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DEUTSCHE WINDGUARD

Side-by-Side Testing to Verify Improvements of Power Curves

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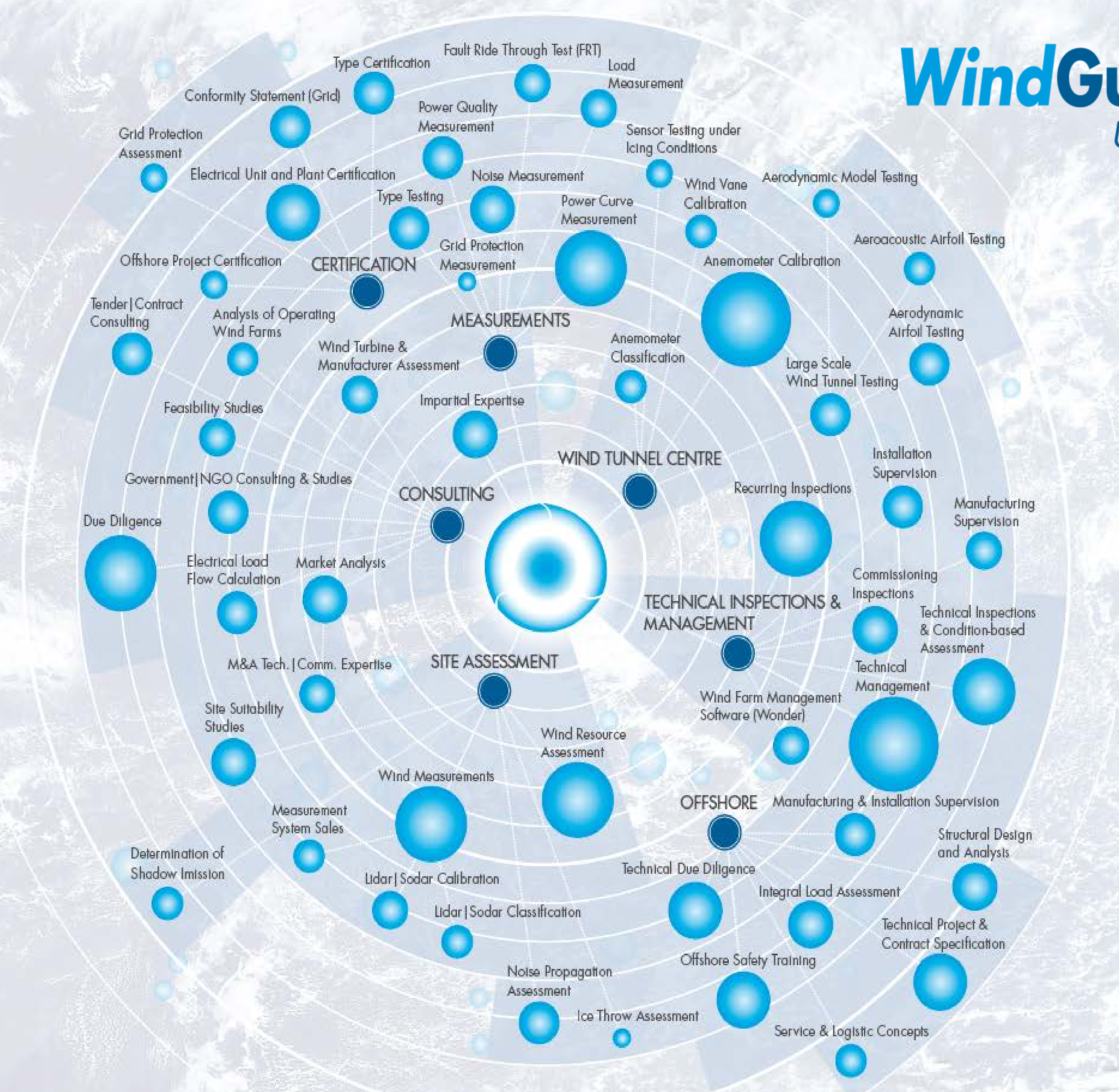
WindGuard Universe



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What Does Side-by-Side Testing Mean?

