Comparison of Resource and Energy Yield Assessment Procedures

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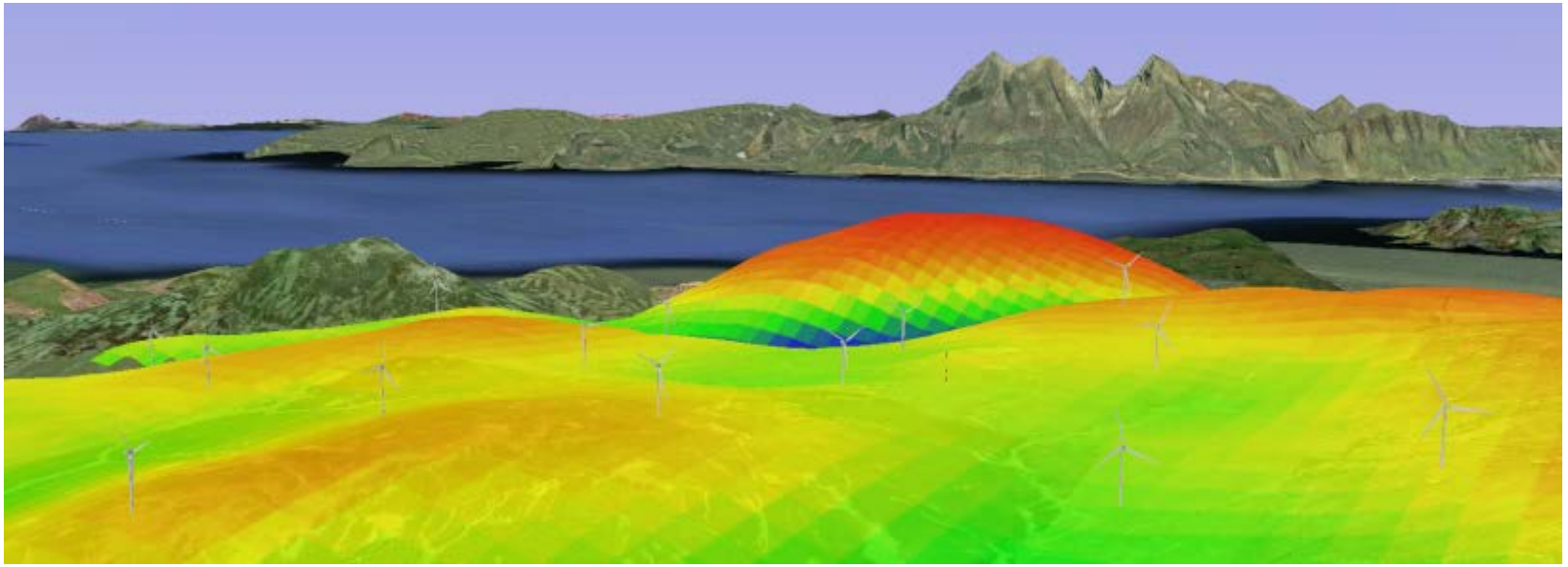
Risø DTU
National Laboratory for Sustainable Energy

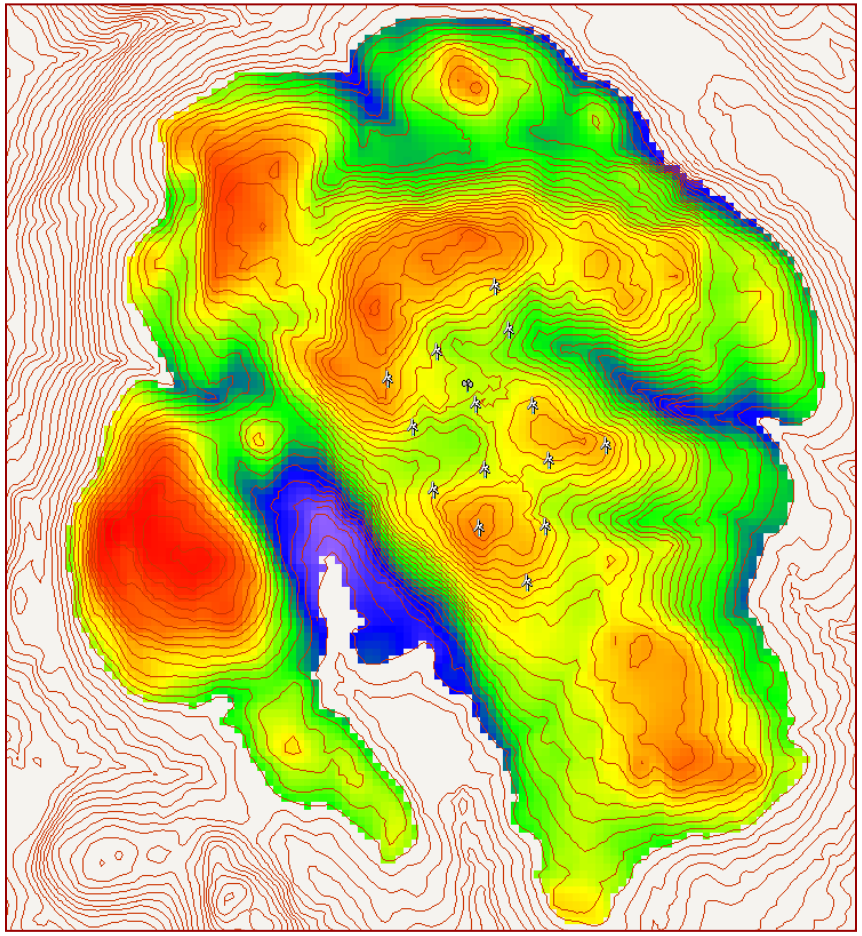
Acknowledgements

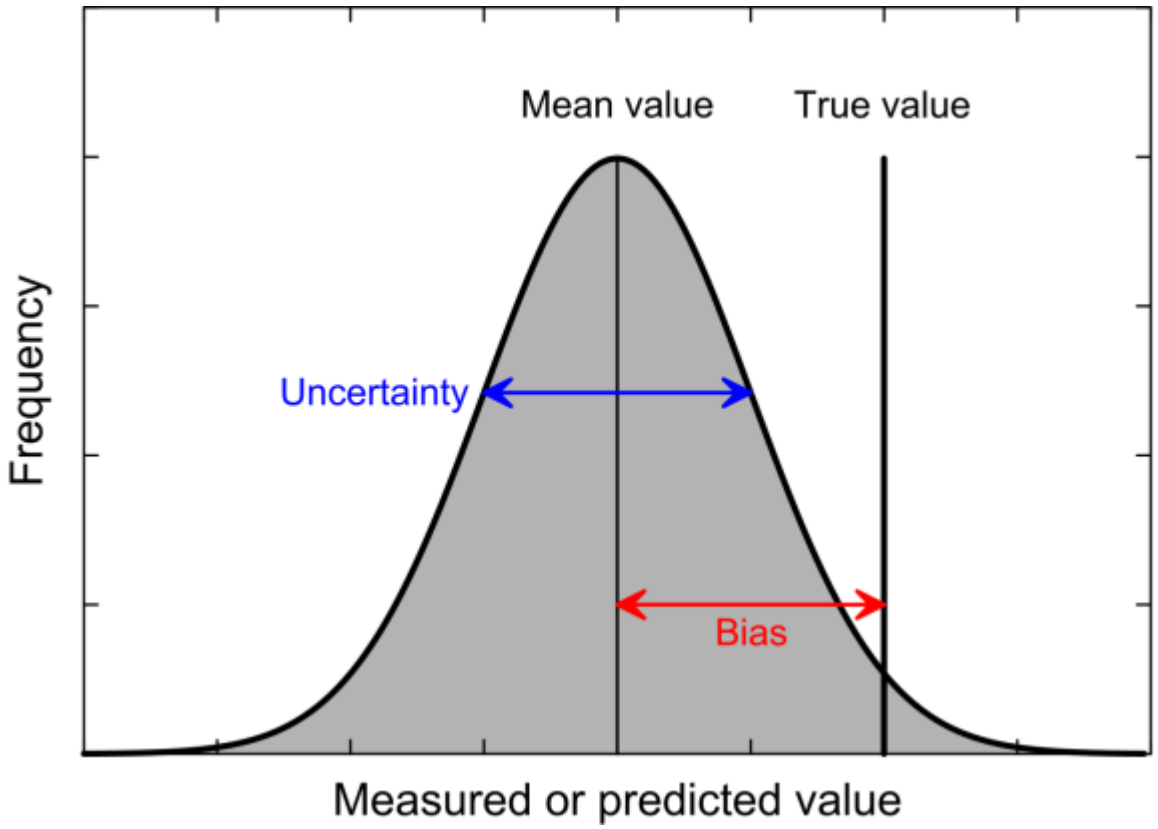
- The data pack used for the comparison was made available by Renewable Energy Systems Ltd. (RES); thanks in particular to Gerd Habenicht, Mike Anderson and Karen-Anne Hutton. The exercise was managed by Tim Robinson, EWEA.
- The 37 sets of results reported here were submitted by 36 organisations from 16 countries; thanks to all of the teams for making the comparison and presentation possible! See www.ewea.org for more info.



Outline

- Participants in the comparison
- Case study wind farm
  - Wind farm and turbine data
  - Wind-climatological inputs
  - Topographical inputs
- Comparison of results and models
  - Long-term wind @ 50 m
  - Long-term wind @ 60 m
  - Reference energy yield
  - Gross energy yield
  - Potential energy yield
  - Net energy yield P_{50}
  - Net energy yield P_{90}
- Summary and conclusions





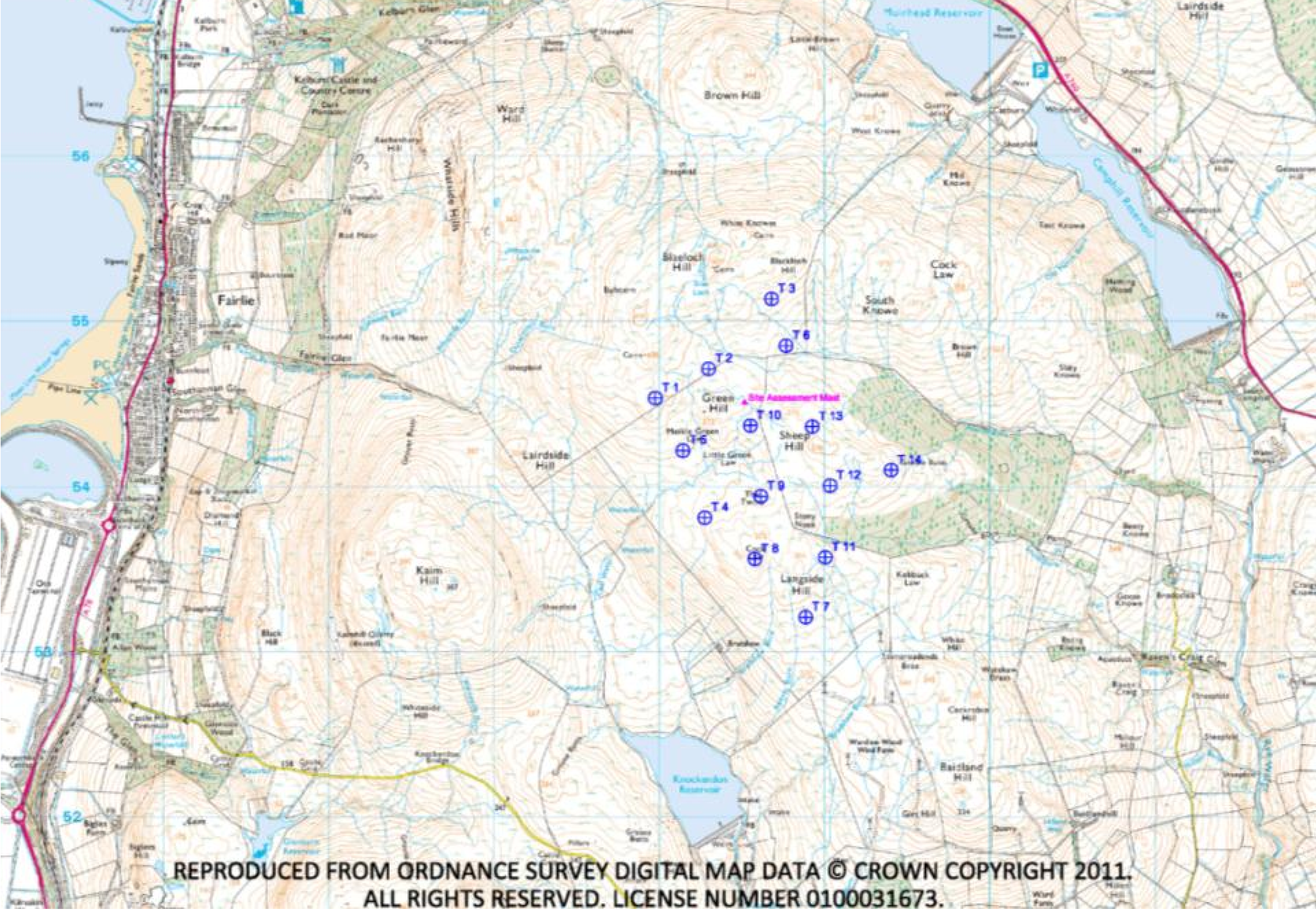
Uncertainty and bias in wind farm predictions

Reliable energy yield predictions are obtained when the bias and the uncertainty are both low. In the present comparison exercise, the 'true value' is not known (to me at least ;-)

Who responded?

- 36 organisations from 16 countries submitted results
  - consultancy (17), developer (7), wind turbine manufacturer (5), electricity generator/utility (3), R&D/university (2), component manufacturer (1), service provider (1)

- Names of organisations
  - 2EN, 3E, CENER, Center for Renewable Energy Sources (CRES), Det Norske Veritas (DNV), DONG Energy A/S, Dulas, Ecofys, EMD International, Eolfi - Veolia, ESB International, GAMESA Innovation & Technology, GL Garrad Hassan, ITOCHU Techno-Solutions Corporation, Kjeller Vindteknikk AS, METEODYN, Mott MacDonald, MS-Techno Co. Ltd., Natural Power, Nordex, ORTECH Power, Prevailing Ltd., REpower Systems AG, RES – Renewable Energy Systems Ltd, RES Americas Inc., RWE Innogy, Samsung Heavy Industries, SgurrEnergy, Suzlon Wind Energy A/S, The Wind Consultancy Service, Tractebel Engineering, Vestas, WIND-consult GmbH, WindGuard, WindSim AS, Windtest Grevenbroich GmbH.


T 1
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T 6
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T 8
T 9
T 10
T 11
T 12
T 13
T 14
Green Hill
Sheep Hill
Langside Hill
Lairdside Hill
Kaim Hill
Brown Hill
Cock Law
South Knowe
Fairlie
Baitland Hill
Ward Hill
Munchead Reservoir
Knockendon Reservoir
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Simplified case study

Which results can be compared?

- Observed and long-term estimated wind climates
  - Site measurements and long-term reference station
- Flow modelling results in hilly to complex terrain
  - Terrain defined in 20×20 km^2 domain by 50-m grid point elevations
- Wake model results
  - Wind farm layout and wind turbine generator data
- Technical losses estimates
  - Electrical design of wind farm
- Uncertainty estimates

What is not taken into account?

