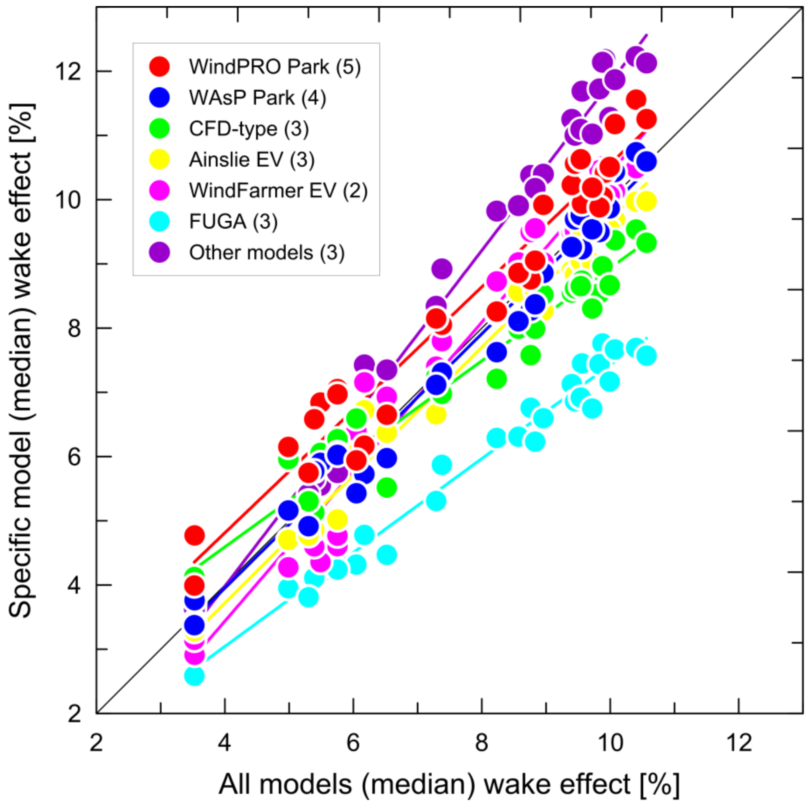


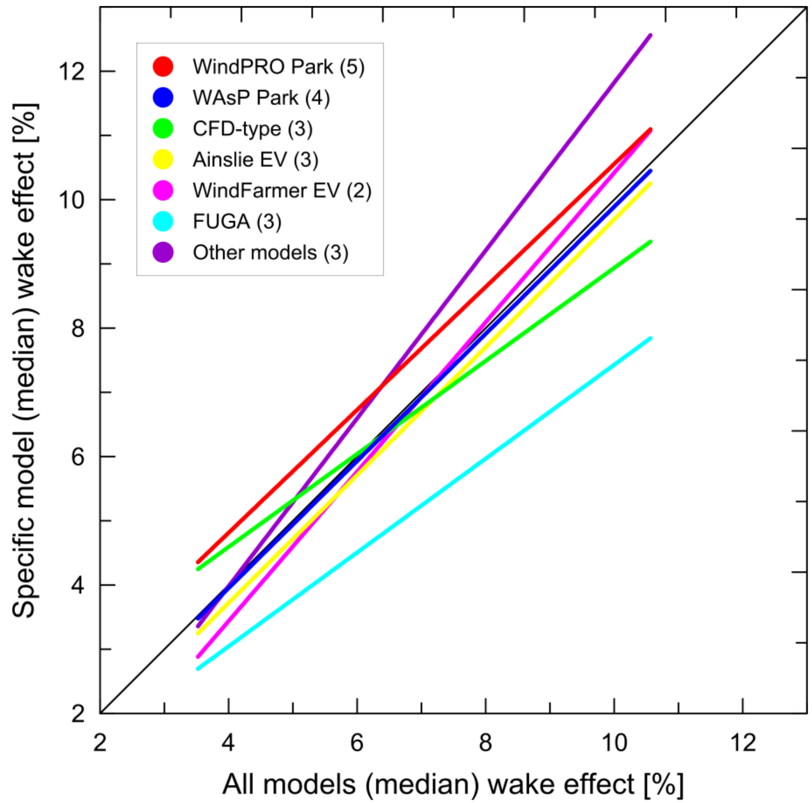
Estimated turbine yields – coefficient of variation



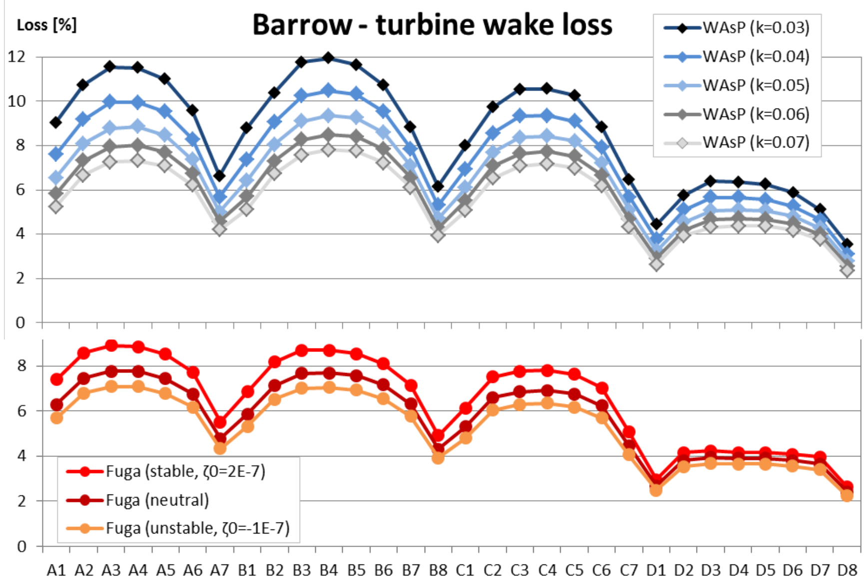


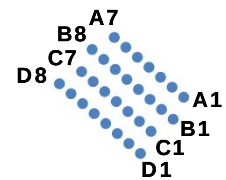
Predicted turbine site wake losses

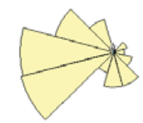




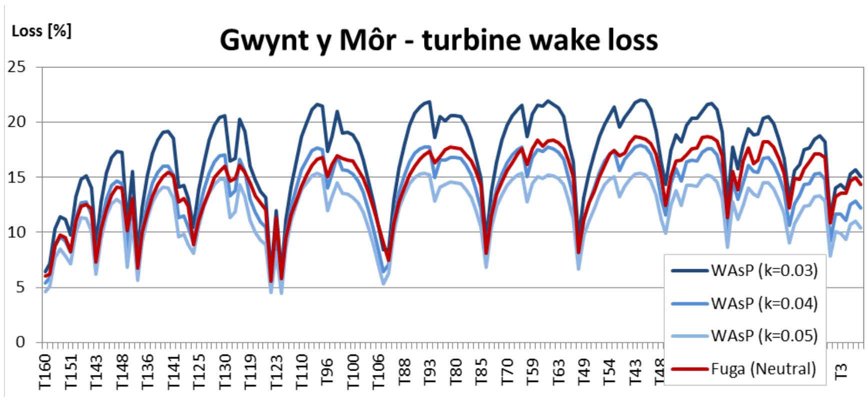
Sensitivity to WAsP and Fuga input parameters

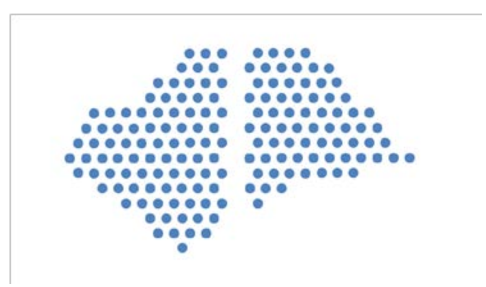






- Variable input parameters explain spread in wake loss predictions
- Impossible to select universal parameters which will match WAsP and Fuga results for all turbine positions



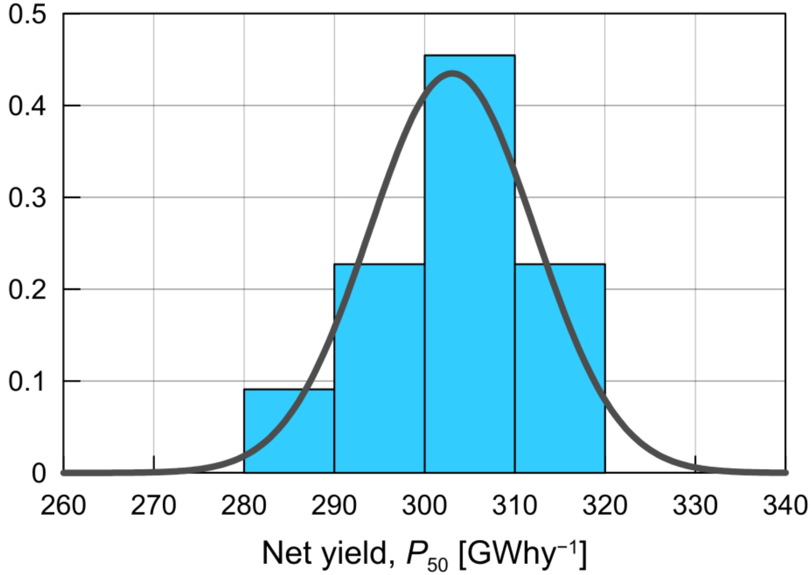


Wake modelling uncertainty (CREYAP 1-4)

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

* N.G. Nygaard, EWEA Offshore 2015

Net energy yield of wind farm, P_{50} (10 y)



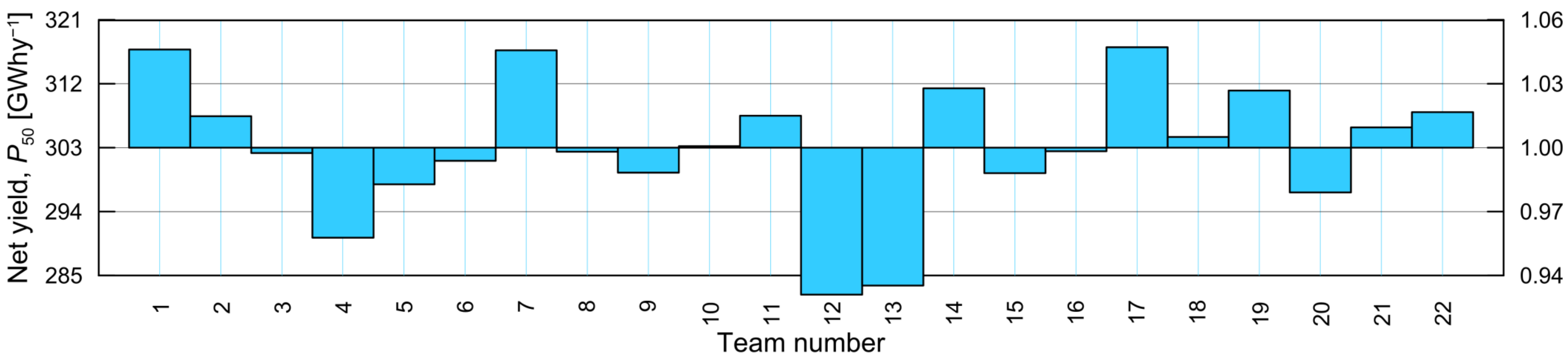
Data points used = 22 (of 22)