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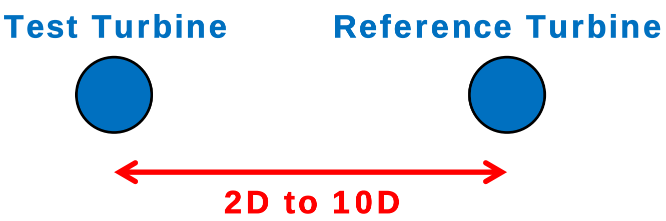
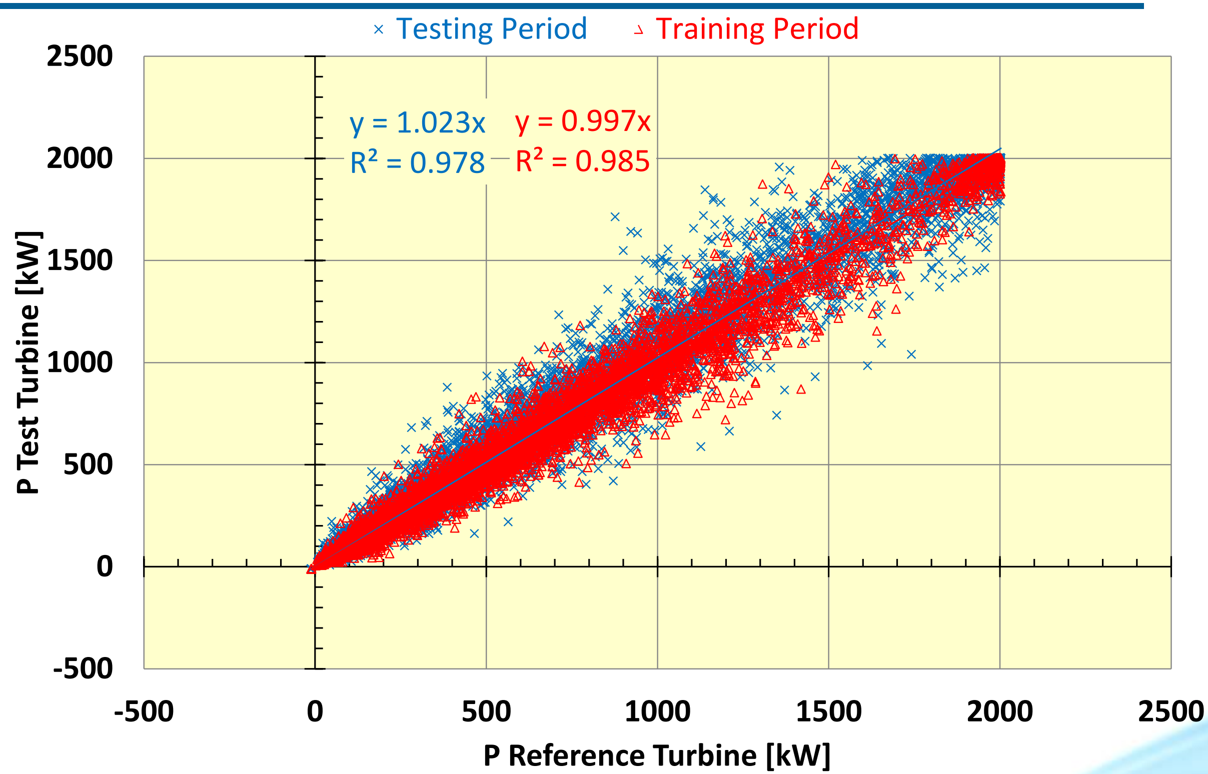
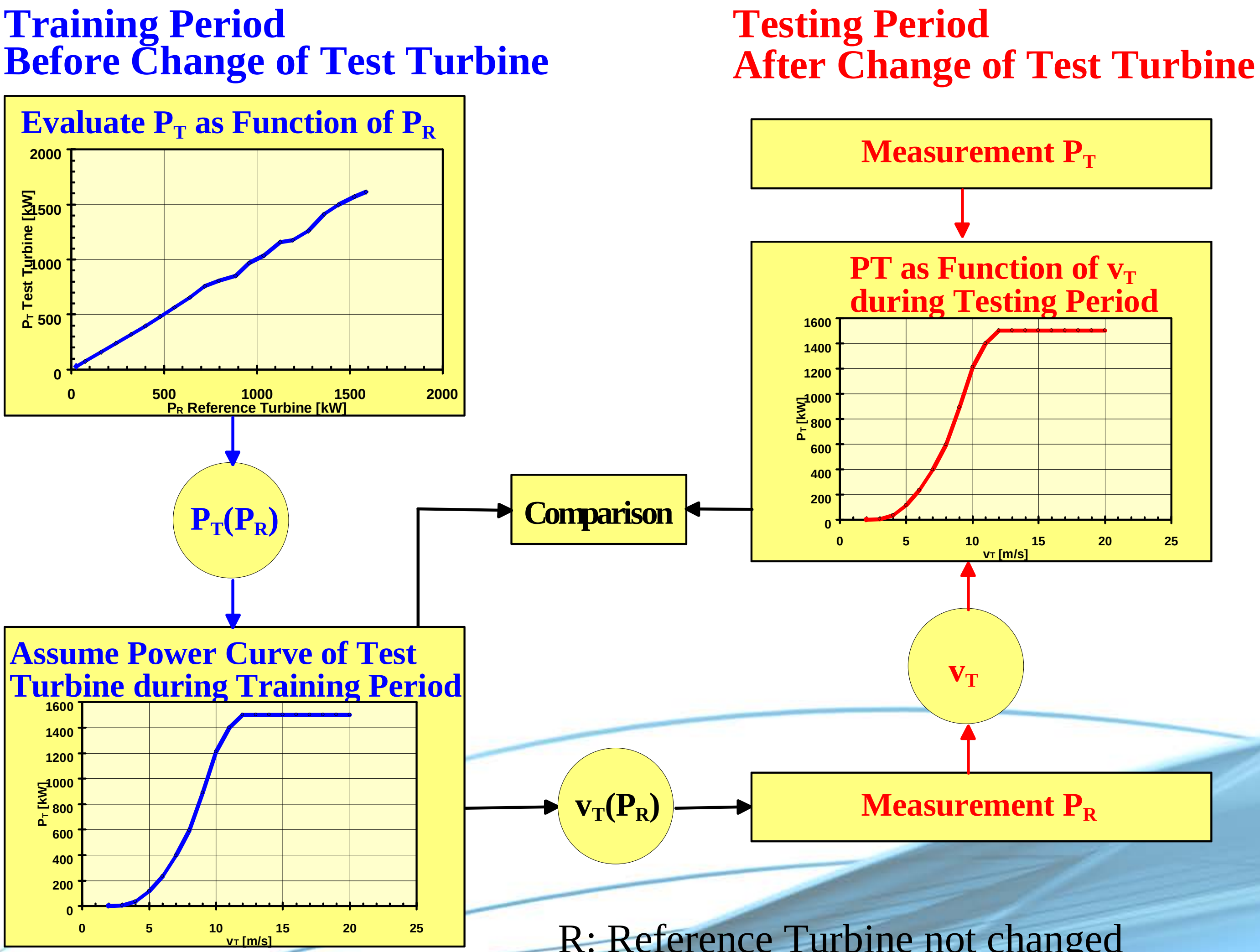