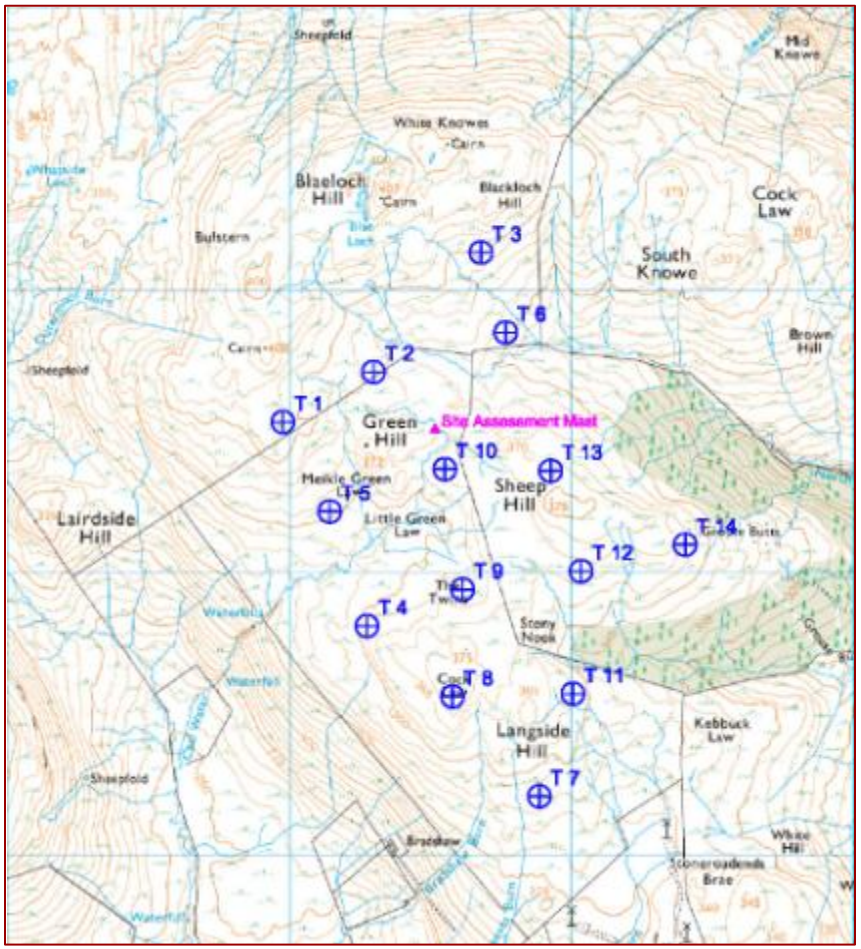
- Roughness and roughness changes
- Forest effects due to nearby forestry
- Shelter effects due to nearby obstacles
- Stability effects over different terrain surfaces

28-MW wind farm

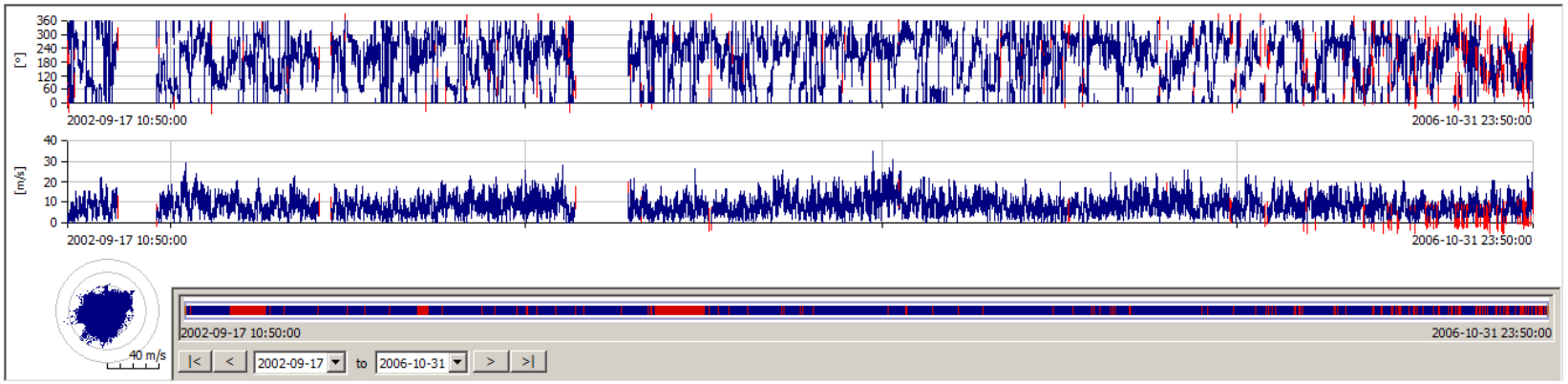
- 14 wind turbines
  - Rated power: 2 MW
  - Hub height: 60 m
  - Rotor diameter: 80 m
  - Air density: 1.225 kg m^{-3}
  - Spacing: irregular, 3.7*D* – 4.8*D* to nearest neighbouring turbine

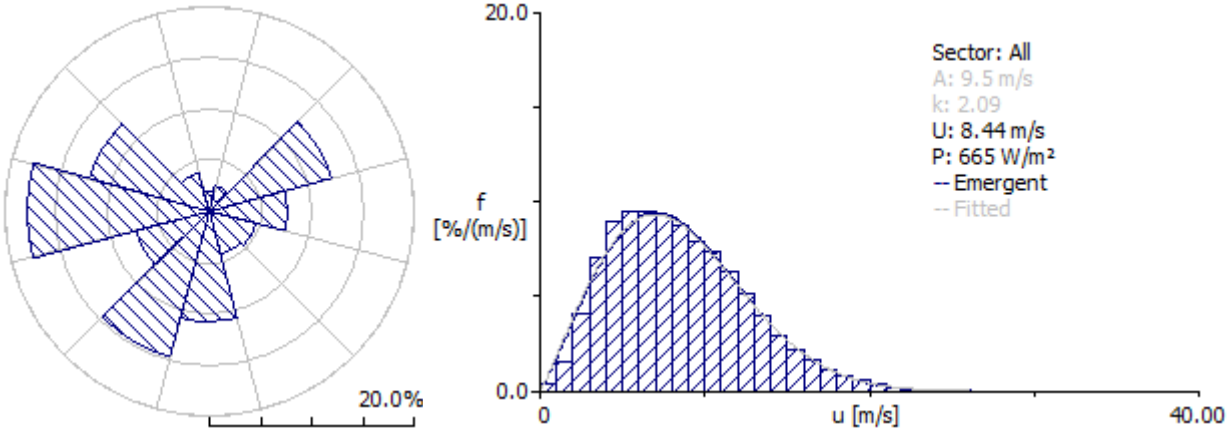
- Site meteorological mast
  - Wind speed @ 49.6 and 35 m
  - Std. deviation @ 49.6 and 35 m
  - Wind direction @ 33.6 m a.g.l.

- Reference station
  - Wind speed and direction



Wind-climatological inputs





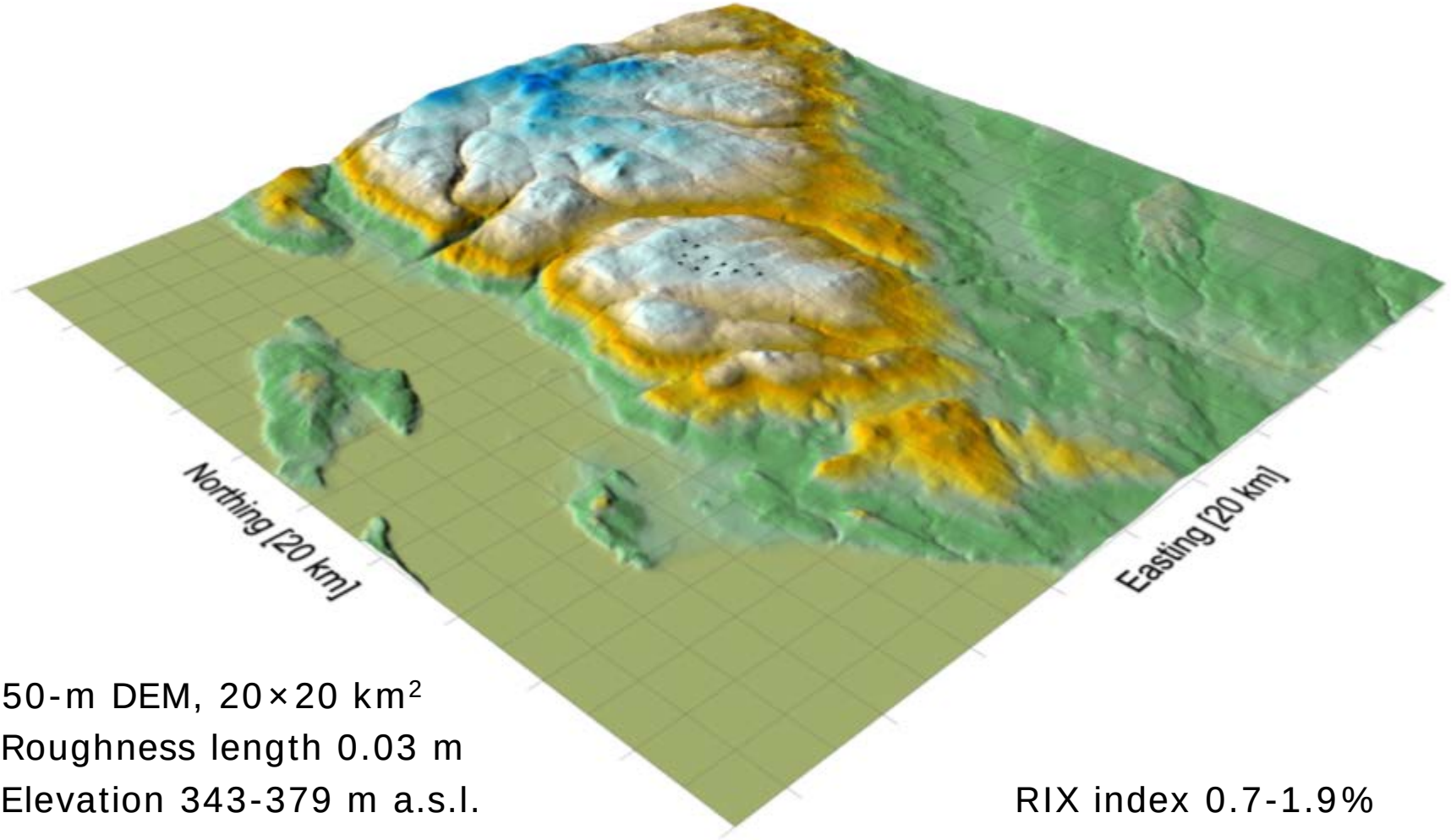
Site data (4y)

- 2002-09 to 2006-10
- Recovery 92%

Reference data (14y)

- Monthly *U* 1993-2006
- Hourly *U* and *D* from 2002-09 to 07-01
- Observed Wind Climate from 1993-2001

Topographical inputs



50-m DEM, 20×20 km^2
Roughness length 0.03 m
Elevation 343-379 m a.s.l.

RIX index 0.7-1.9%

Data analysis & presentation

Data material

- Results spreadsheets from 37 teams
- Additional questions to nine teams

Data analysis

- Quality control
- Reformatting of data
- Calculation of missing numbers, but no comprehensive reanalysis!

Data presentation

- Team results for each parameter
- Overall distribution of all results
  - Normal distribution fitted to the results
  - Statistics (mean, standard deviation, variation coefficient, range)
- Comparison of methods where possible

Results

1. LT wind @ 50 m = Measured wind ± [long-term correlation effects]
   - comparison of long-term correlation methods
2. LT wind @ 60 m = LT wind @ 50 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×[uncertainty estimate]
   - comparison of uncertainty estimates

Which tools have been used?

- Data analysis – long-term correlation
  - MCP (matrix method, hourly values, monthly means), correlation with NWP or reanalysis data (2), NOAA-GSOD index (1), none (3)
- Vertical extrapolation
  - Observed power law/log law profile (19), WAsP (10), WindSim (2), unspecified CFD (2), NWP (1)
- Horizontal extrapolation – flow models
  - WAsP (23), MS3DJH (2), WindSim (2), unspecified CFD (2), NWP (1), MS-Micro/3 (1), other (1)
- Wake models
  - WAsP PARK (17), WindPRO PARK (8), WindFarmer Eddy Viscosity (5), Ainslie Eddy Viscosity (3), EWTS II (2), CFD Actuator (1), Confidential (1)

Long-term wind at the meteorological mast

Wind @ 50 m = Measured wind ± [long-term corr. effects]

Long-term correlation effects

Data points used = 36 (of 37)

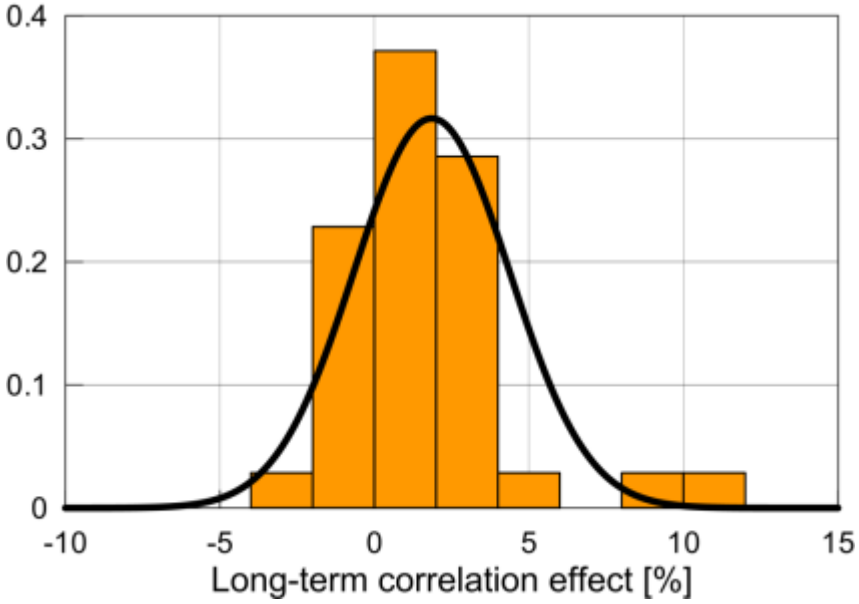
Team 19 result disregarded

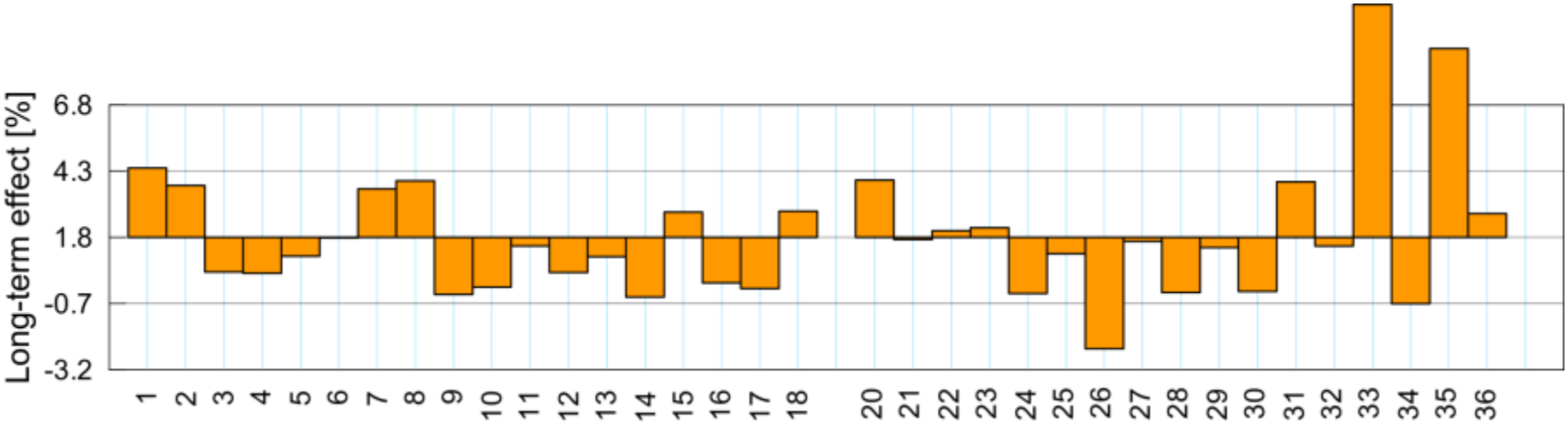
Mean long-term effect = **1.8%**

Std. deviation = **2.5%** (139%)