Mean net yield = 303 GWhy^{-1}

Standard deviation = 9.4 GWhy^{-1}

Coefficient of variation = 3.1%

Range = 282 to 317 GWhy^{-1}

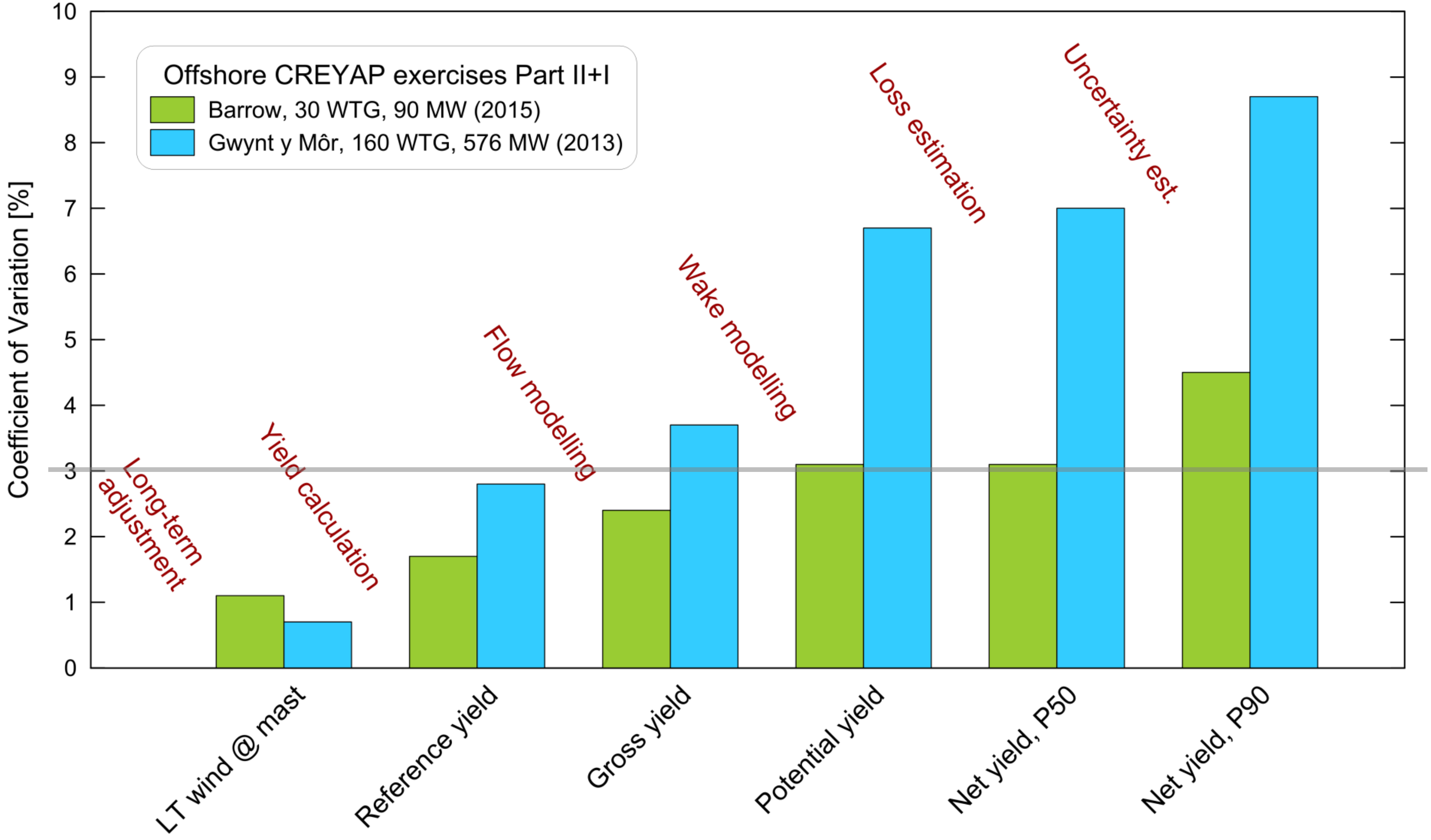


Wind farm key figures (10-y estimates)

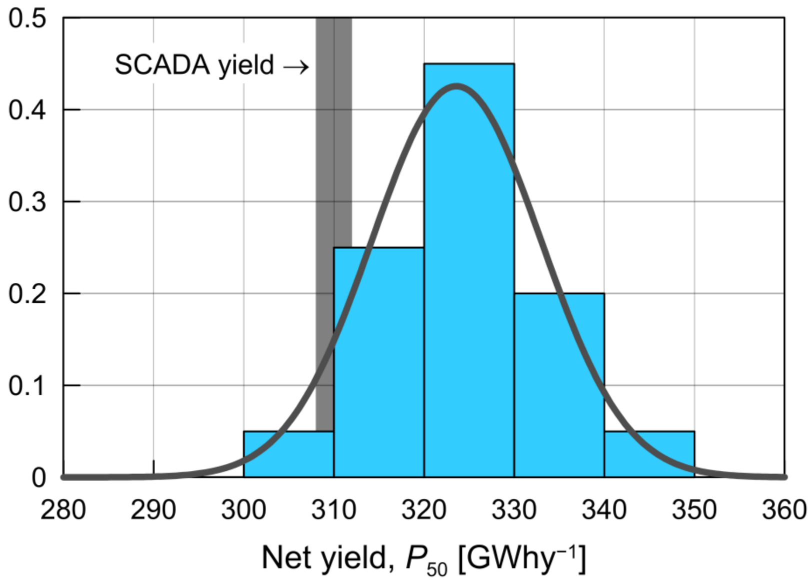
Barrow (10 y)		**Mean**	**σ**	**CV***	**Min**	**Max**
Gross yield	GWh	366	8.9	2.4	338	377
Wake loss	%	7.9	1.3	16.0	5.5	10.4
Potential yield	GWh	334	10.3	3.1	311	350
Technical losses	%	9.3	0.1	1.0	9.2	9.6
Net yield P_{50}	GWh	303	9.4	3.1	282	317
Uncertainty	%	9.7	2.3	23.4	6.1	13.7
Net yield P_{90}	GWh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

* Coefficient of Variation in per cent

Spread for different steps in the prediction process



Comparison of predicted to observed P_{50} (1 year)



Data points used = 20 (of 22)

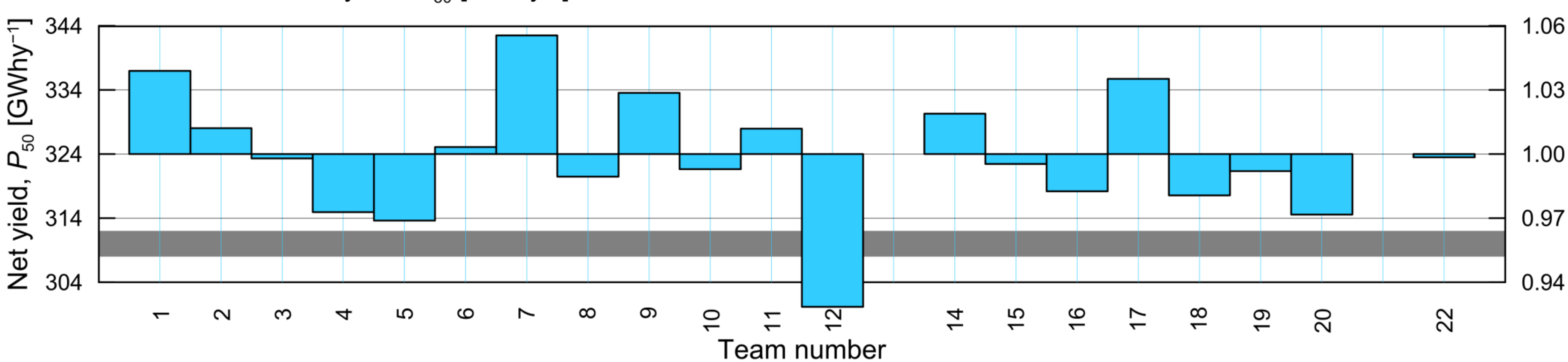
Mean predicted P_{50} = 324 $GWhy^{-1}$

Standard deviation = 9.6 $GWhy^{-1}$

Coefficient of variation = 3.0%

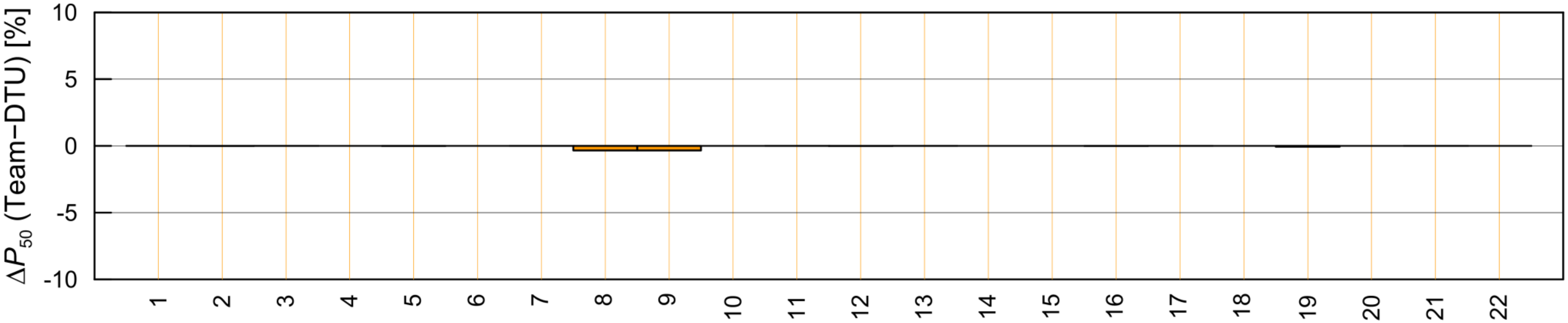
Range = 300 to 343 $GWhy^{-1}$

Prediction bias = +4%



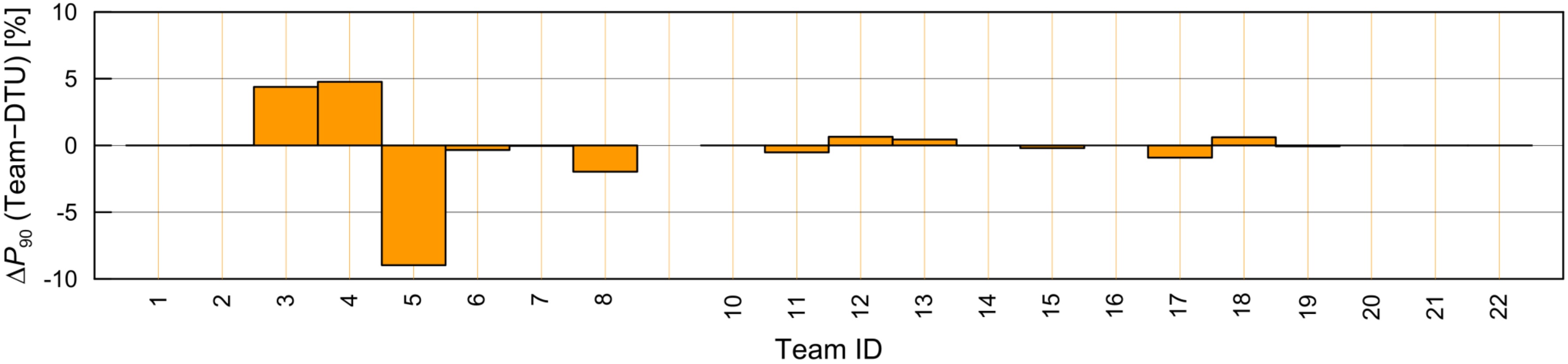
Quality assurance of submitted spreadsheets

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

Offshore datums and transition piece	Input change	AEP change in %
• Met. mast height	MSL → HAT	+0.9
• Wind turbine hub height	MSL = HAT – 5 m	–1.1
Modelling parameter (examples)		
• Wake decay parameter *k* in Park	0.01 in *k*	0.7
• Stability settings in FUGA	1/1000 in 1/*L*	0.5
Wind climatology		
• Calibration of anemometer	1% in *U*	1.3
• Long-term correlation	1% in *U*	1.3
Power production estimation		
• Air density estimation	1% in ρ	0.6
• Power curve / turbine specification	several	???
Observed production statistics		
• Independent calculations		1.3

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!