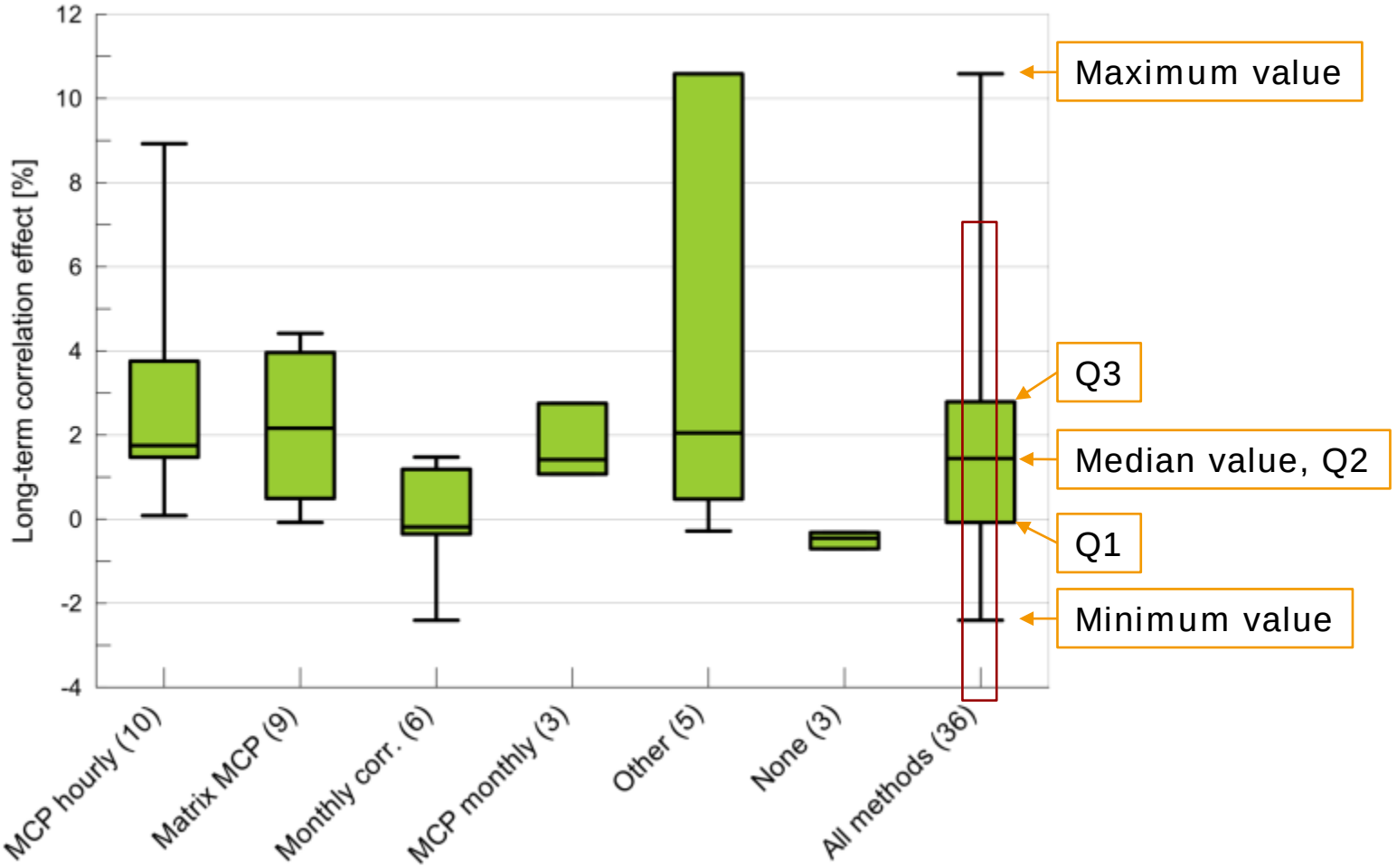
Range = -2.4 to 10.6% (713%)

(measured U_{50} of 8.5 ms^{-1} assumed)

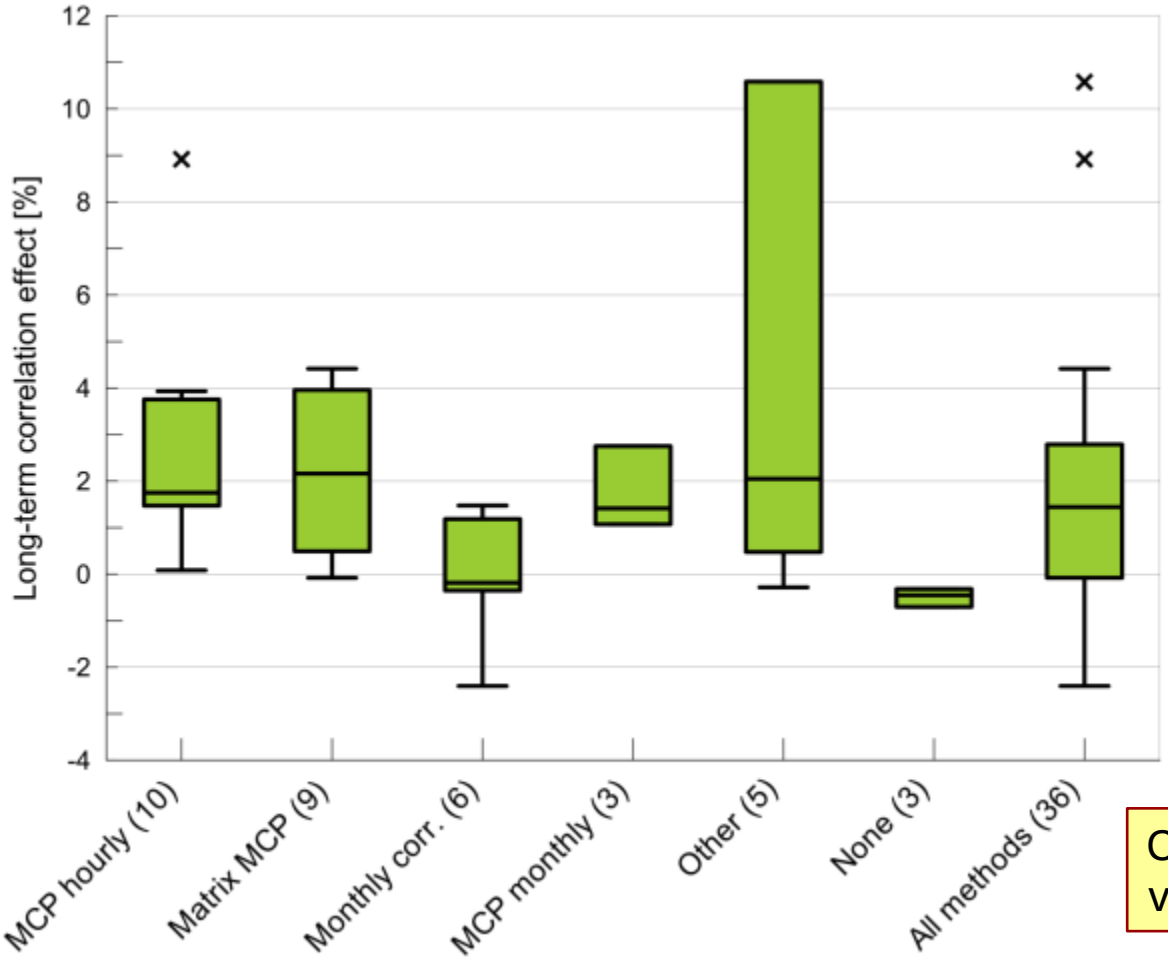




Comparison of correlation methods (caution!)



Comparison of correlation methods (caution!)



Categories not very well defined!

LT mean wind speed @ 49.6 m

Data points used = 37 (of 37)

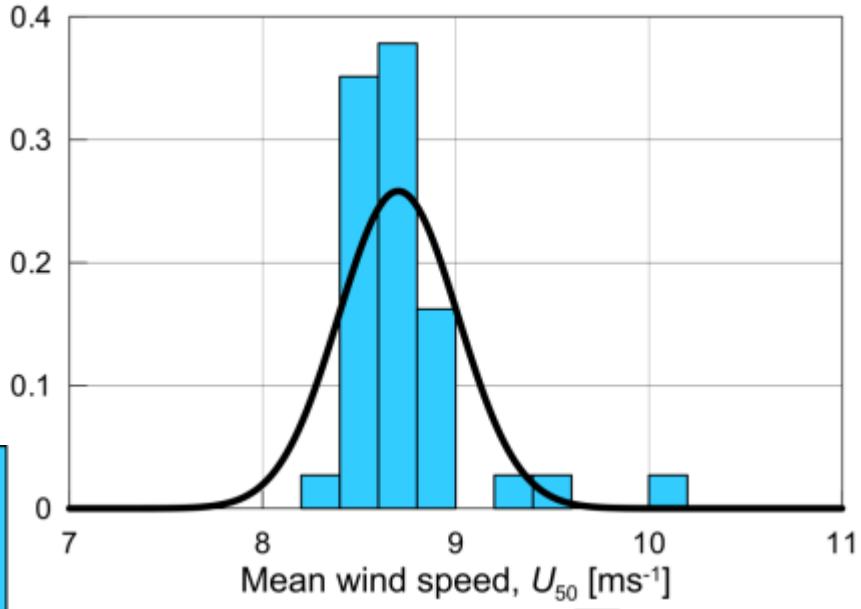
All teams report results

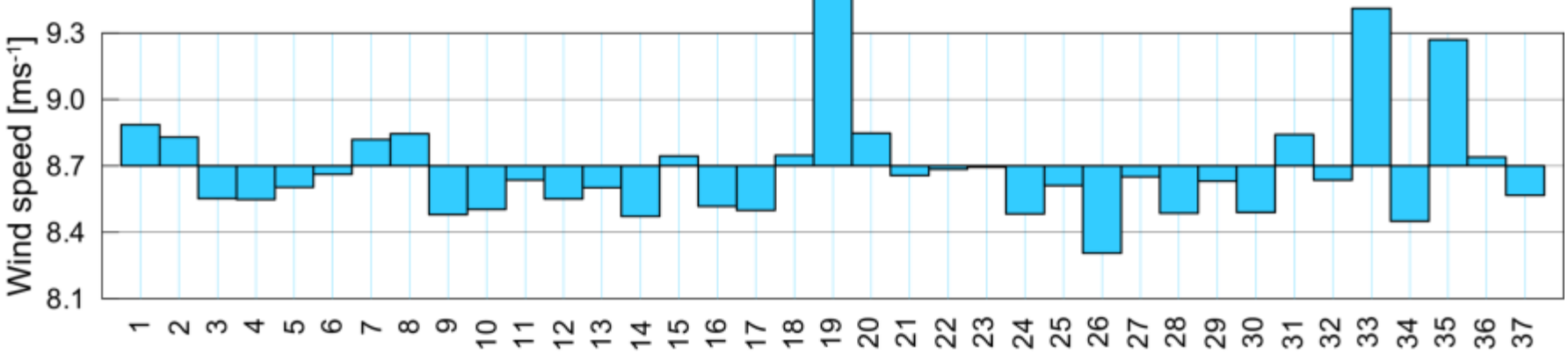
Mean wind speed = **8.7 ms^{-1}**

Std. deviation = **0.2 ms^{-1}** (2.5%)

Range = 8.3 to 9.4 ms^{-1} (13%)

(statistics without single high outlier)

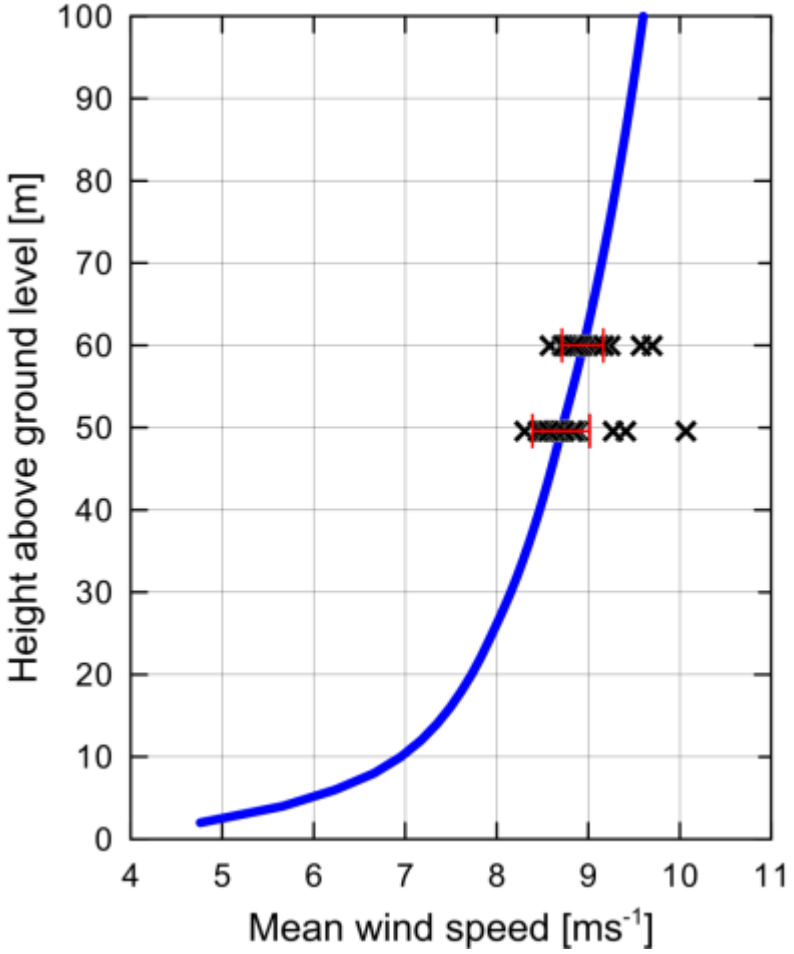


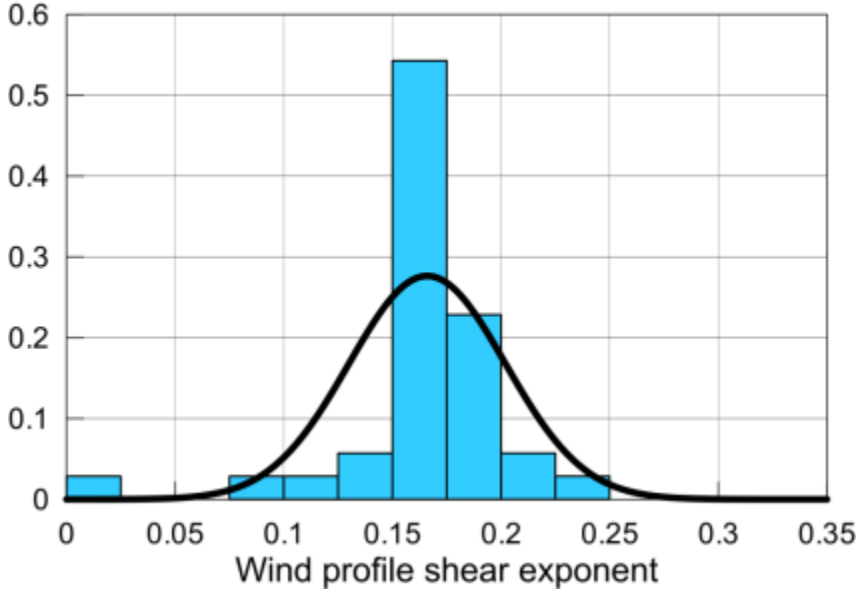


Long-term wind at the meteorological mast

Wind @ 60 m = Wind @ 50 m + [wind profile effects]

Wind profile and shear exponent





Data points used = 35 (of 37)

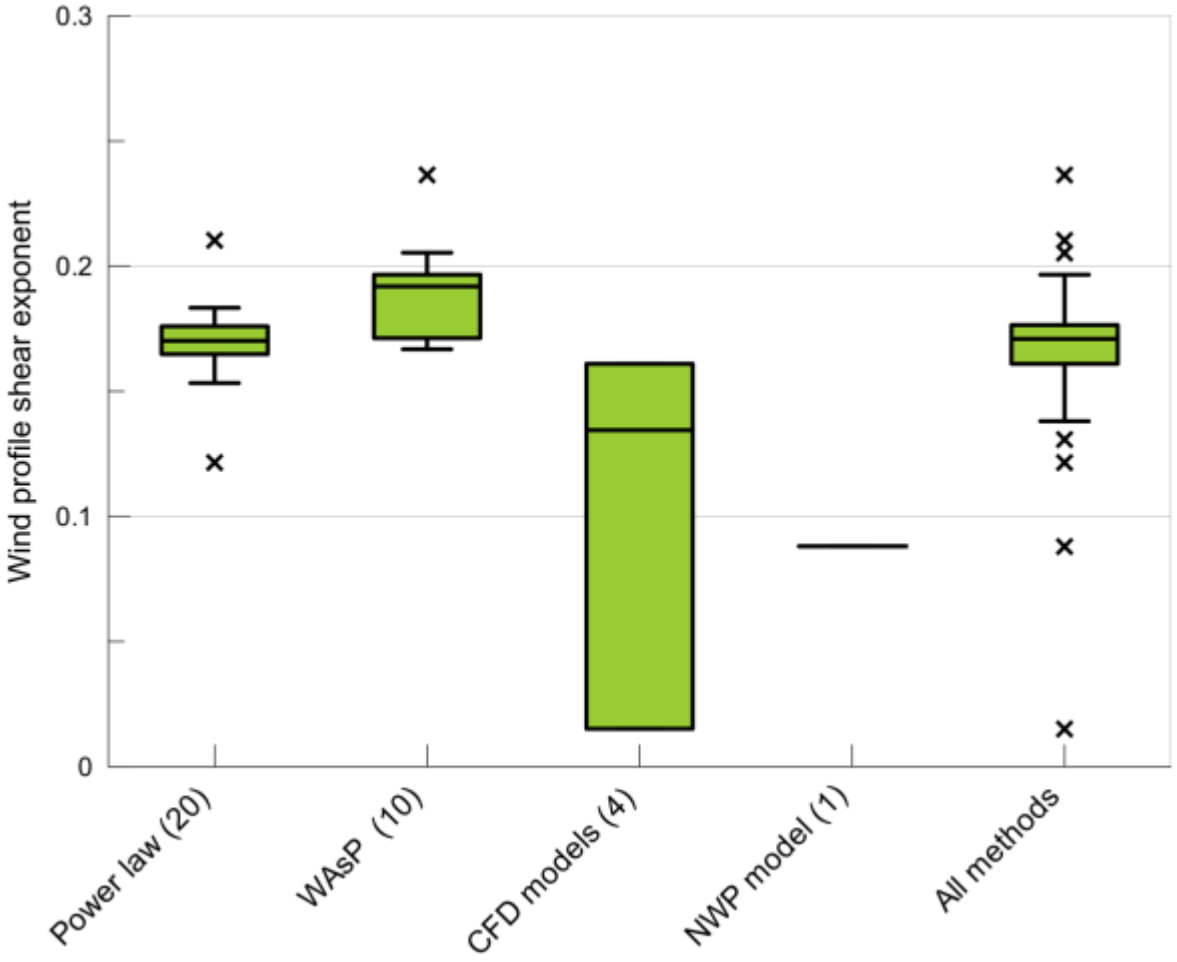
Team 2 and 19 report no results

Mean shear exponent = **0.166** (1/6)

Std. deviation = **0.037** (22%)

Range = 0.015 to 0.237 (133%)

Comparison of vertical extrapolation methods



LT mean wind speed @ 60 m

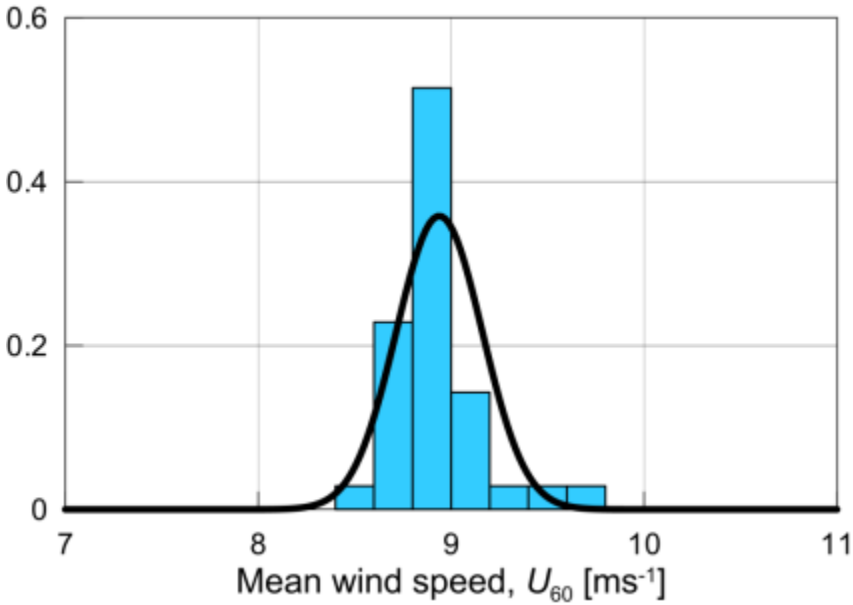
Data points used = 35 (of 37)

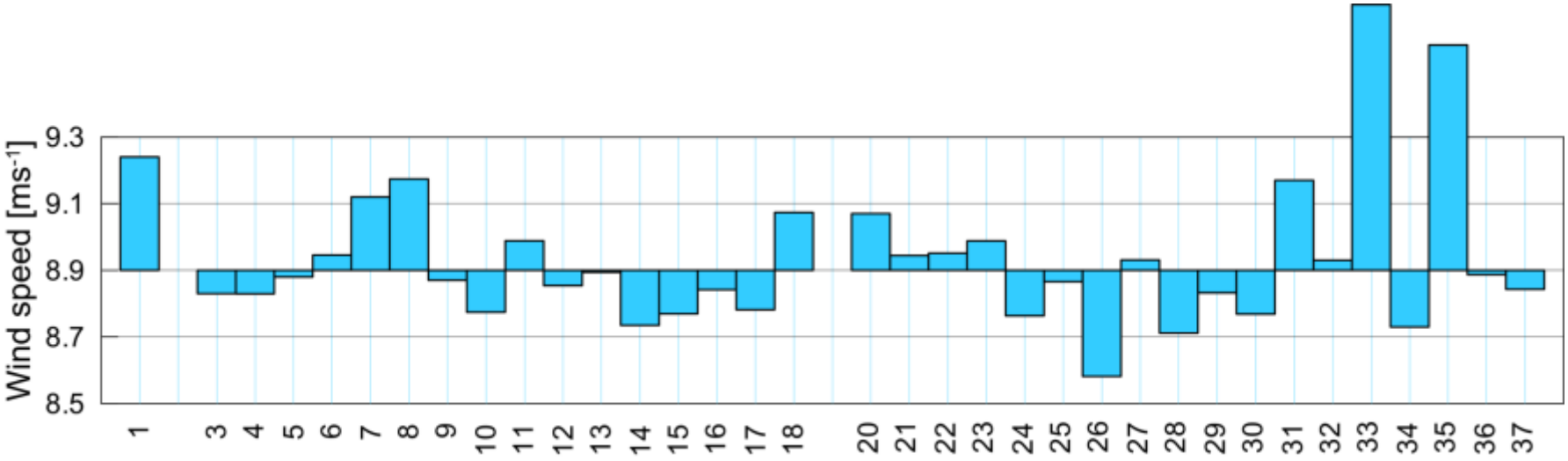
Team 2 and 19 report no results

Mean wind speed = **8.9 ms^{-1}**

Std. deviation = **0.2 ms^{-1}** (2.5%)

Range = 8.6 to 9.7 ms^{-1} (13%)





Turbulence intensity @ 49.6 m

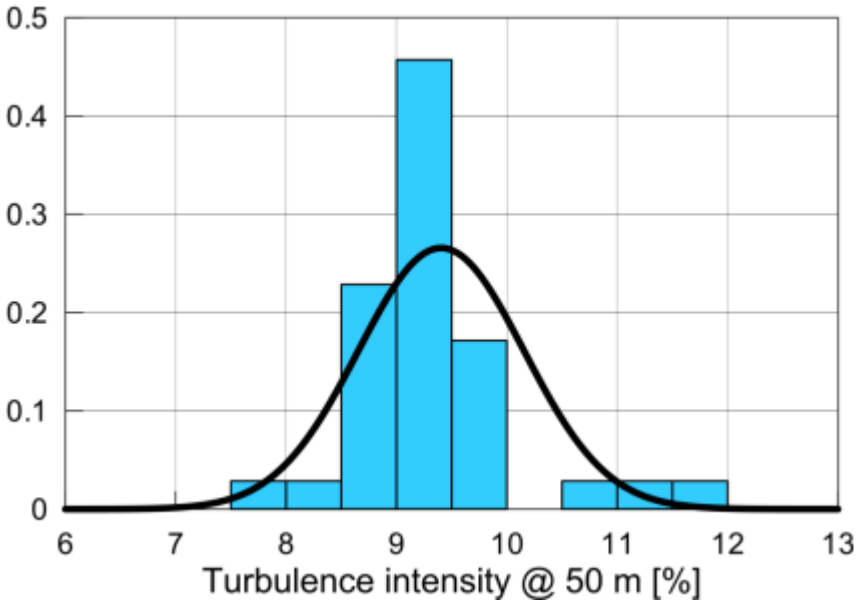
Data points used = 35 (of 37)

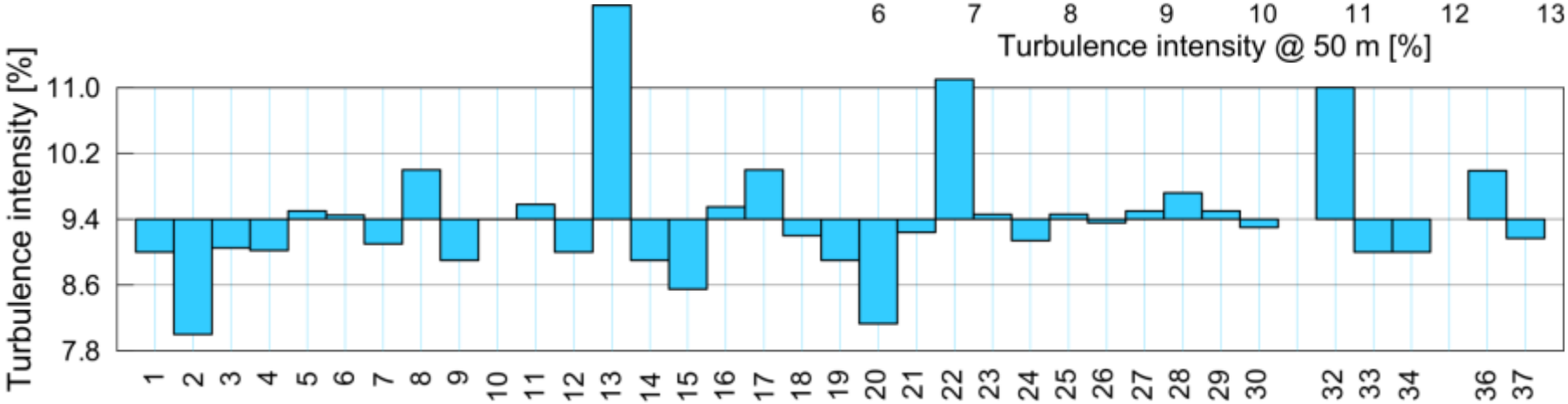
Team 31 and 35 report no results

Mean turb. intensity = **9.4%**

Std. deviation = **0.8%** (8%)

Range = 8% to 12% (43%)





Turbulence intensity @ 60 m

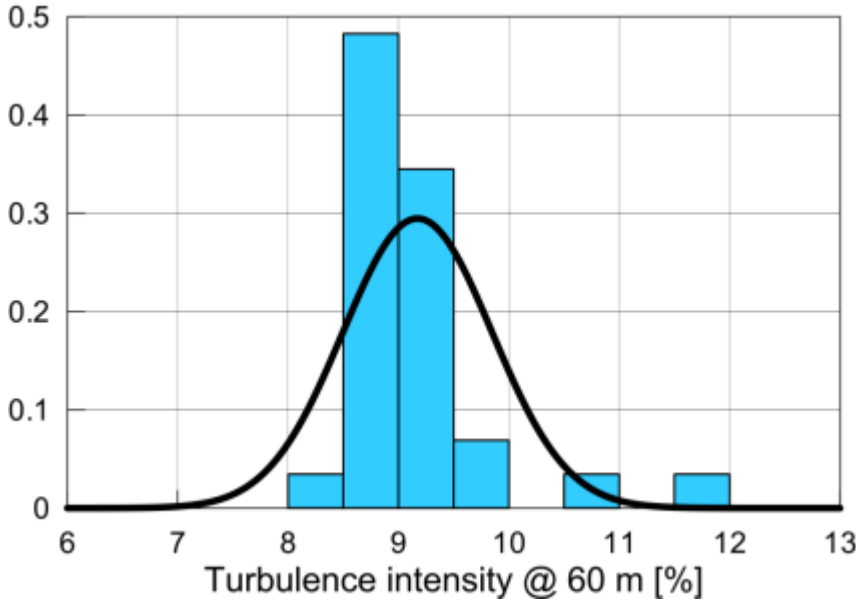
Data points used = 29 (of 37)

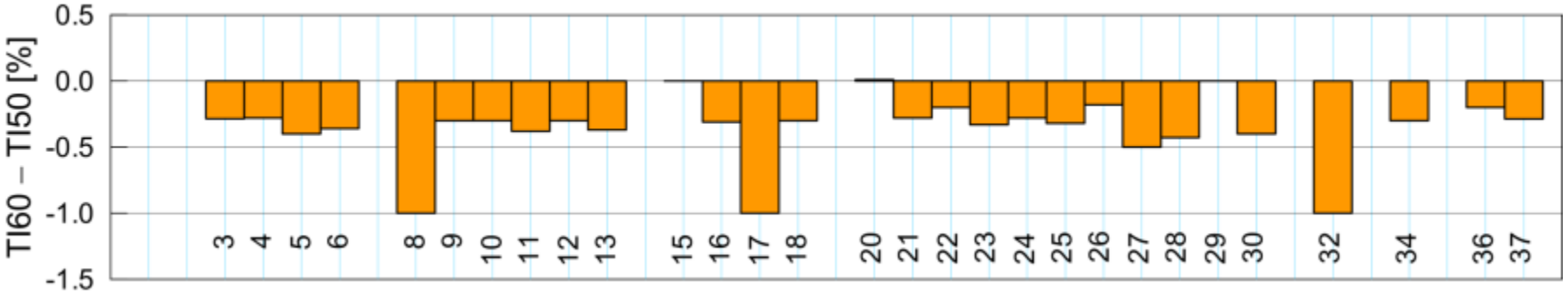
Eight teams report no results

Mean turb. intensity = **9.2%**

Std. deviation = **0.7%** (7.8%)

Range = 8.1% to 12% (38%)





Gross energy yield of wind farm

Gross AEP = Reference AEP ± [terrain effects]

Reference yield of wind farm

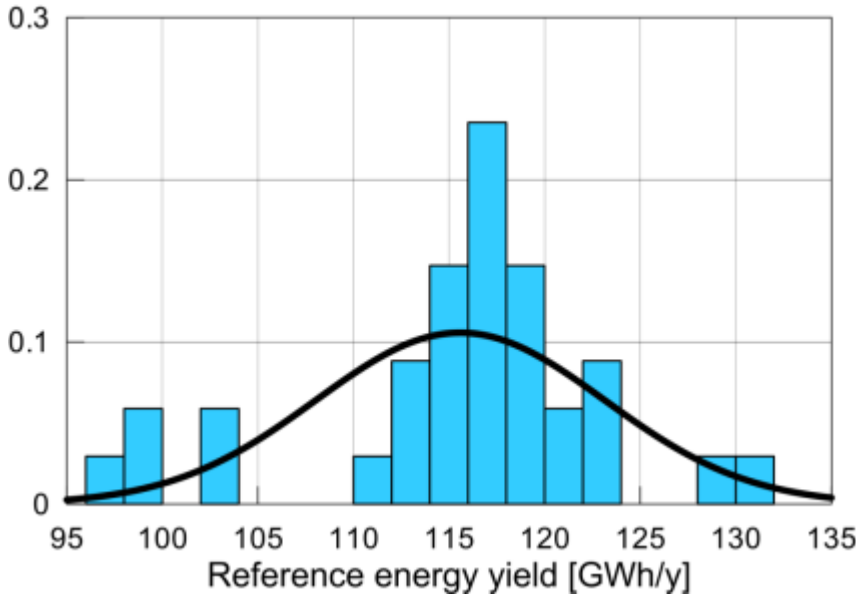
Data points used = 34 (of 37)

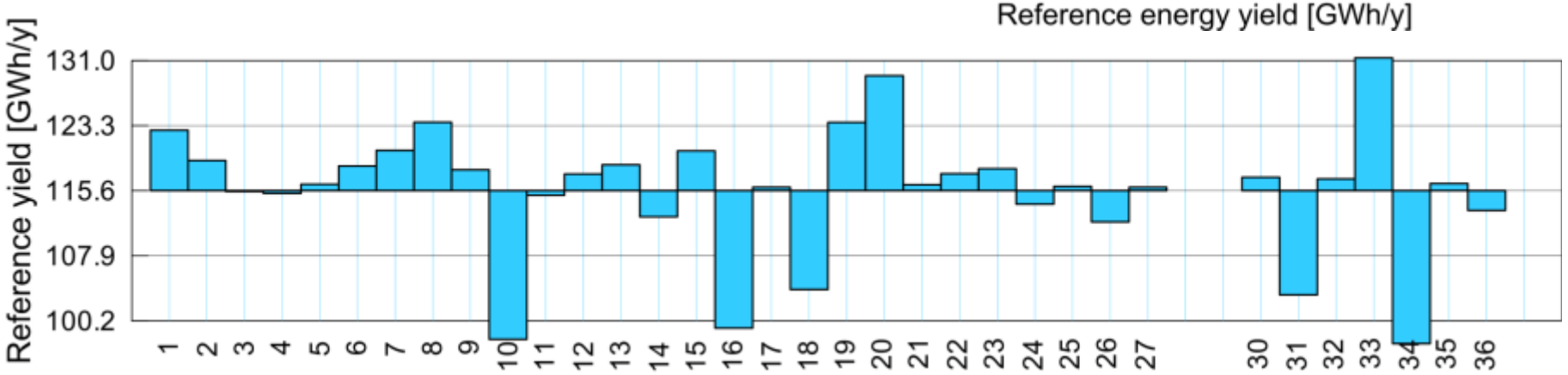
Team 28, 29 and 37 report no results

Mean reference yield = **116 GWh**

Std. deviation = **7.7 GWh** (6.6%)

Range = 98 to 131 GWh (29%)