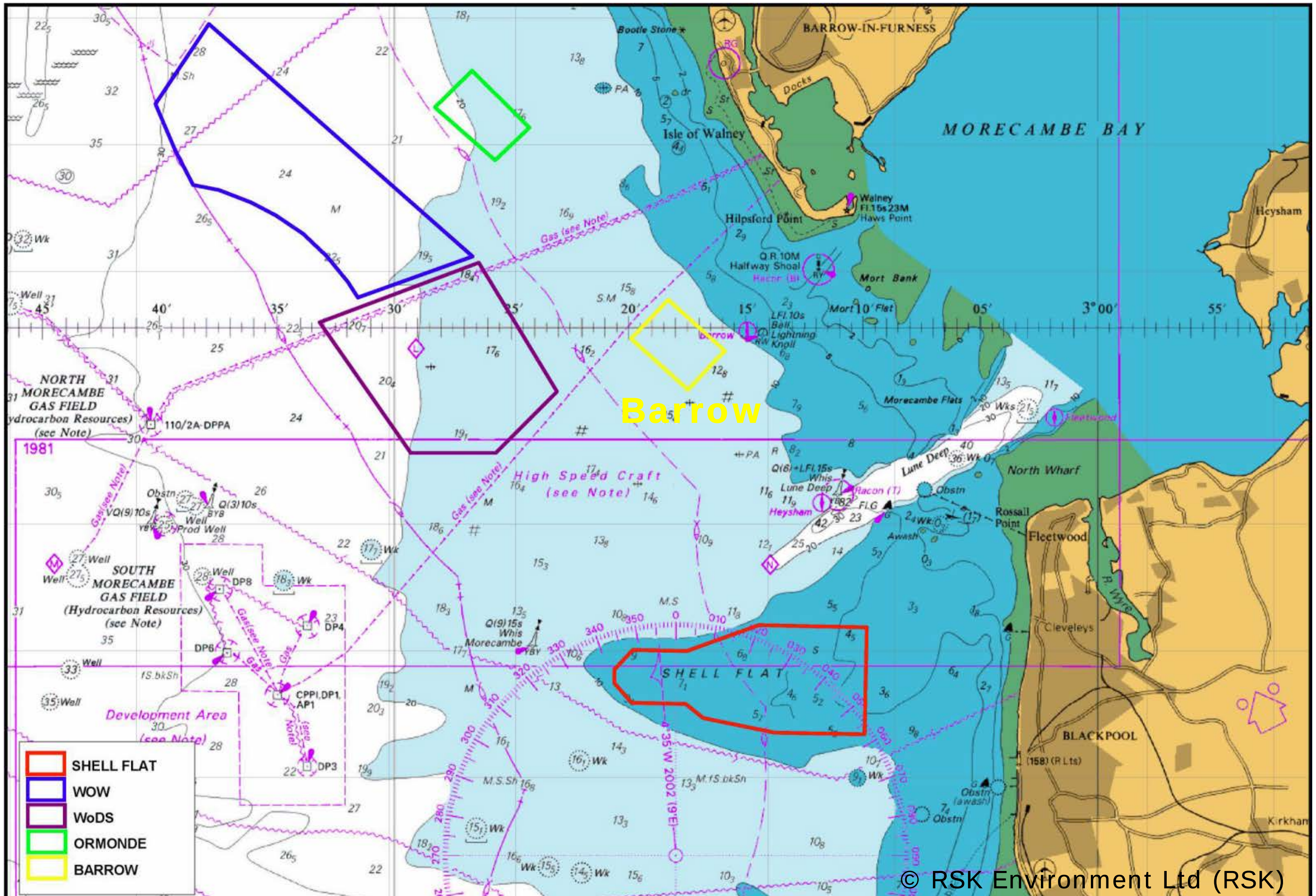
Thank you for your attention!

Who submitted results?

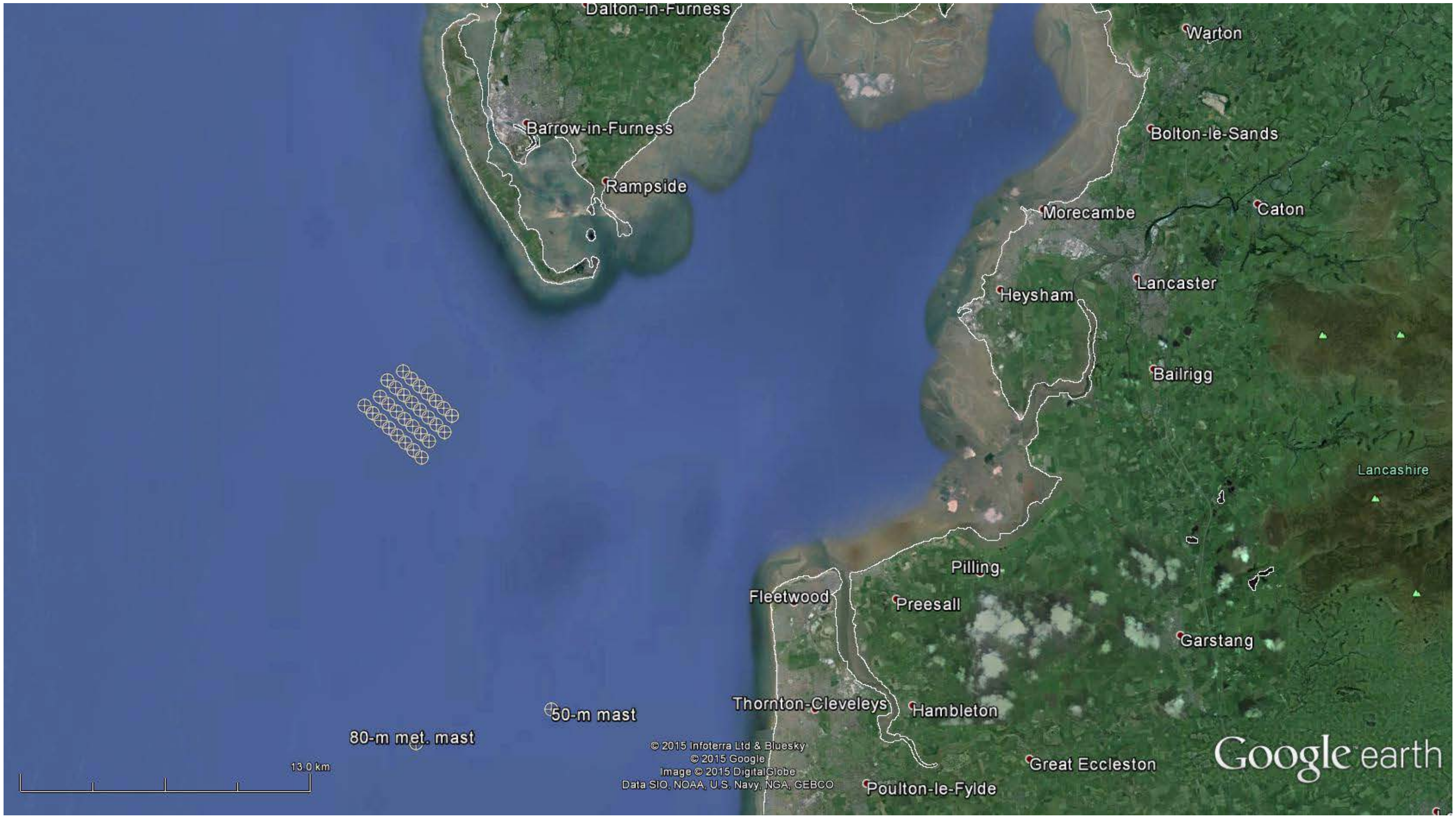
- 20 organisations (22 teams) from 8 countries submitted results
  - Belgium, Denmark, Germany, India, Norway, Spain, UK, US

- Names of organisations
  - AWS Truepower LLC, Barlovento Recursos Naturales, CENER, CIRCE, COWI A/S, Deutsche WindGuard, DONG Energy, DTU Wind Energy, Mott MacDonald, Mytrah Energy (India) Ltd, Natural Power, OST Energy, RES, ScottishPower Renewables – Iberdrola, Senvion SE, UL International GmbH (DEWI), Wind Prospect Ltd, WIND-consult GmbH, WindSim AS, YCON BVBA

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 × [uncertainty estimate]
    - comparison of uncertainty estimates
7. Comparison to teams average AEP – spread and bias

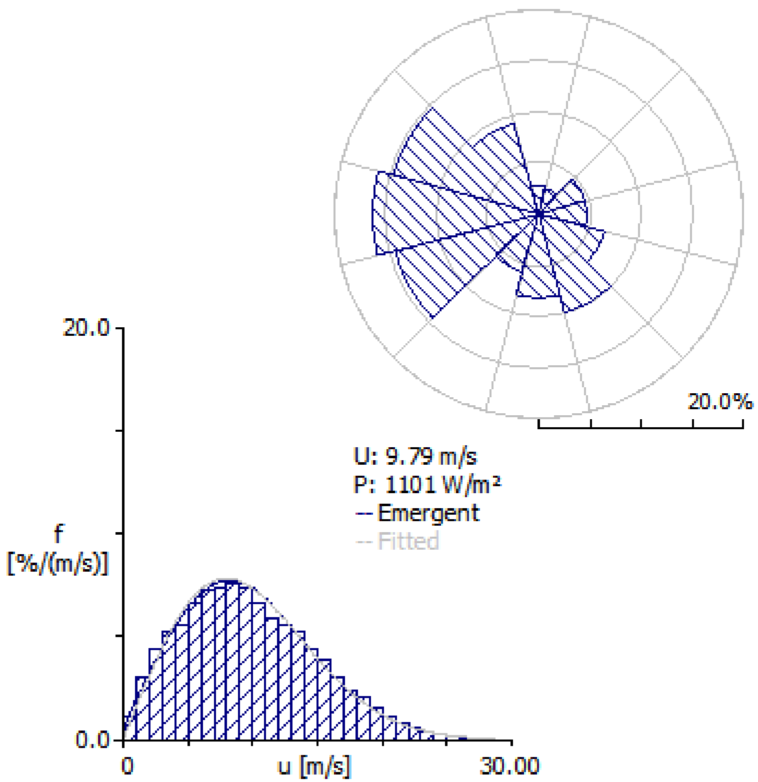
Comparisons of results and methods {notes}

- 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

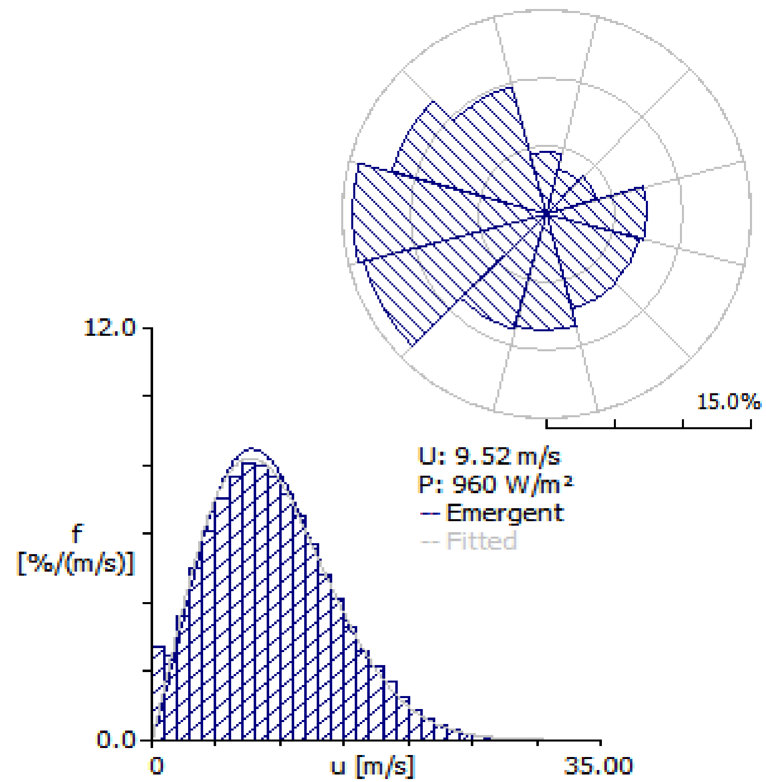
Site meteorological mast

- 1 y of 10-min data (2011-12)