Topographical effects

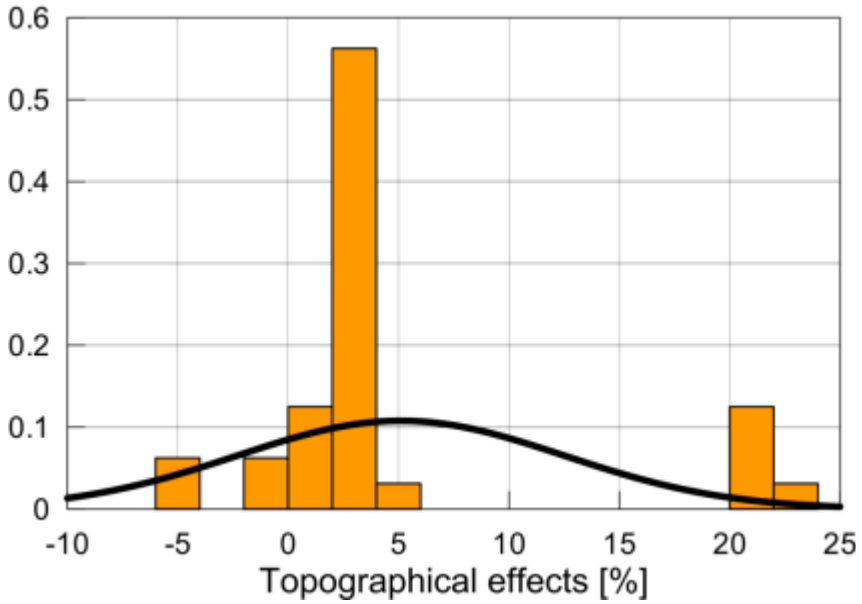
Data points used = 32 (of 37)

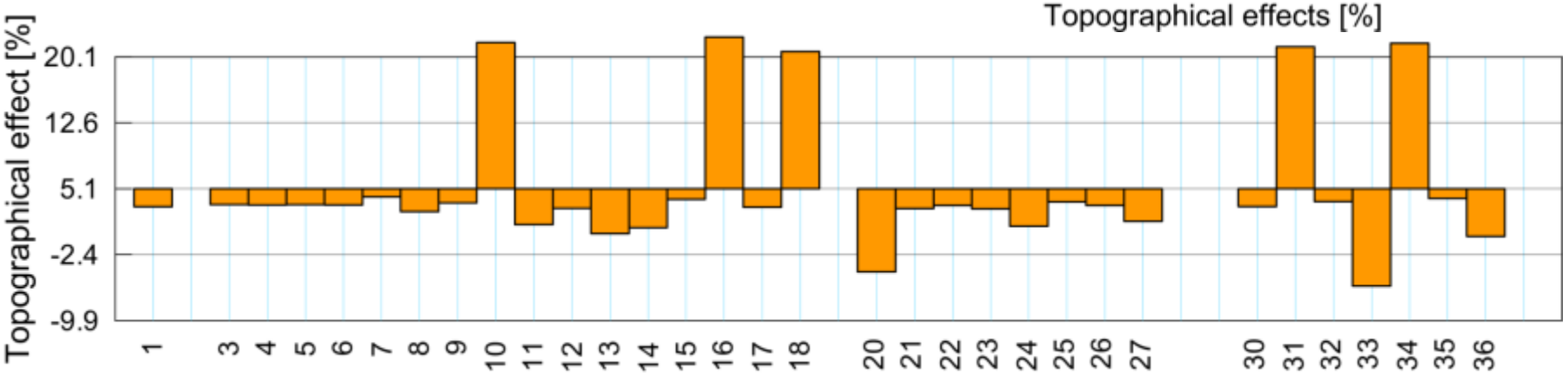
Team 2, 19, 28, 29, 37 report no result

Mean terrain effect = **5.1 %**

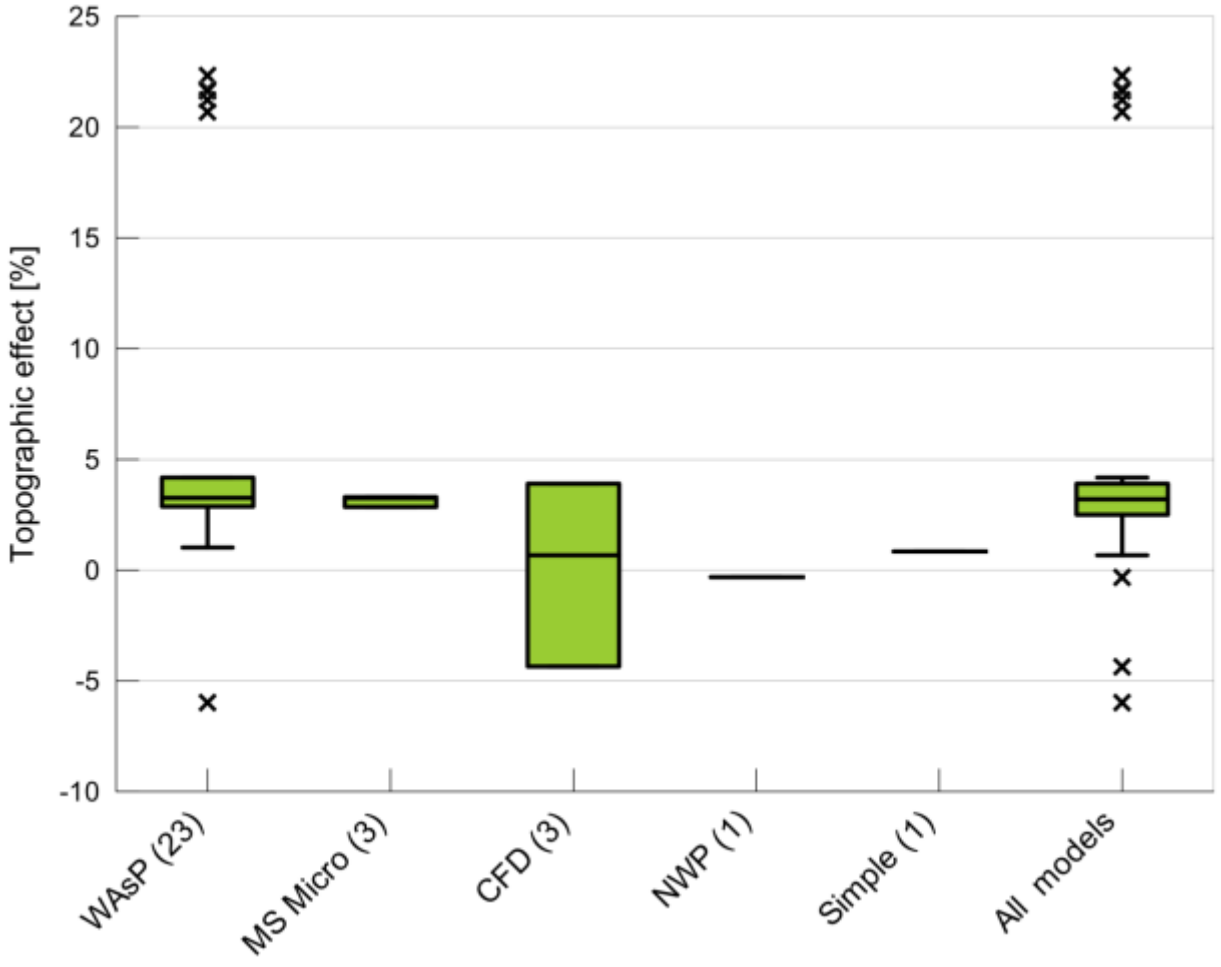
Std. deviation = **7.5%** (147%)

Range = -6 to 22% (554%)





Comparison of flow models



Gross energy yield of wind farm

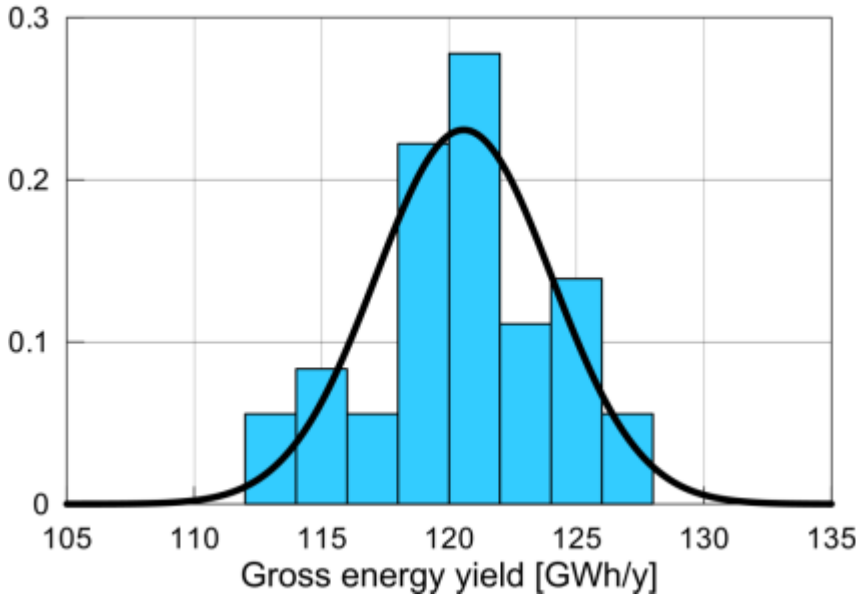
Data points used = 36 (of 37)

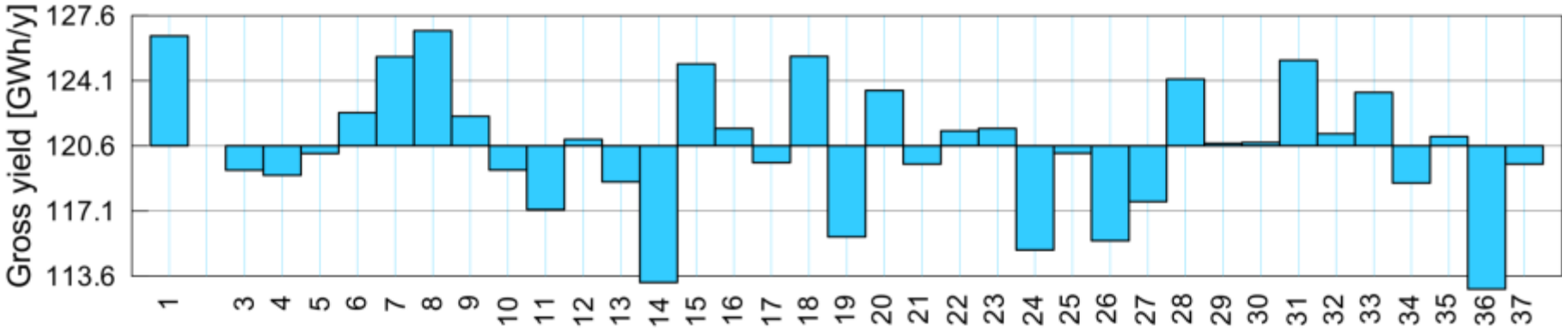
Team 2 reports no result

Mean gross yield = **121 GWh**

Std. deviation = **3.5 GWh** (2.9%)

Range = 113 to 127 GWh (12%)





Potential energy yield of wind farm

Potential AEP = Gross AEP – [wake losses]

Wake losses

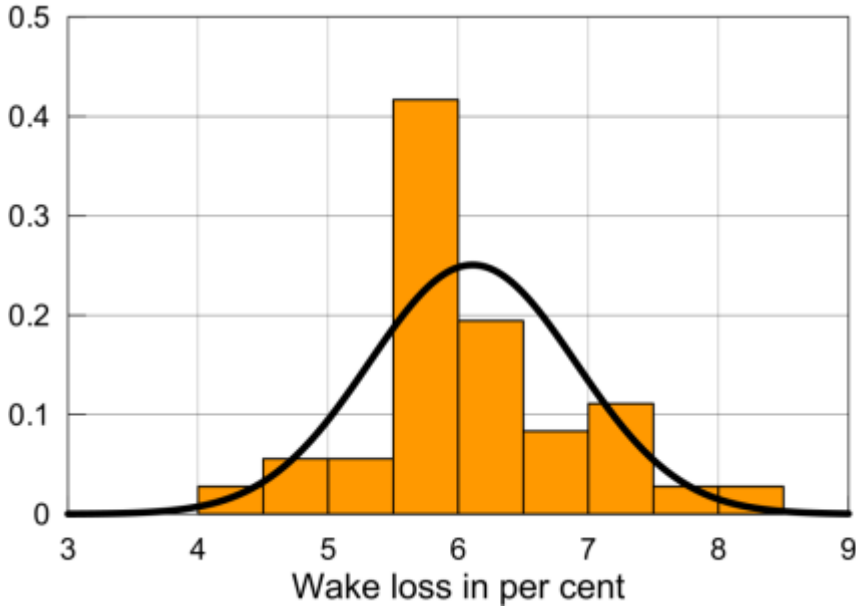
Data points used = 36 (of 37)

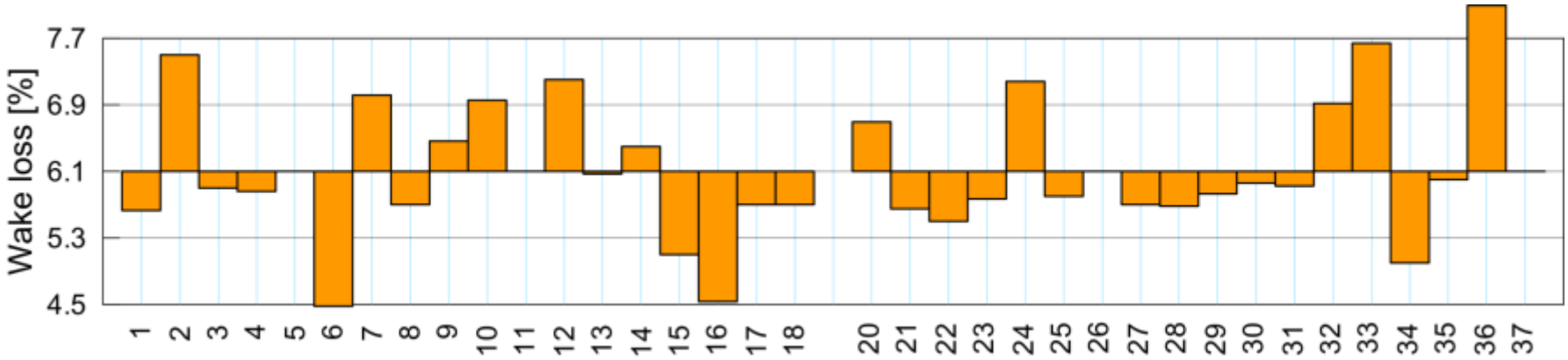
Team 19 reports no result

Mean wake loss = **6.1%**

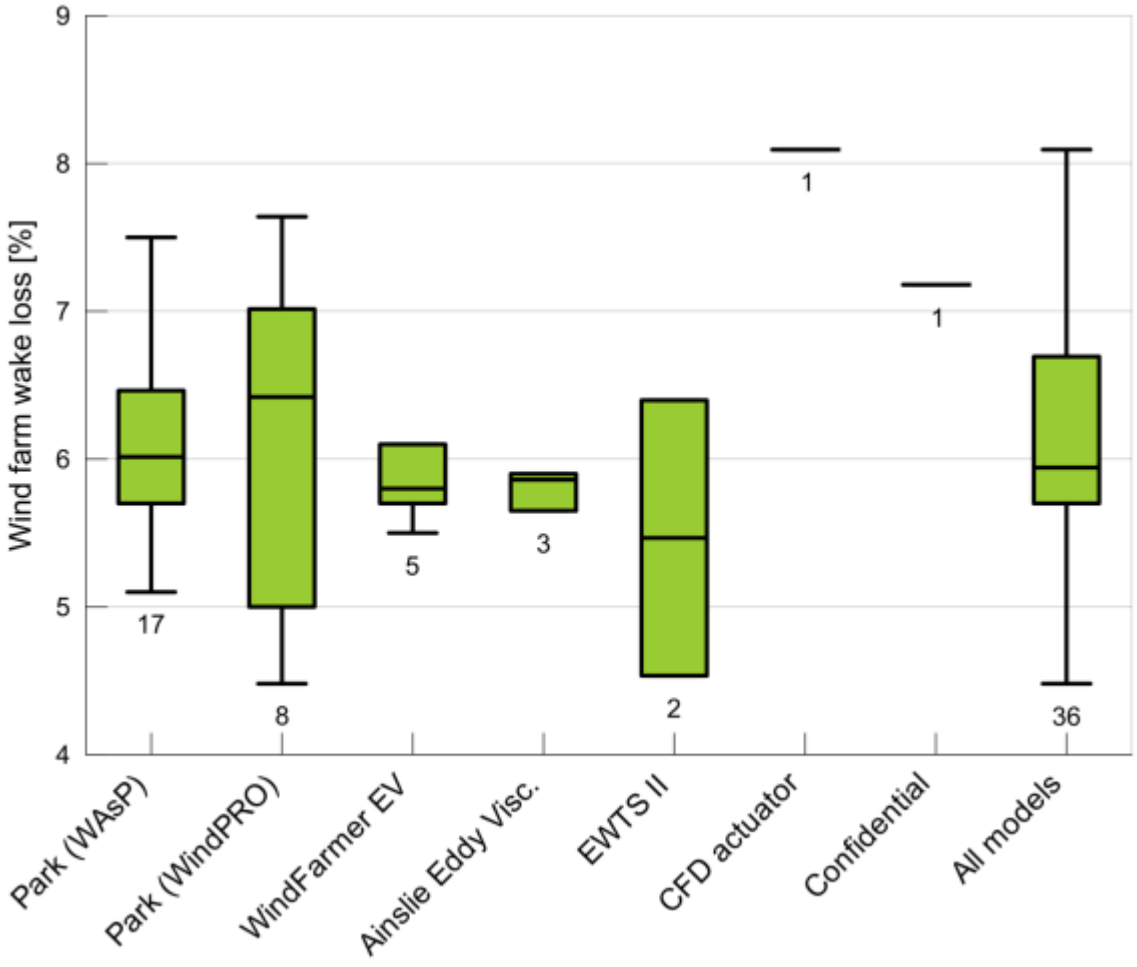
Std. deviation = **0.8%** (13%)