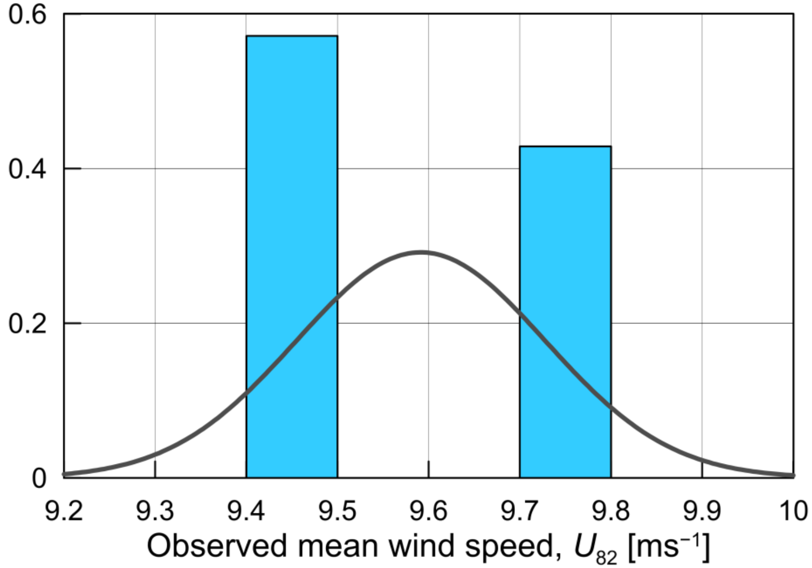


MERRA reanalysis data

- 16 y of hourly data (1998-2013)



Observed wind speed @ 82 m



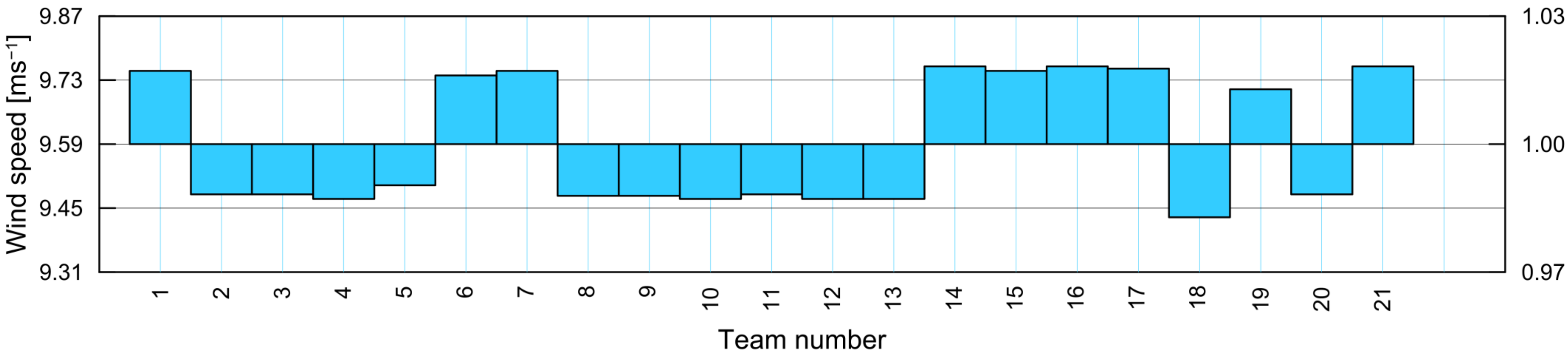
Data points used = 21 (of 22)

Mean wind speed = 9.59 ms^{-1}

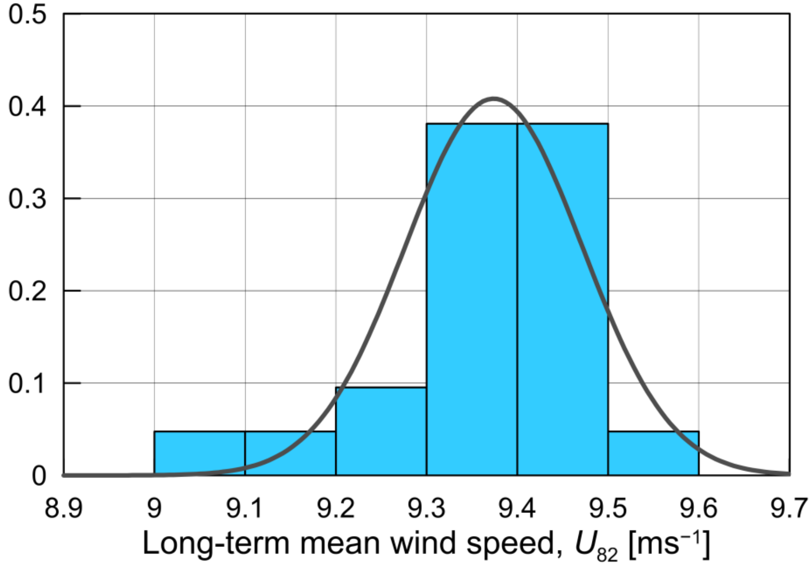
Standard deviation = 0.14 ms^{-1}

Coefficient of variation = 1.5%

Range = 9.43 to 9.76 ms^{-1}



Long-term wind speed @ 82 m



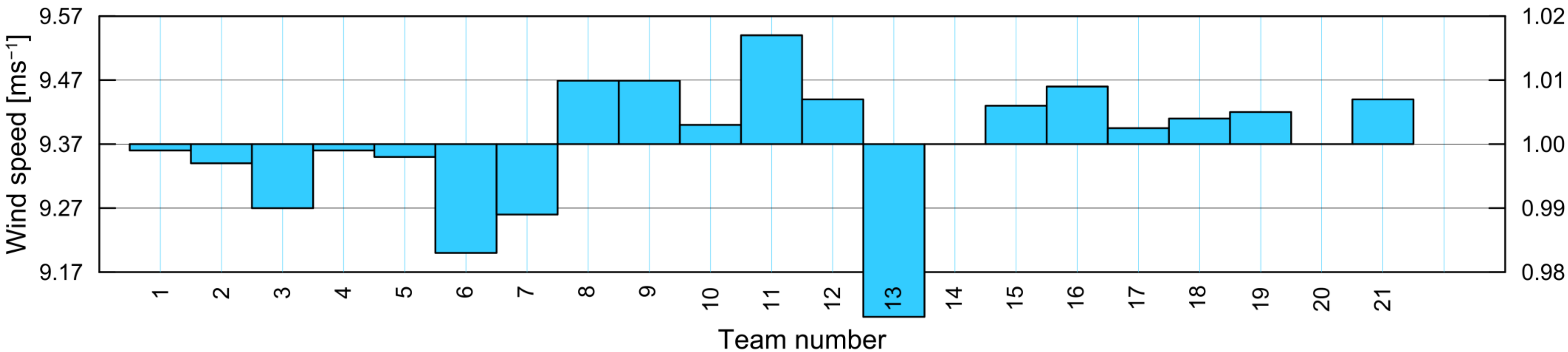
Data points used = 21 (of 22)

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

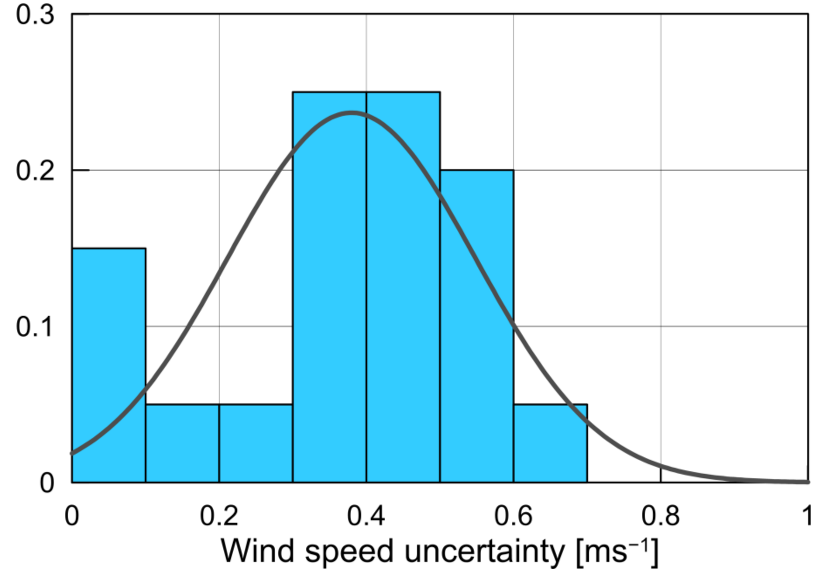
Data points used = 20 (of 22)

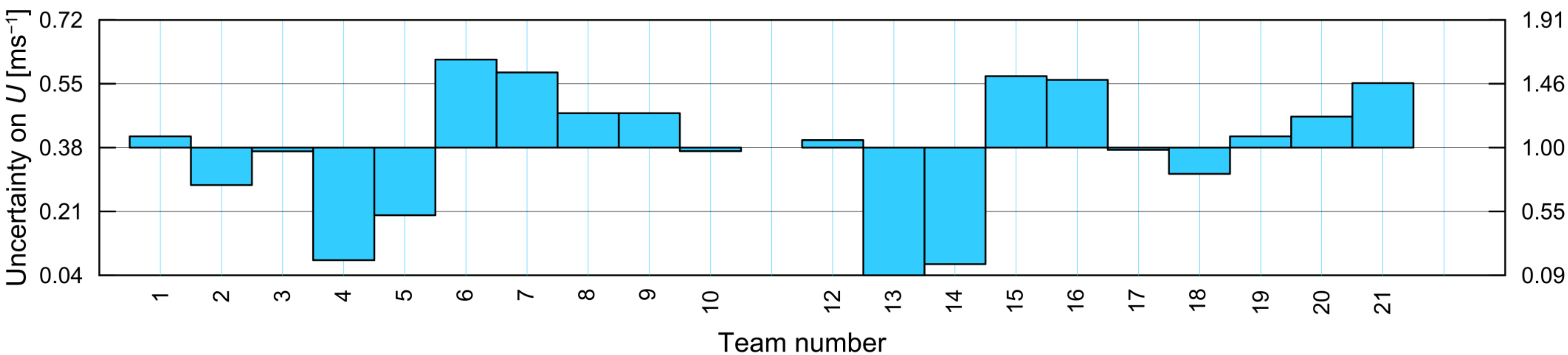
Mean uncertainty = 0.38 ms^{-1}

Standard deviation = 0.17 ms^{-1}

Coefficient of variation = 46%

Range = 0.04 to 0.61 ms^{-1}





Turbulence intensity @ 82 m

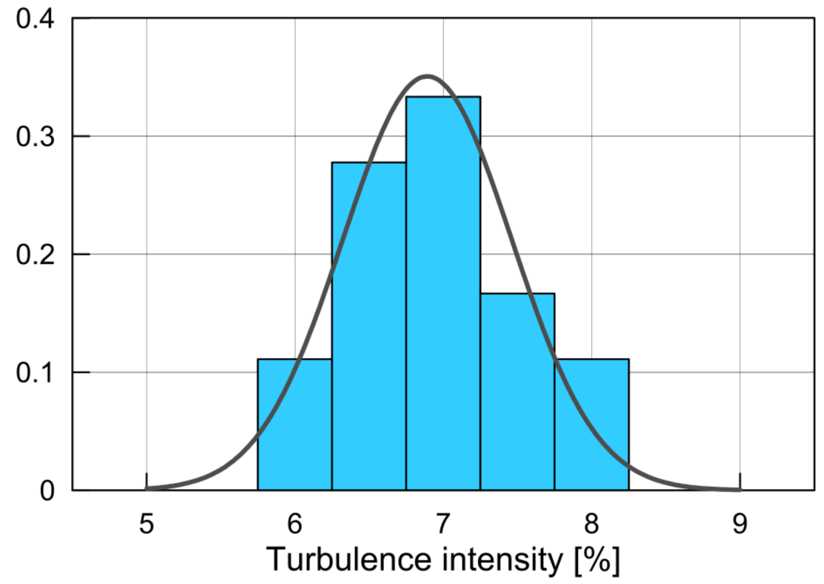
Data points used = 18 (of 22)