Range = 4.5% to 8.1% (59%)





Comparison of wake models



Potential energy yield of wind farm

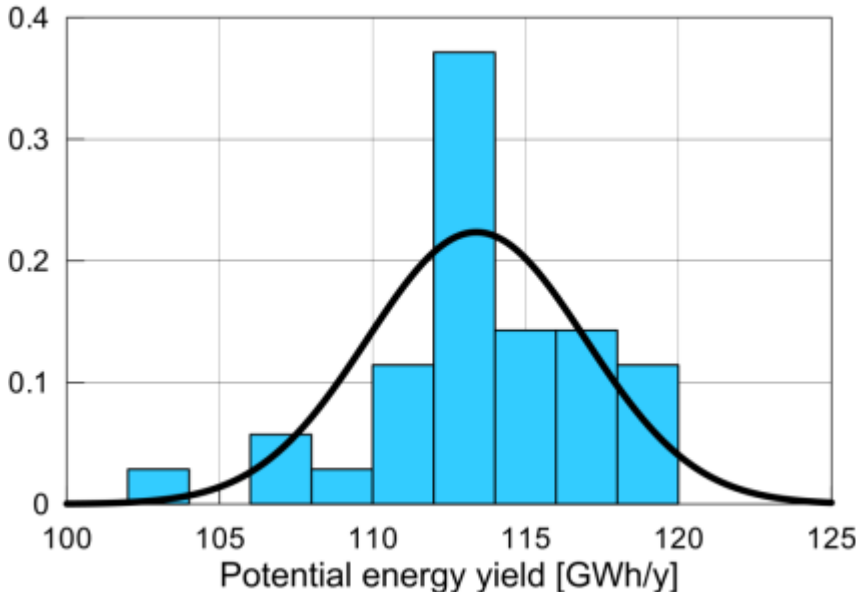
Data points used = 35 (of 37)

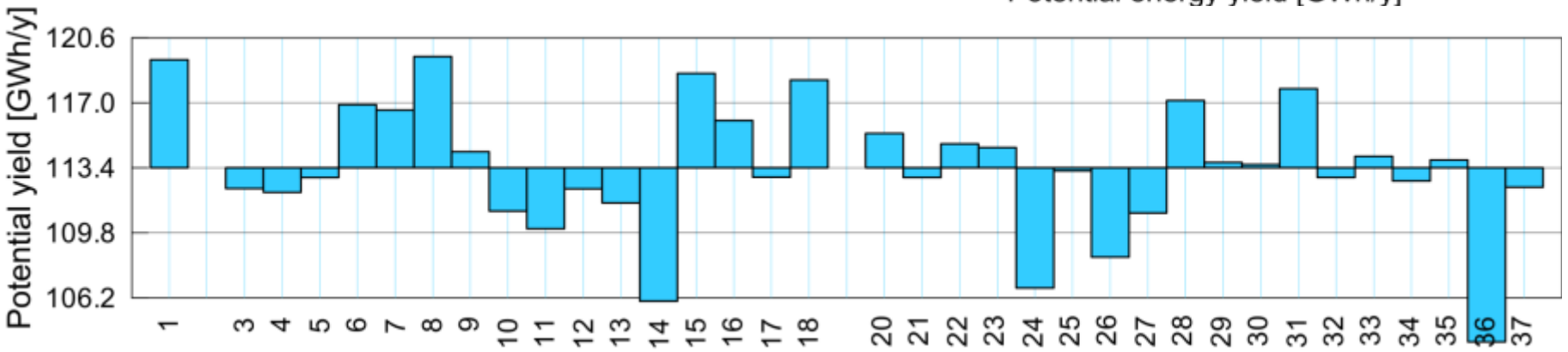
Team 2 and 19 report no results

Mean potential yield = **113 GWh**

Std. deviation = **3.6 GWh** (3.2%)

Range = 104 to 120 GWh (14%)





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

Net AEP (P_{50}) = Potential AEP – [technical losses]

Technical losses

Data points used = 34 (of 37)

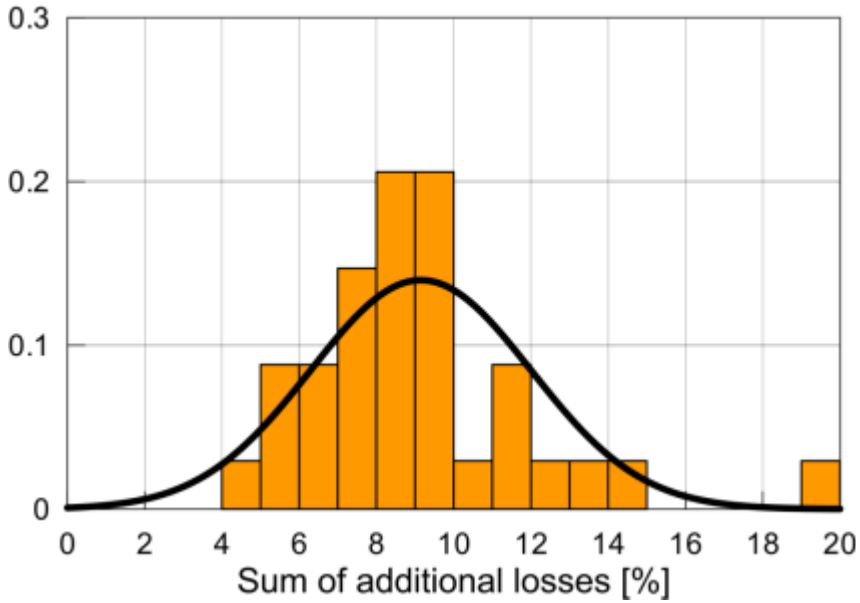
Team 2, 8 and 9 report no results

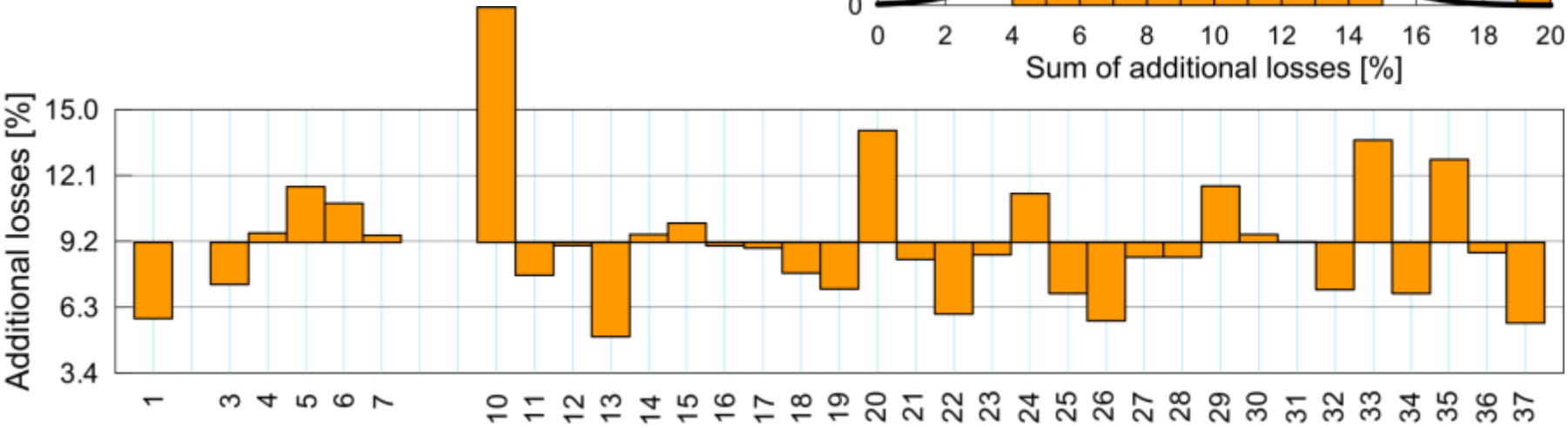
Mean total loss = **9.2%**

Std. deviation = **2.9%** (32%)

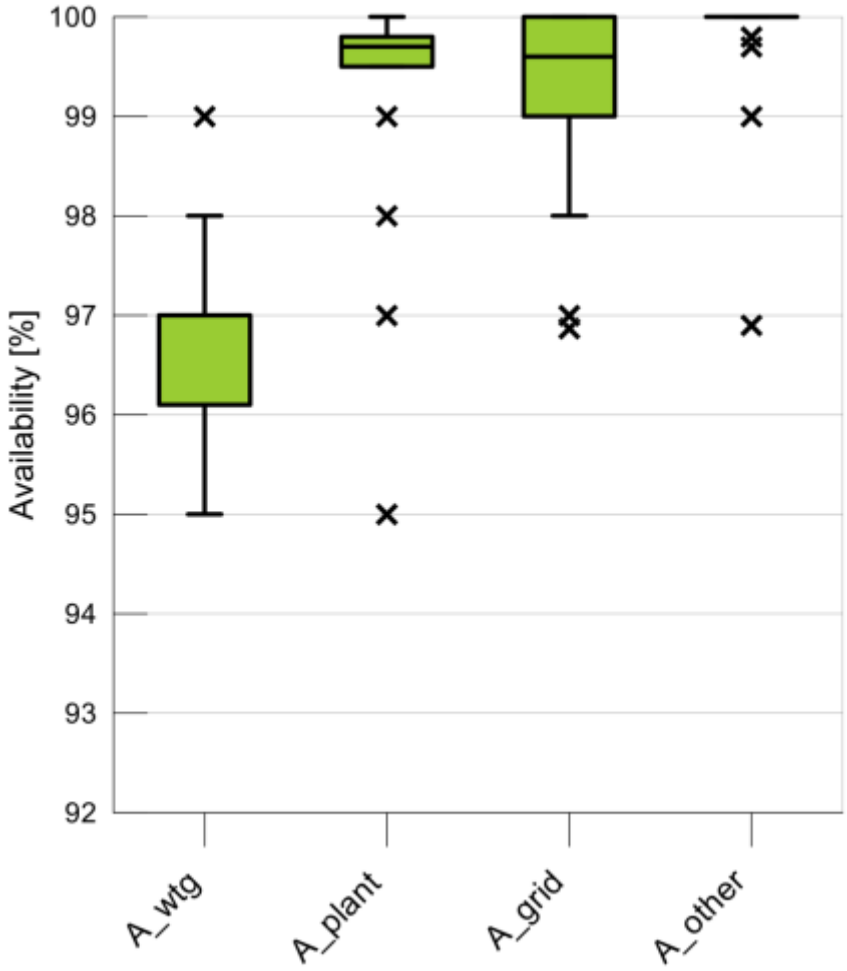
Range = 5 to 20% (159%)

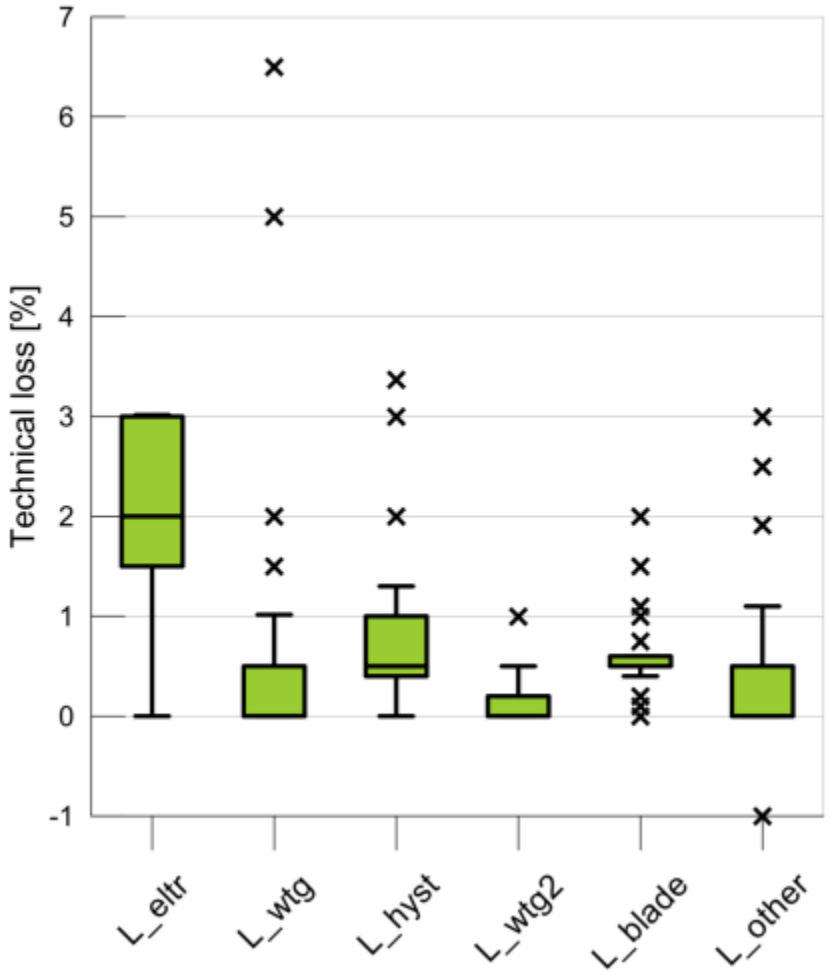
Median value = 8.8%





Technical losses by type





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

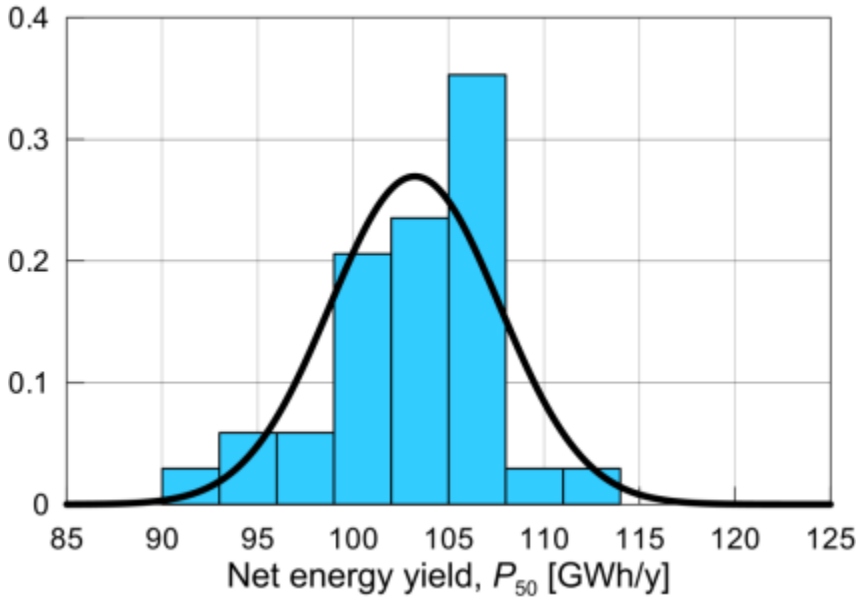
Data points used = 34 (of 37)

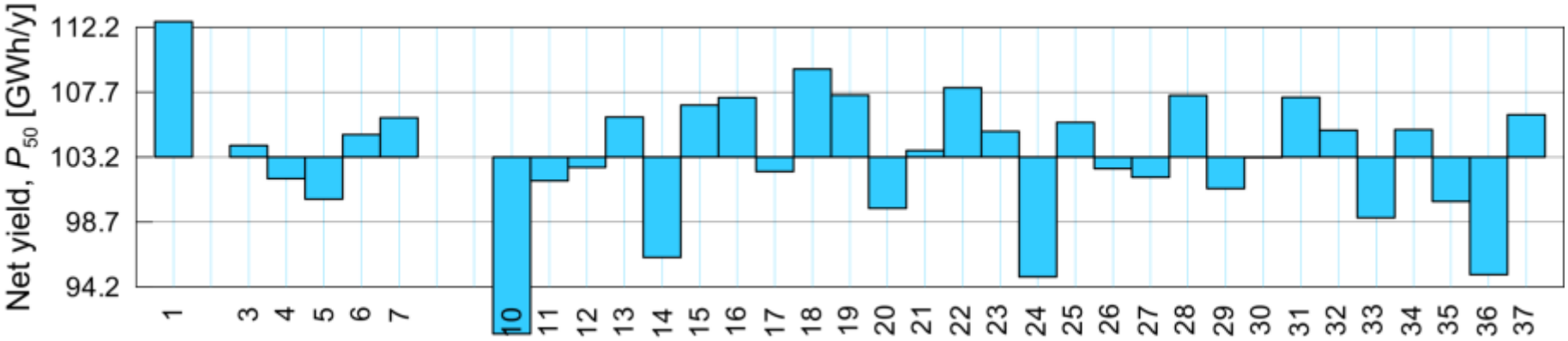
Team 2, 8 and 9 report no results

Mean net yield = **103 GWh**

Std. deviation = **4.5 GWh** (4.4%)

Range = 91 to 113 GWh (21%)





Capacity factor

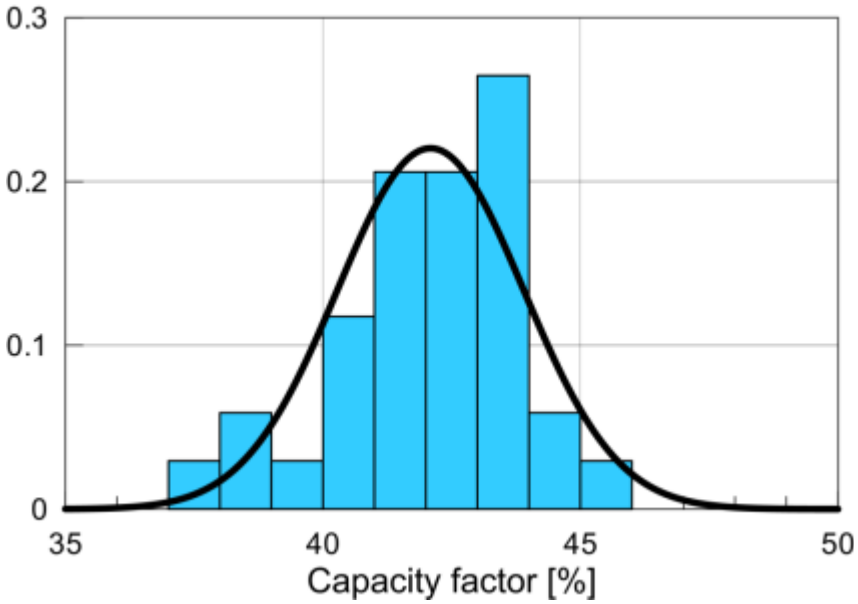
Data points used = 34 (of 37)

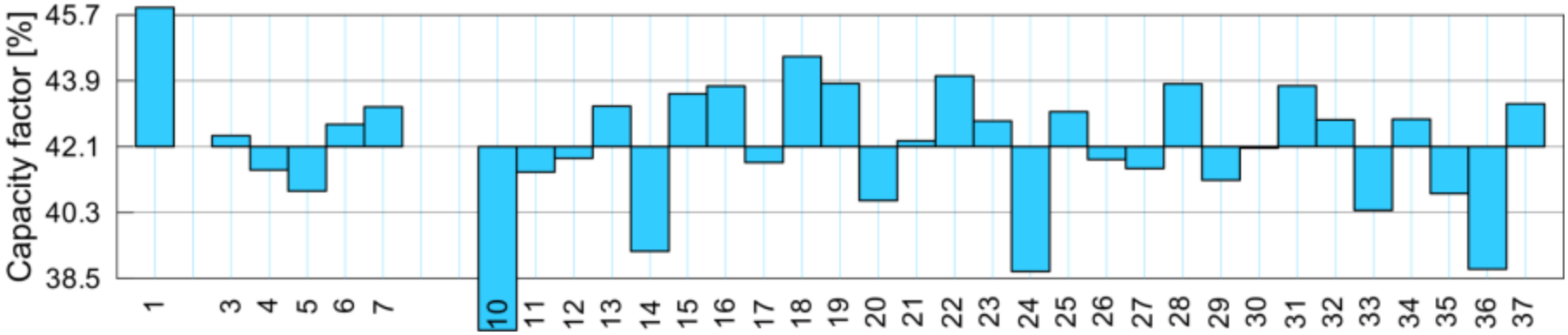
Team 2, 8 and 9 report no results

Mean capacity factor = **42.1%**

Std. deviation = **1.8%** (4.4%)

Range = 37 to 46% (21%)





Net energy yield of wind farm (P_{90})

Net AEP (P_{90}) = Net AEP (P_{50}) – 1.282 × [uncertainty]

Uncertainty estimates

Data points used = 35 (of 37)

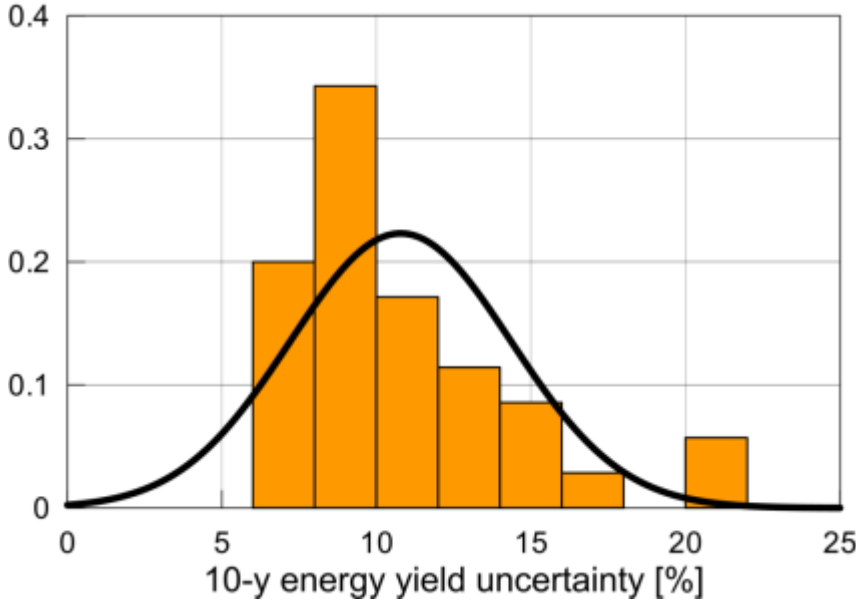
Team 2 and 9 report no results

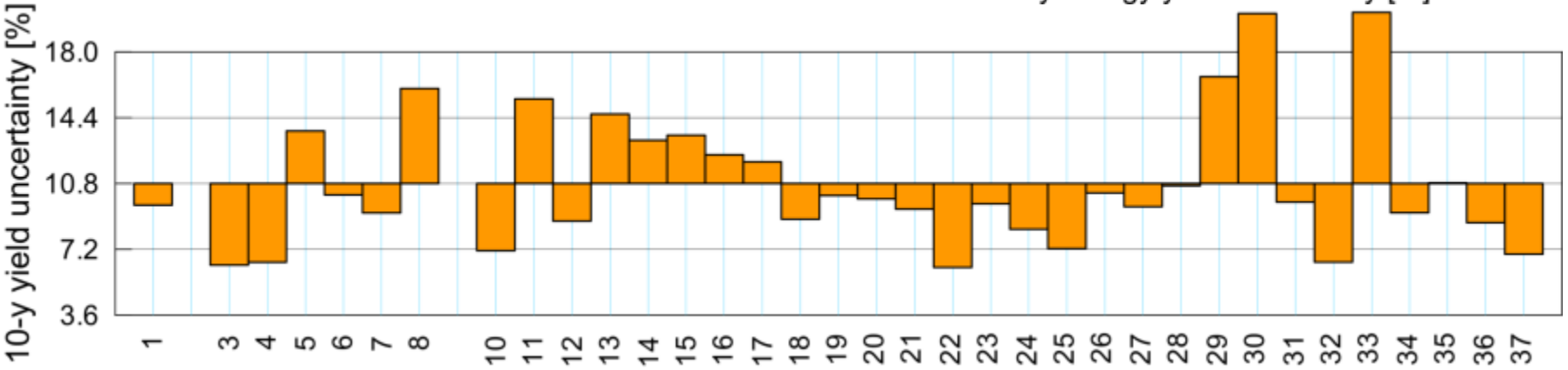
Mean uncertainty = **11%**

Std. deviation = **3.6%** (34%)

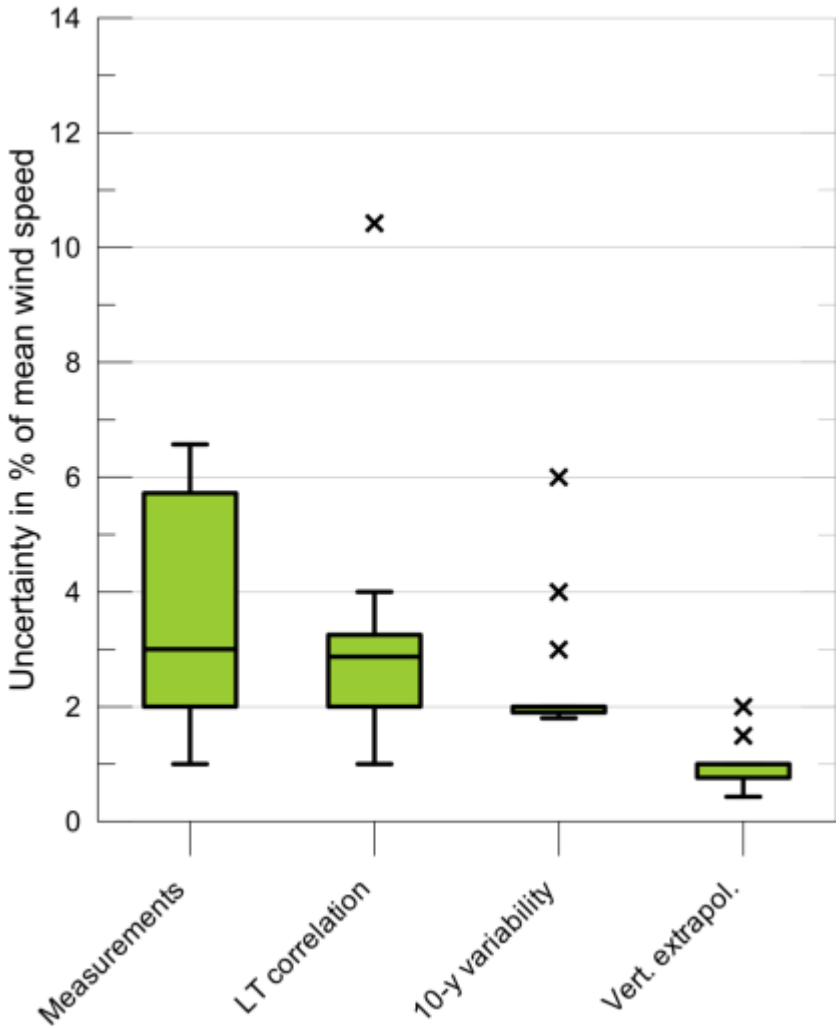
Range = 6 to 20% (129%)

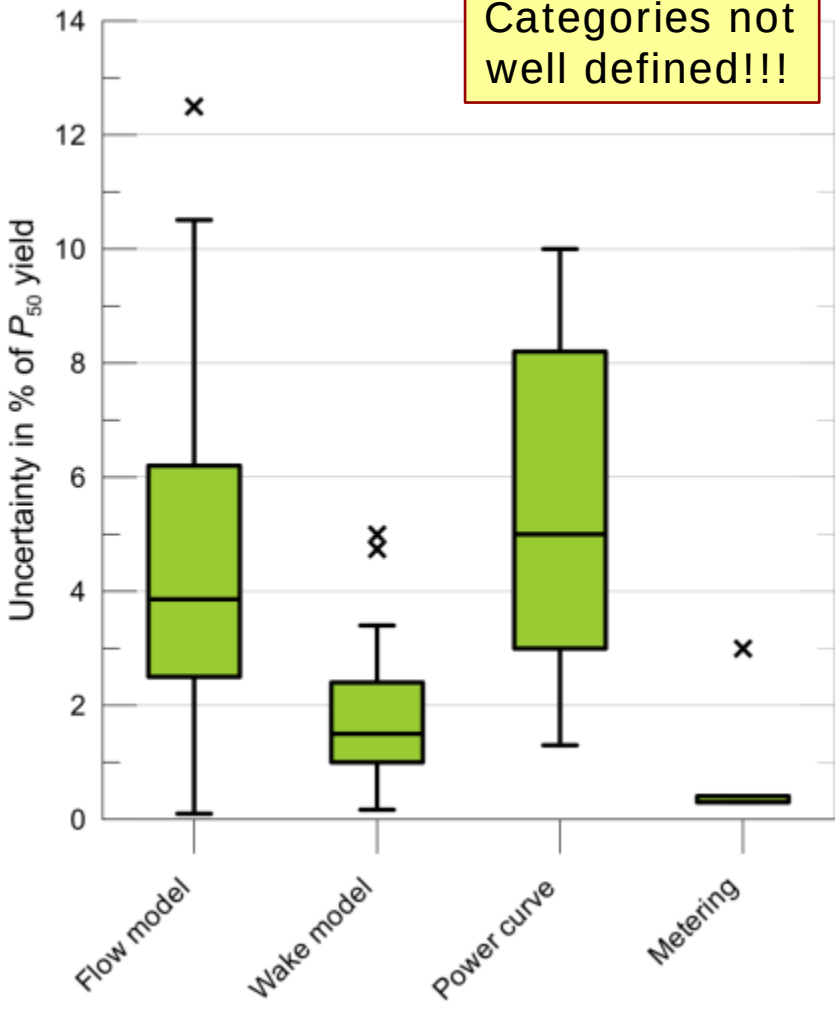
(Calculated from P_{50} and P_{90})





Uncertainty estimates by type (caution!!!)





Categories not well defined!!!