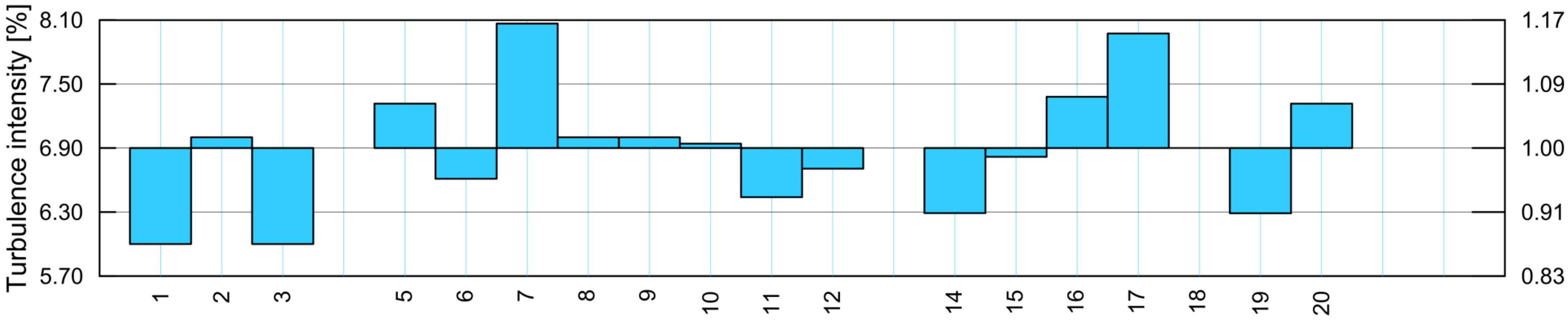
Mean turbulence intensity = 6.9%

Standard deviation = 0.6%

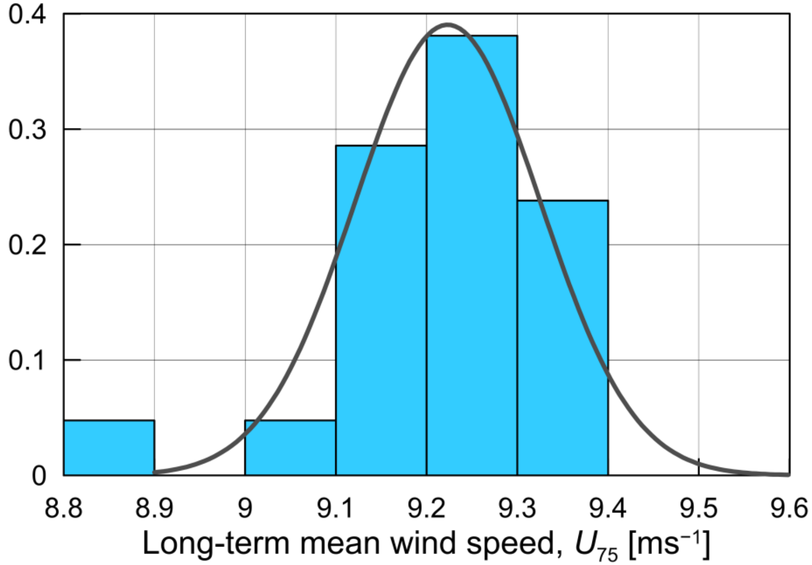
Coefficient of variation = 8.5%

Range = 6.0 to 8.1%





Long-term wind speed @ 75 m



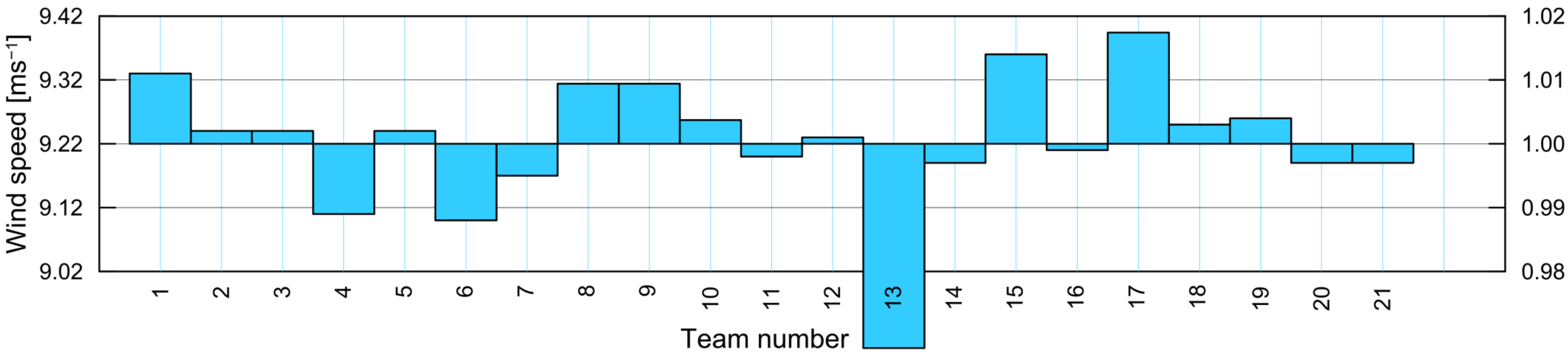
Data points used = 21 (of 22)

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 ρ @ hub height

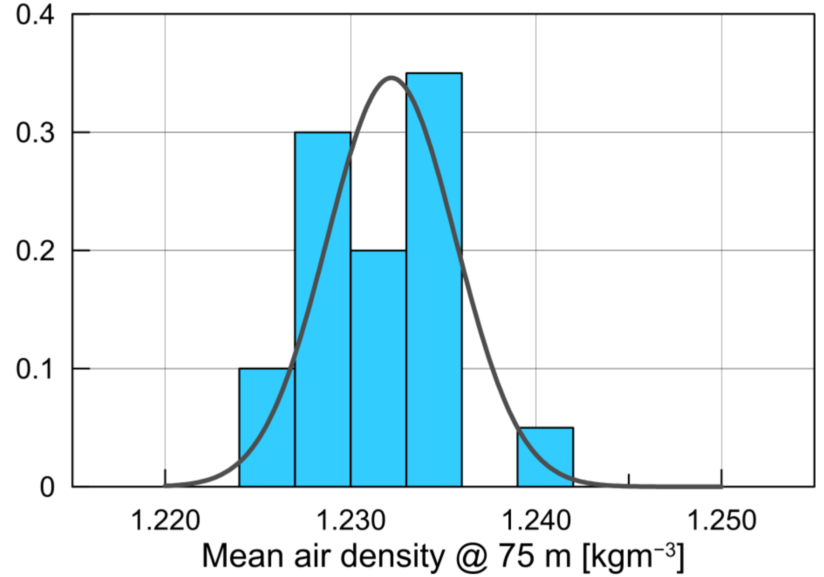
Data points used = 21 (of 22)

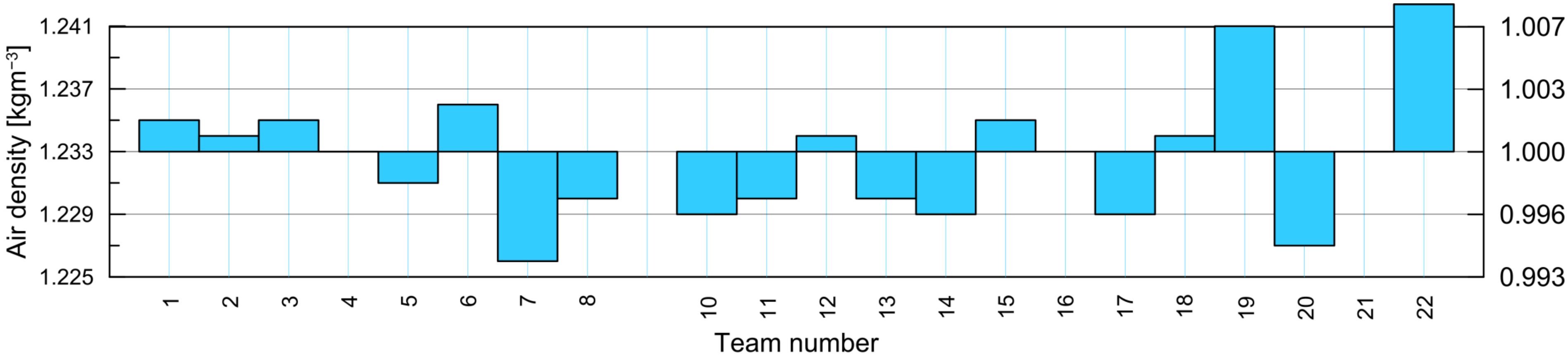
Mean air density = 1.233 kgm^{-3}

Standard deviation = 0.004 kgm^{-3}

Coefficient of variation = 0.3%

Range = 1.226 to 1.242 kgm^{-3} (1%)



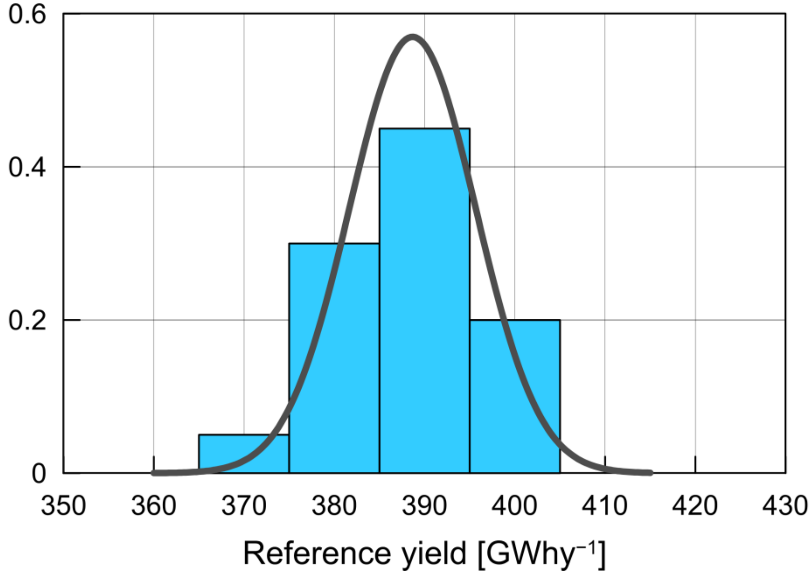


Wind farm key figures – 1 year estimates

Barrow (1 y)		Mean	σ	CV*	Min	Max
Potential yield	GWh	389	7.0	1.8	373	399
Wake loss	%	7.5	1.1	14.8	5.2	9.2
Gross energy yield	GWh	357	10.7	3.0	331	378
Technical losses	%	9.3	0.1	1.0	9.2	9.6
Net energy yield P_{50}	GWh	324	9.6	3.0	300	343
Measured	GWh	**308**	312			
Difference	%	5.2	3.8			

* Coefficient of Variation in per cent.

Reference yield of wind farm (1 y)



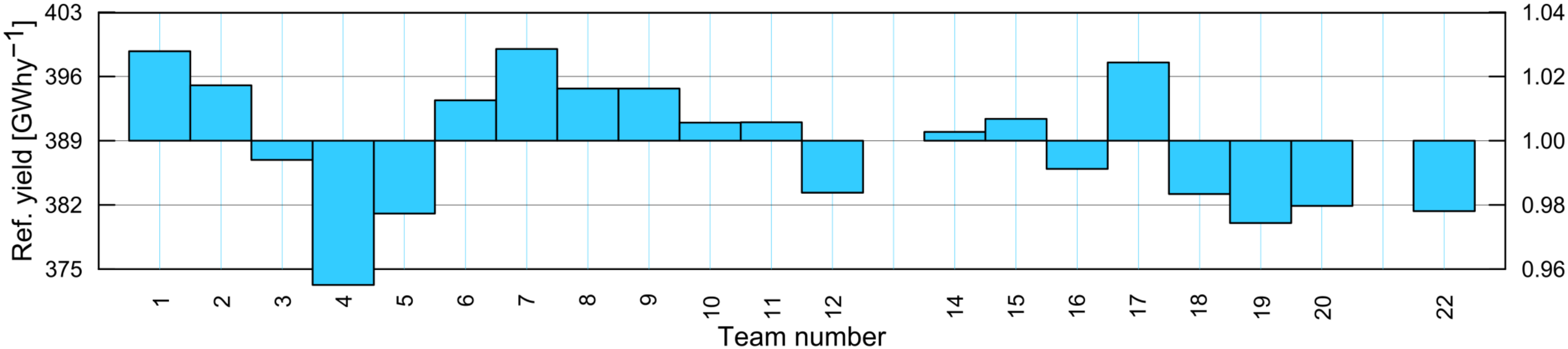
Data points used = 20 (of 22)

Mean net yield = 389 $GWhy^{-1}$

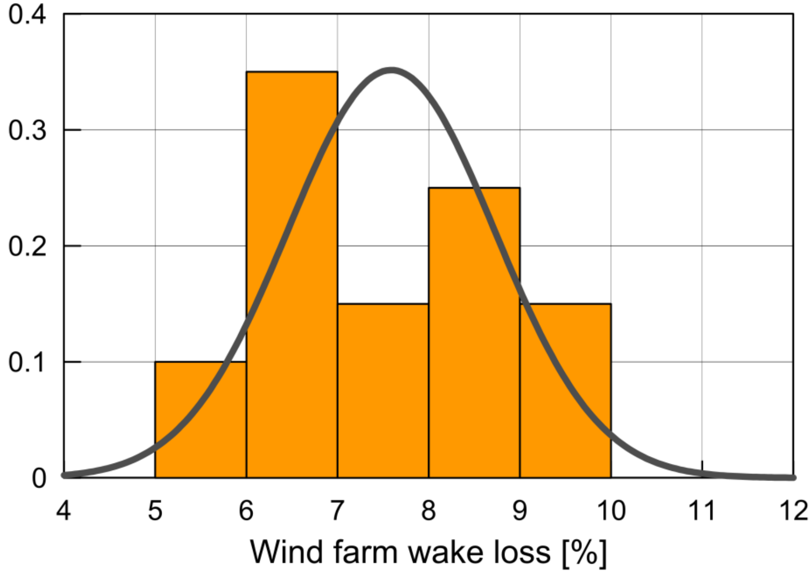
Standard deviation = 7.2 $GWhy^{-1}$

Coefficient of variation = 1.8%

Range = 373 to 399 $GWhy^{-1}$



Predicted wind farm wake losses (1 y)



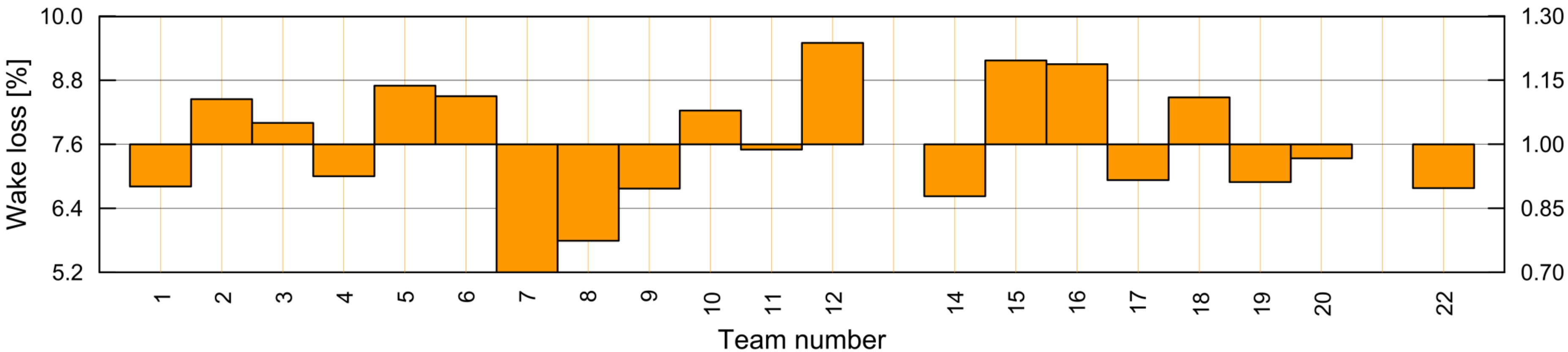
Data points used = 21 (of 22)

Mean wake loss = 7.6%

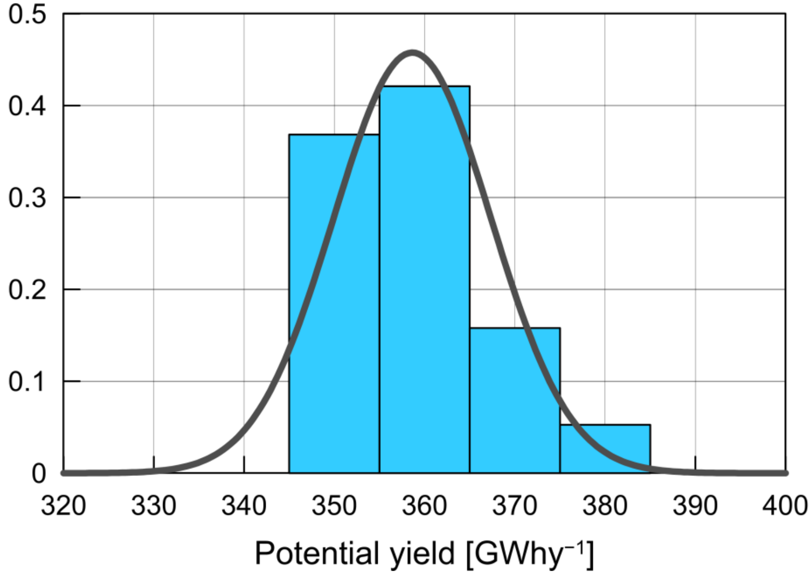
Standard deviation = 1.2%

Coefficient of variation = 15%

Range = 5.2 to 9.5%



Potential yield of wind farm (1 y)



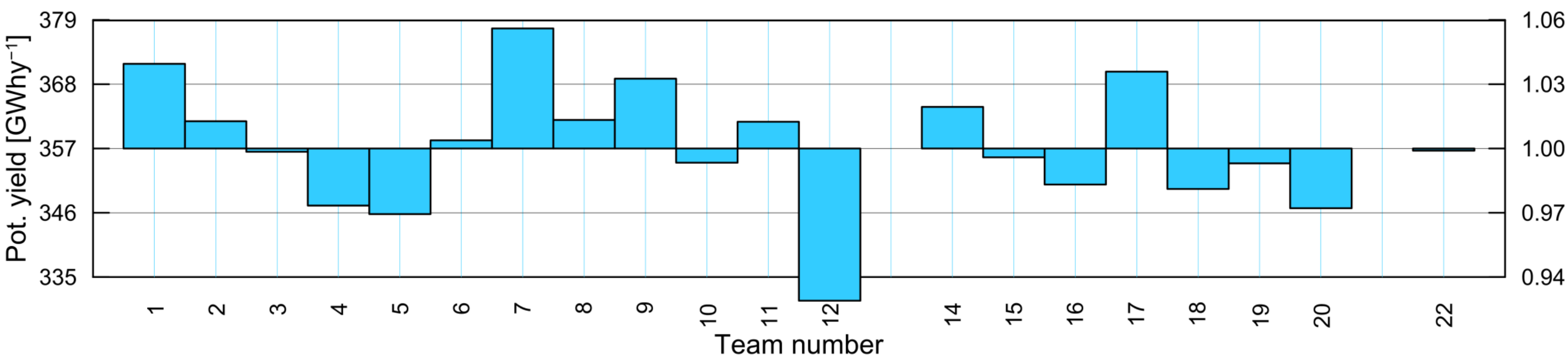
Data points used = 20 (of 22)

Mean net yield = 357 $GWhy^{-1}$

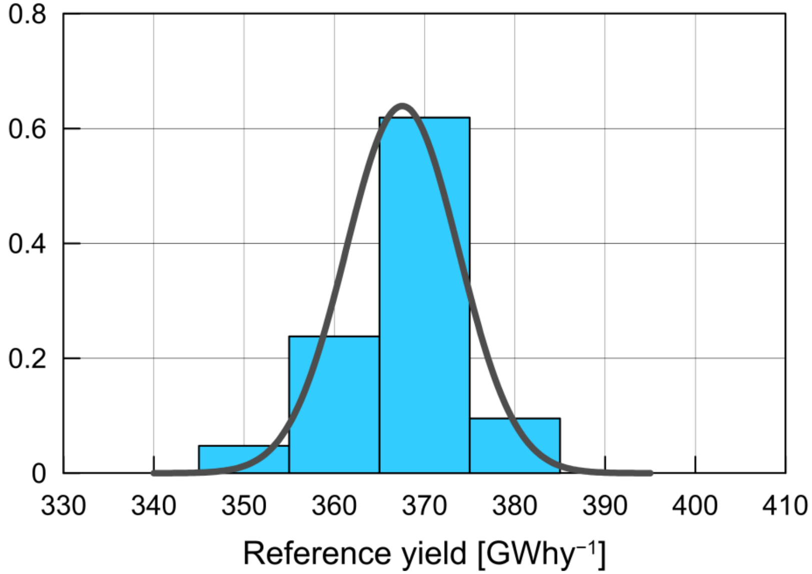
Standard deviation = 10.7 $GWhy^{-1}$

Coefficient of variation = 3.0%

Range = 331 to 378 $GWhy^{-1}$



Reference yield of wind farm



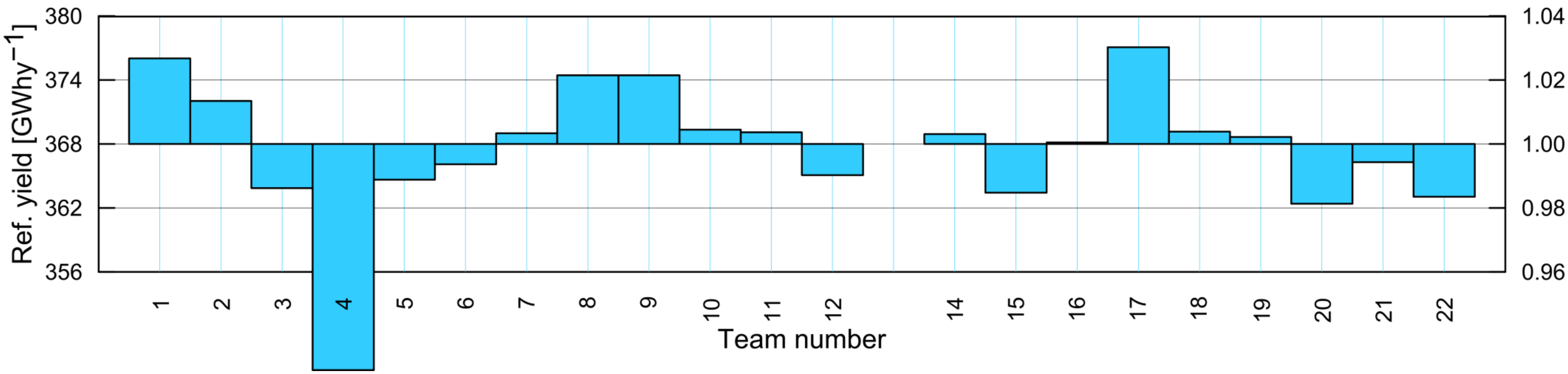
Data points used = 22 (of 22)