Net energy yield of wind farm (P_{90})

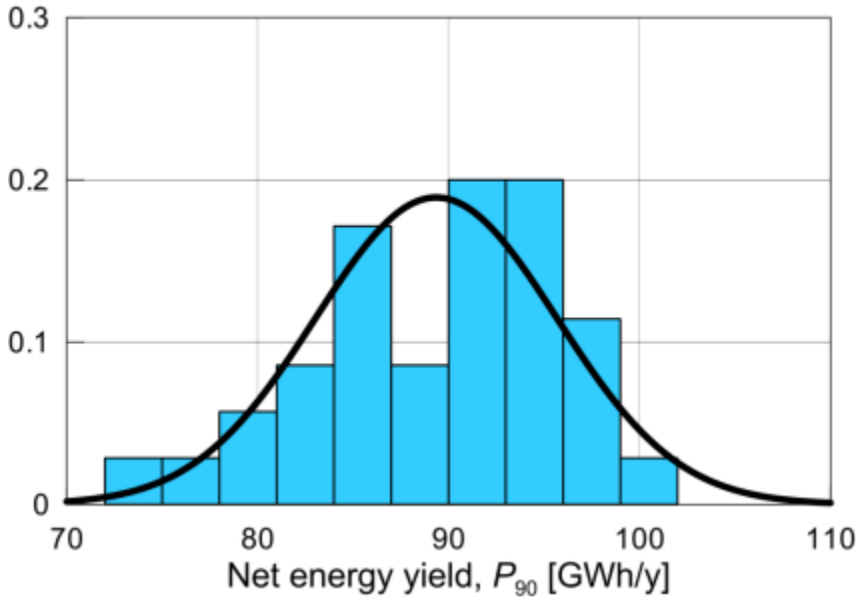
Data points used = 35 (of 37)

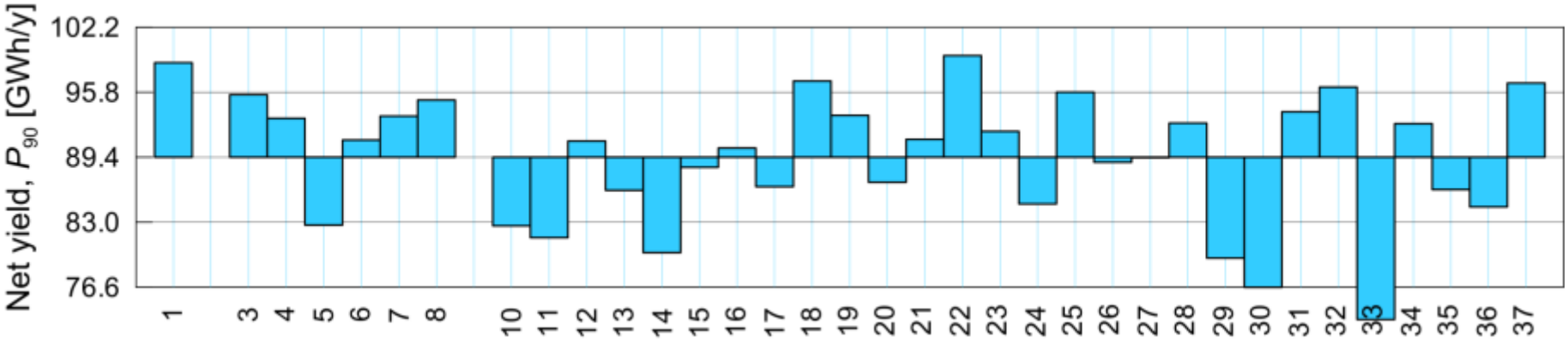
Team 2 and 9 report no results

Mean net yield = **89 GWh**

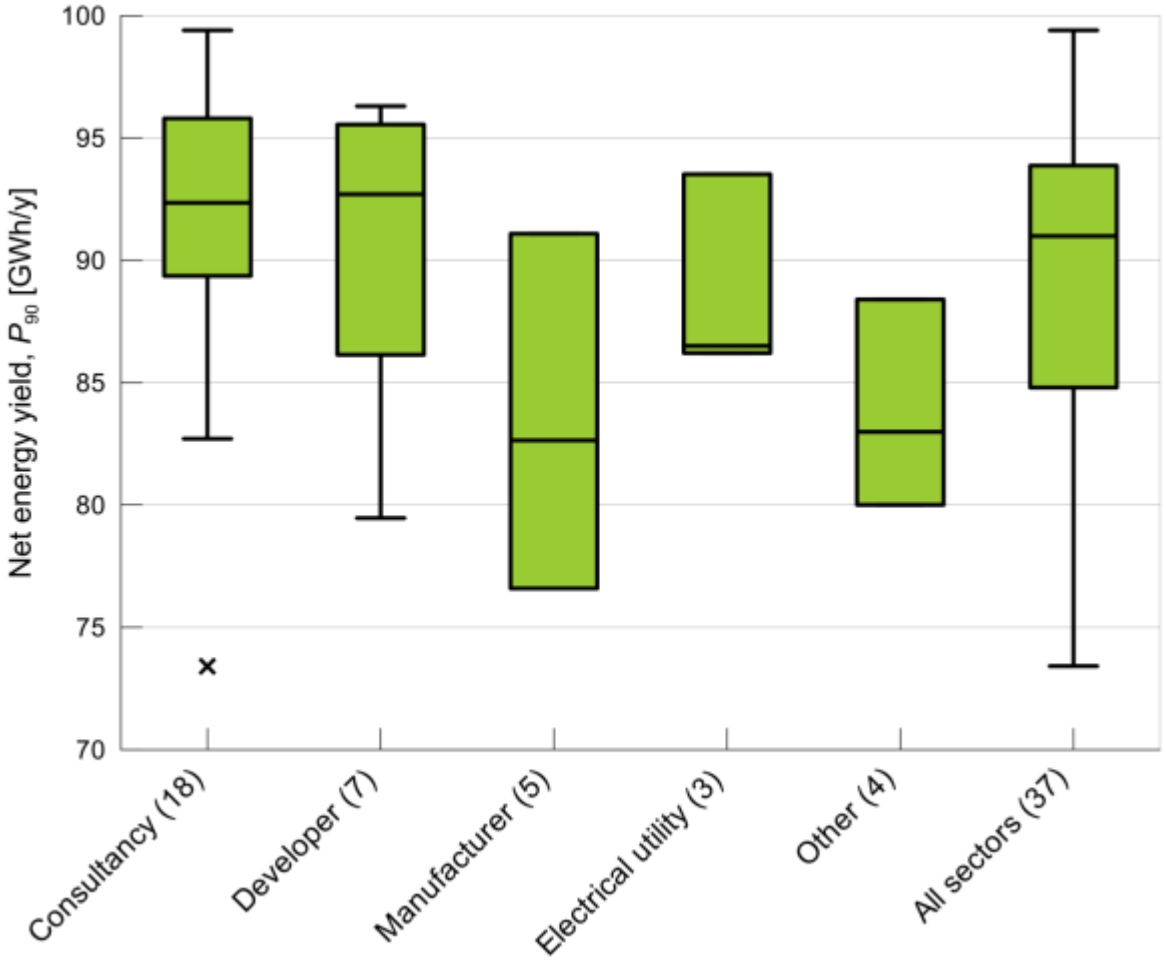
Std. deviation = **6.4 GWh** (7.2%)

Range = 73 to 99 GWh (29%)





Comparison of P_{90} versus business sector

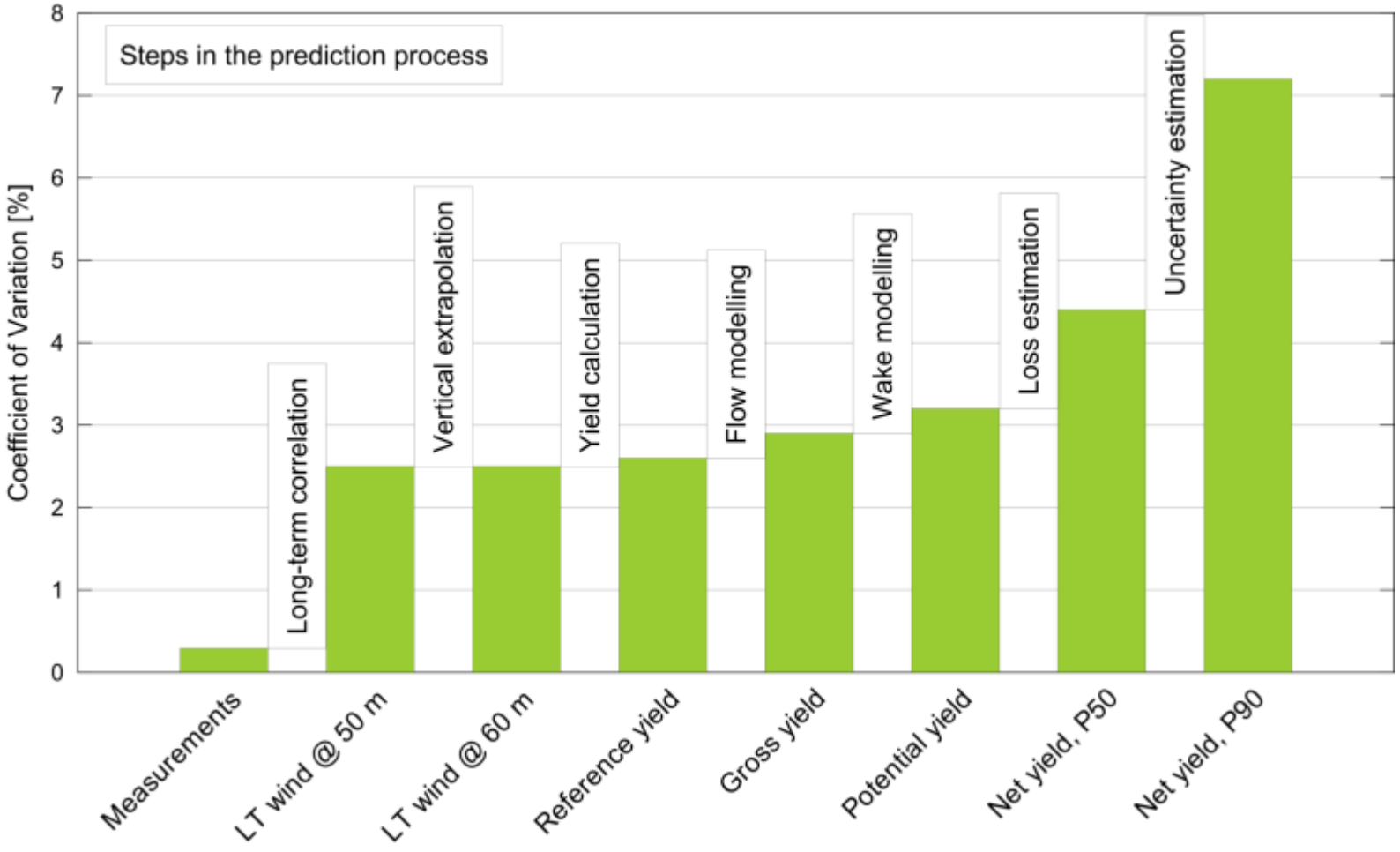


Summary of wind farm key figures

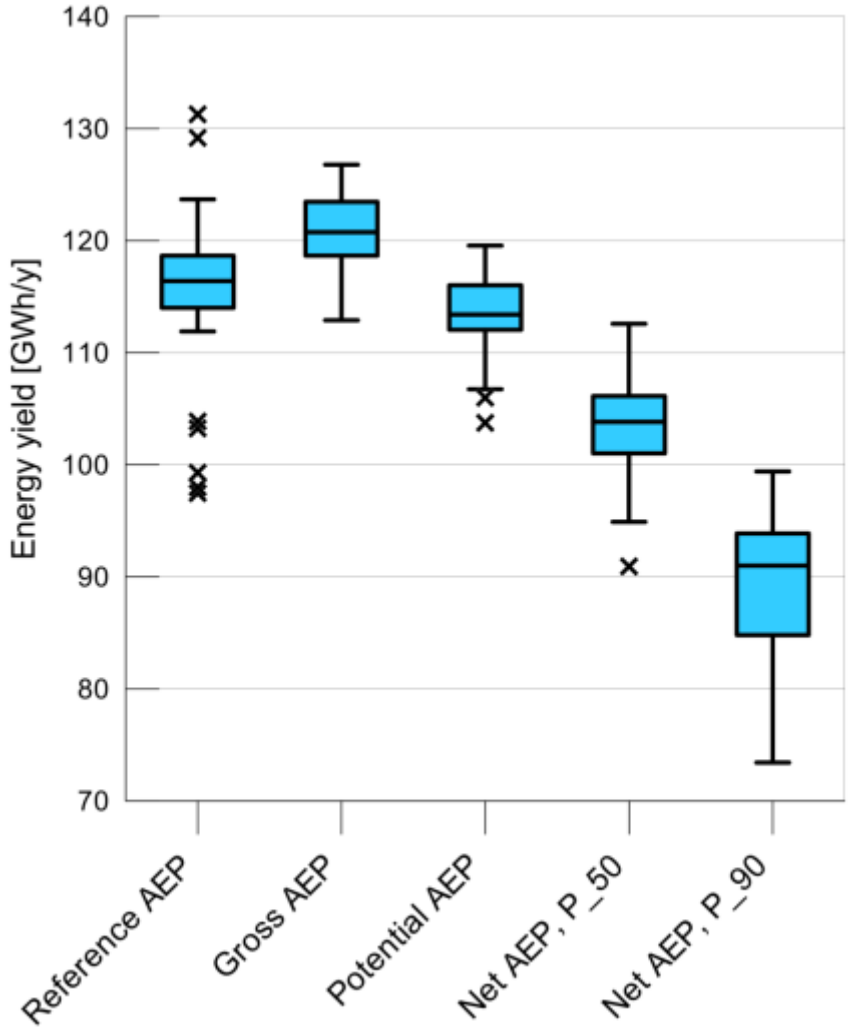
		Mean	σ	CV*	Min	Max
Reference yield	GWh	116	7.7	6.6	98	131
Topographic effects	%	5.1	7.5	147	-6.0	22
Gross energy yield	GWh	121	3.5	2.9	113	127
Wake effects	%	6.1	0.8	13	4.5	8.1
Potential yield	GWh	113	3.6	3.2	104	120
Technical losses	%	9.2	2.9	32	5	20
Net energy yield P_{50}	GWh	103	4.5	4.4	91	113
Uncertainty	%	11	3.6	34	6	20
Net energy yield P_{90}	GWh	89	6.4	7.2	73	99

* coefficient of variation in per cent

Steps in the prediction process

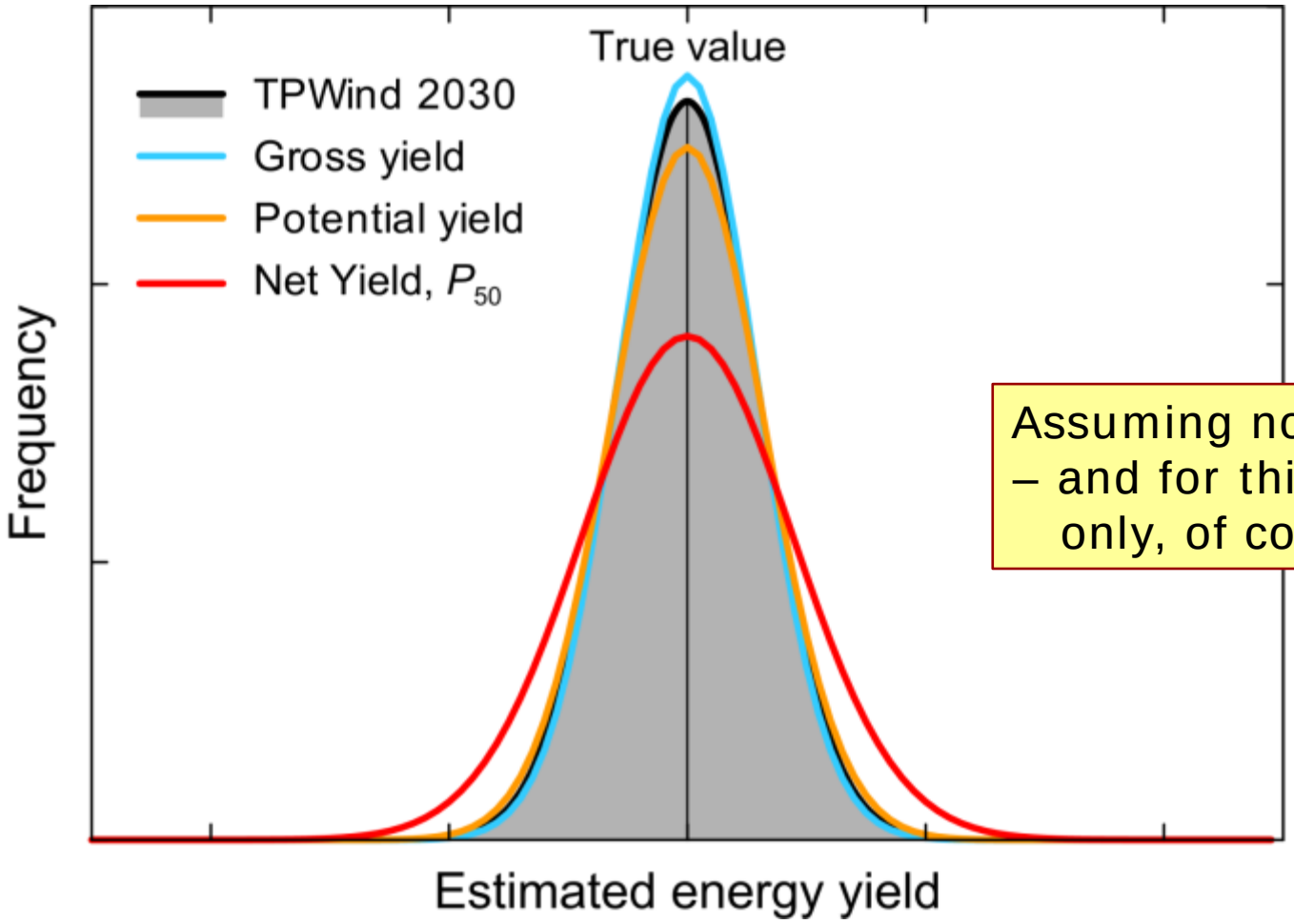


Summary and conclusions



- We must all draw the conclusions
- Steps that add little to the spread
  - Vertical extrapolation
  - Flow modelling
  - Wake modelling
- Which steps could be improved?
  - Long-term correlation
  - Technical loss estimation
  - Uncertainty estimation
- What else could be improved?
  - Definition and usage of concepts
  - Engineering best practices
  - Guidelines for reporting

How does this compare to TPWind 2030?



Assuming no bias!
– and for this site only, of course…

Future comparisons?

Should there be regular (yearly) comparison exercises?

- Wind farm site with roughnesses and roughness changes
- Wind farm site where vertical extrapolation is more important
- Wind farm site where stability effects are important (coastal site)
- Offshore wind farm site
- Forested wind farm site
- Complex terrain wind farm site
- Real wind farm(s) with production data

Future comparison exercises could be more focussed in order to highlight specific topics.

— Thank you for your attention!