Mean reference yield = 368 $GWhy^{-1}$

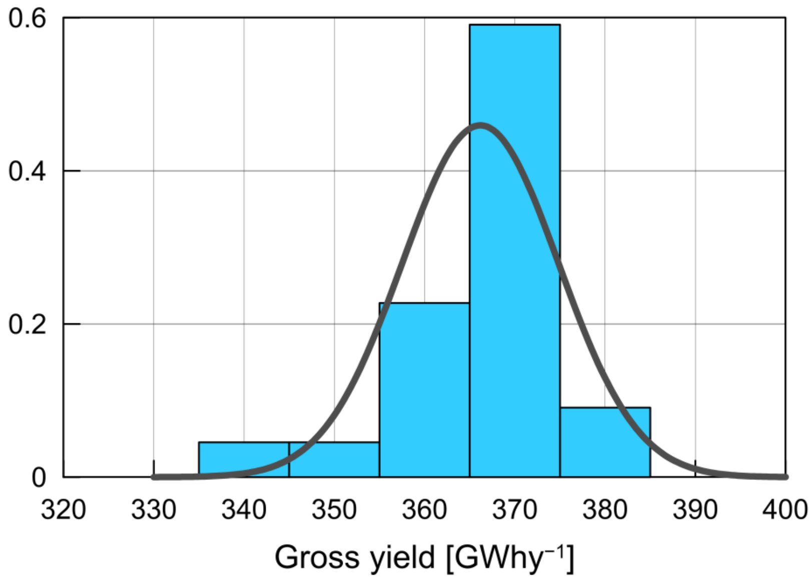
Standard deviation = 6.4 $GWhy^{-1}$

Coefficient of variation = 1.7%

Range = 347 to 377 $GWhy^{-1}$



Gross yield of wind farm



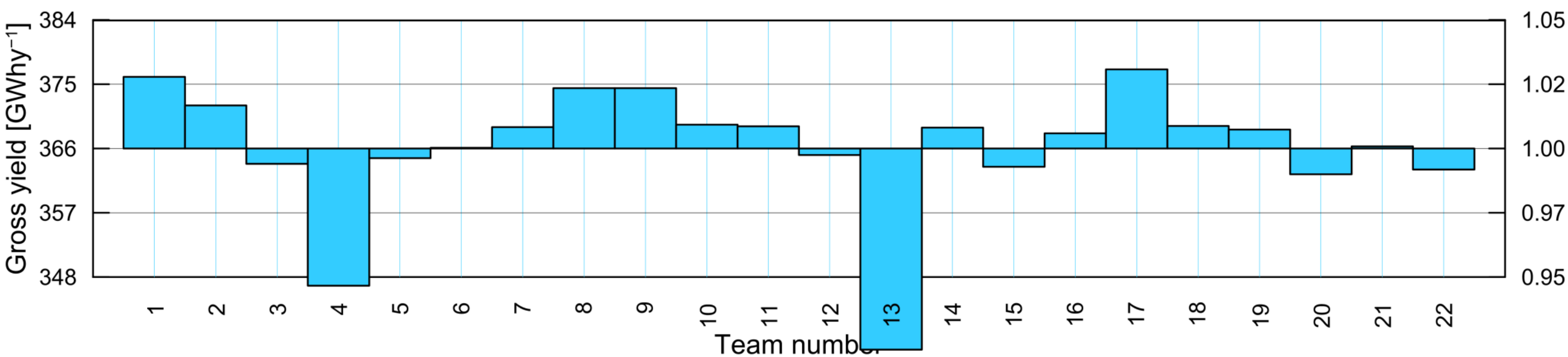
Data points used = 22 (of 22)

Mean gross yield = 366 $GWhy^{-1}$

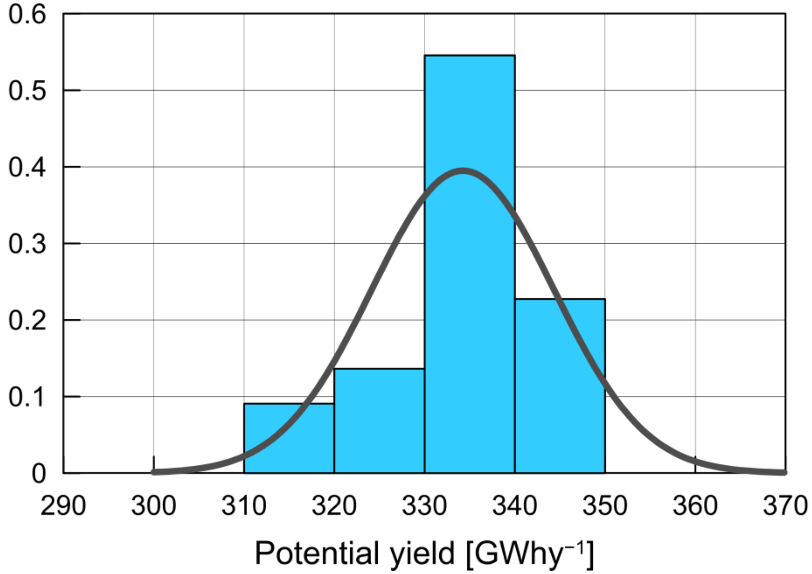
Standard deviation = 8.9 $GWhy^{-1}$

Coefficient of variation = 2.4%

Range = 338 to 377 $GWhy^{-1}$



Potential yield of wind farm



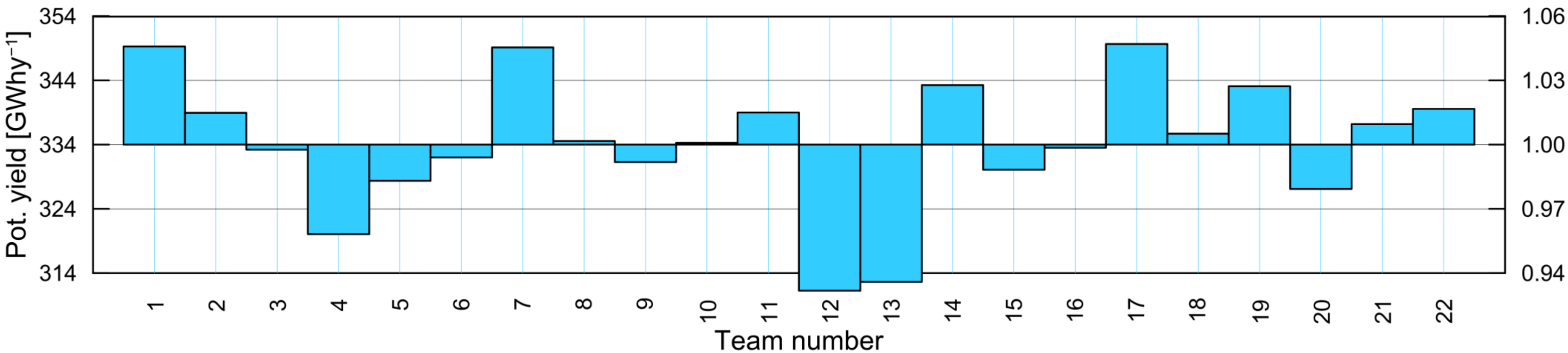
Data points used = 20 (of 22)

Mean potential yield = 334 $GWhy^{-1}$

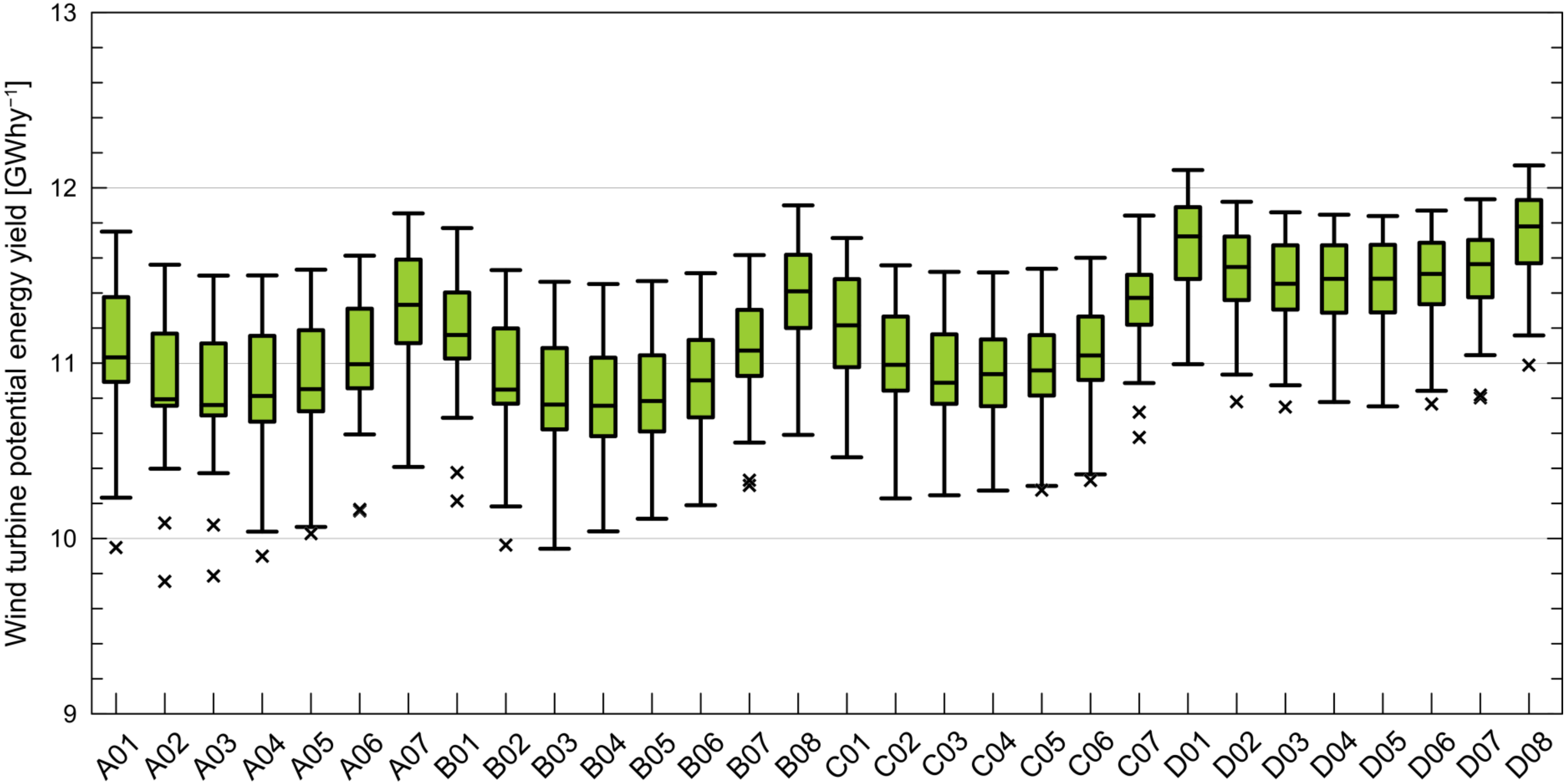
Standard deviation = 10.3 $GWhy^{-1}$

Coefficient of variation = 3.1%

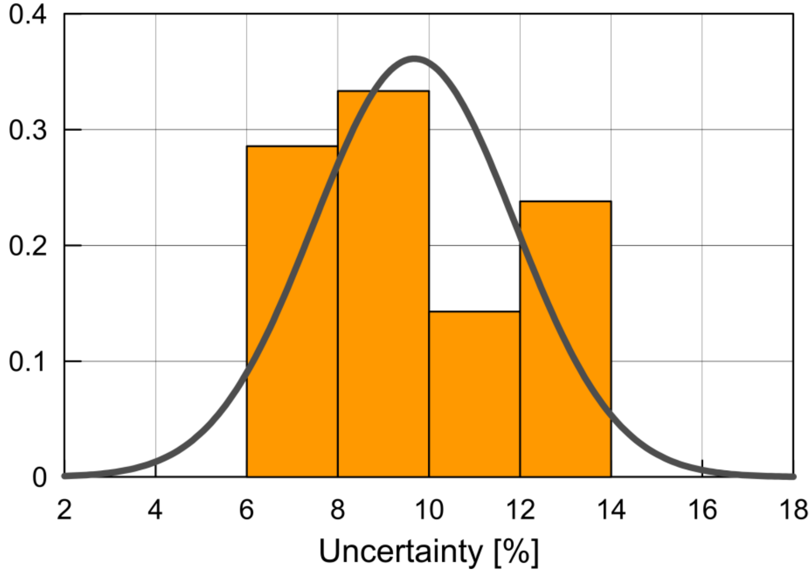
Range = 311 to 350 $GWhy^{-1}$



Predicted turbine site energy yield



Uncertainty estimates



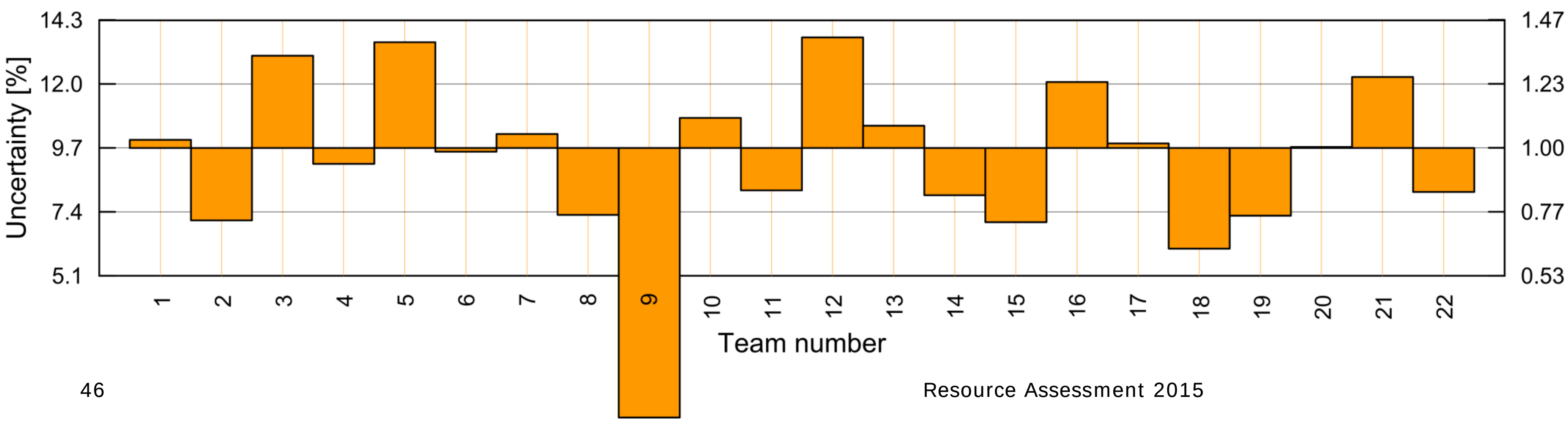
Data points used = 22 (of 22)

Mean uncertainty = 9.7%

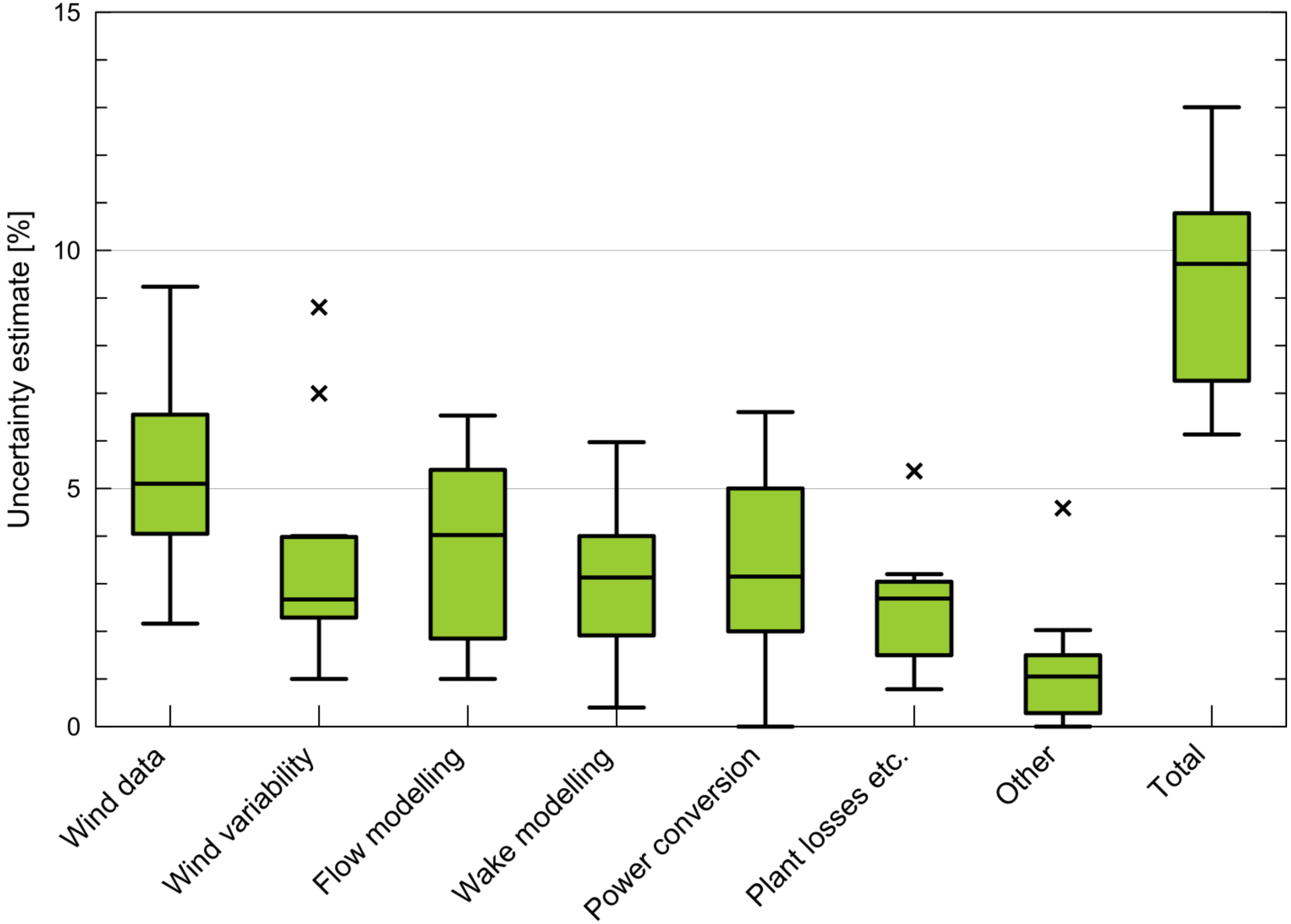
Standard deviation = 2.3%

Coefficient of variation = 23%

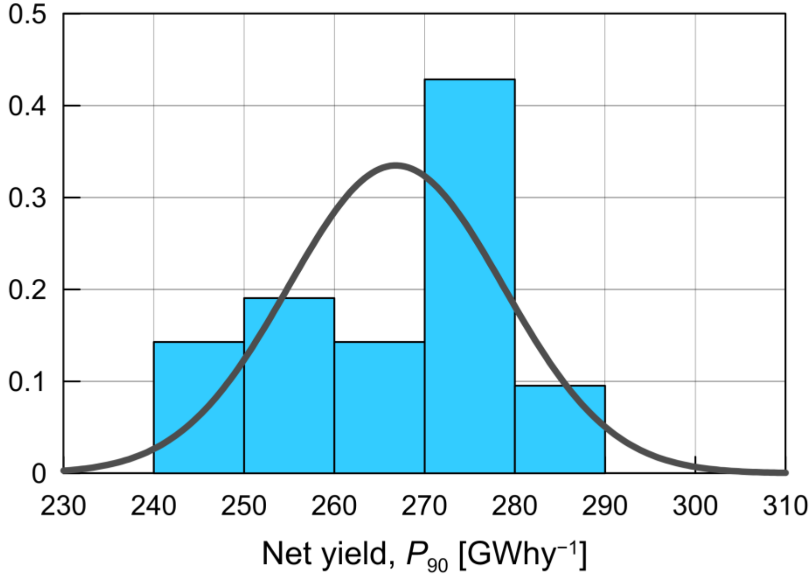
Range = 6.1 to 14%



Uncertainty estimates by type



Net energy yield of wind farm, P_{90}



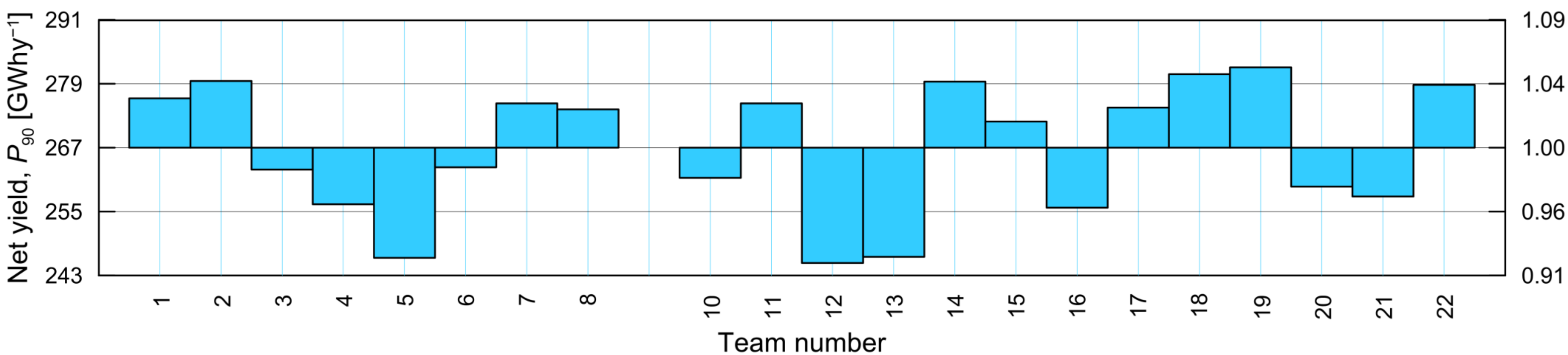
Data points used = 21 (of 22)

Mean net yield = 267 $GWhy^{-1}$

Standard deviation = 12.2 $GWhy^{-1}$

Coefficient of variation = 4.6%

Range = 245 to 282 $GWhy^{-1}$



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

- Mortensen, N. G., & Ejsing Jørgensen, H. (2011). Comparison of resource and energy yield assessment procedures. In *Proceedings.* European Wind Energy Association (EWEA).
- Mortensen, N. G., Ejsing Jørgensen, H., Anderson, M., & Hutton, K-A. (2012). Comparison of resource and energy yield assessment procedures. *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition.* European Wind Energy Association.
- Mortensen, N. G., & Ejsing Jørgensen, H. (2013). *Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Pt. II.* EWEA Technology Workshop: Resource Assessment, Dublin, Ireland, 26/06/13.
- Anderson, M., & Mortensen, N. G. (2013). *Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Pt. II.* AWEA Wind Resource & Project Energy Assessment Seminar, Las Vegas, NV, United States, 10/12/13.

Offshore

- Mortensen, N. G., Nielsen, M., & Ejsing Jørgensen, H. (2013). *First Offshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP).* EWEA Offshore 2013, Frankfurt, Germany, 19/11/13.
- Mortensen, N. G., & Nielsen, M. (2015). *Offshore CREYAP Part 2 – preliminary results* European Wind Energy Association (EWEA). EWEA Offshore 2015 Conference, Copenhagen, Denmark, 10/03/15.