- 2 adjacent turbines (Reference and Test Turbine)
- 2 periods (Training and Testing)
- Reference Turbine remains unchanged
- Power curve of Test Turbine is changed
- Shift of power to power relation is analysed

Principle of Side-by-Side Testing or Relative Power Curve Analysis



R: Reference Turbine not changed
T: Test Turbine changed

Needed Data

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- SCADA-data fully sufficient
- 10-minute resolution
- Data channels for Test Turbine and Reference Turbine

  Required:

  - active power output
  - nacelle (azimuth) position
  - status code turbine operational (can be generated via RPM)

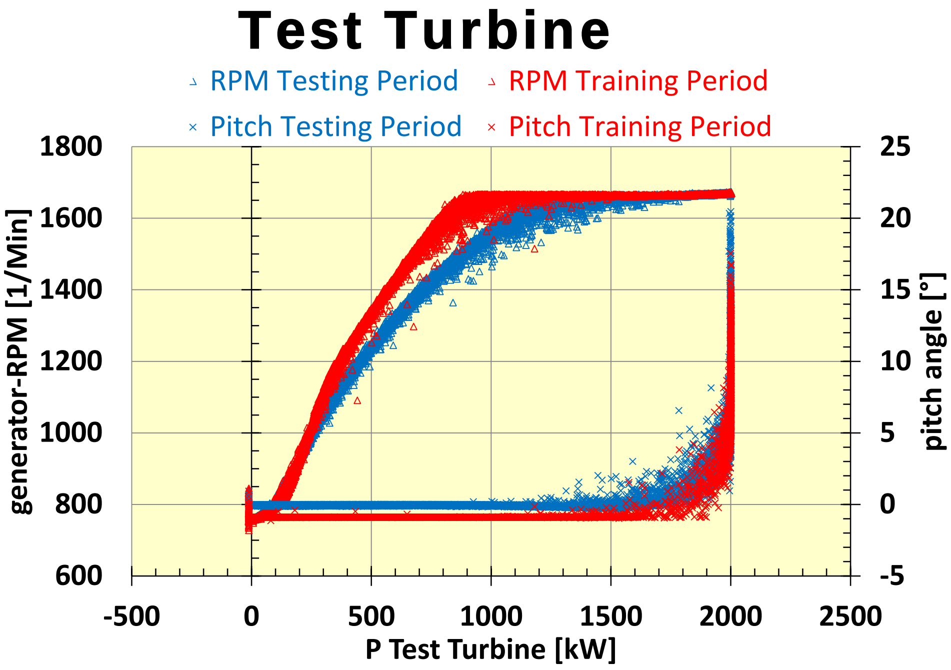
  Useful additional signals:

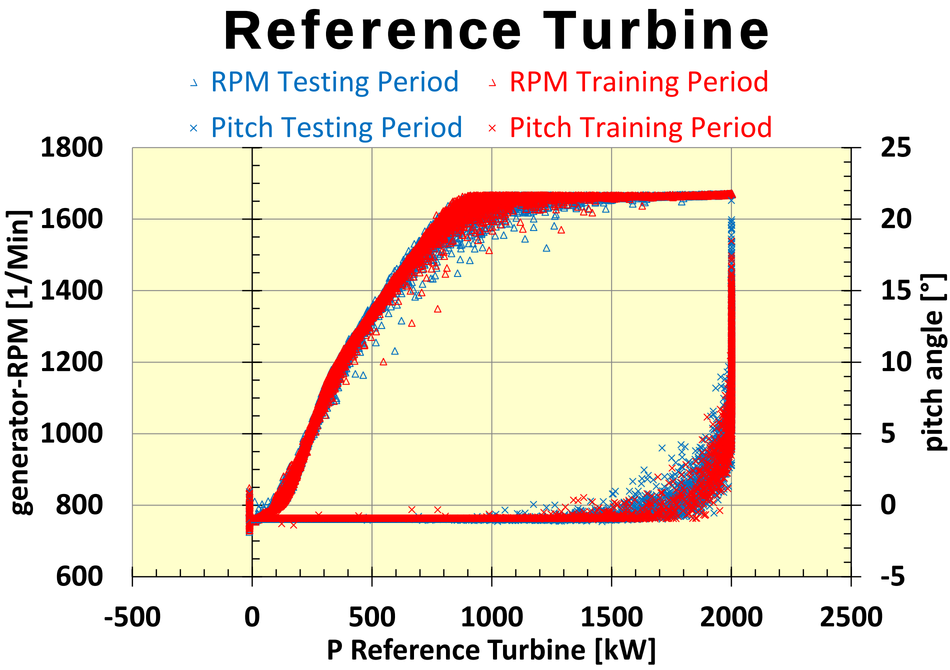
  - RPM (rotor or generator)
  - pitch angle
  - air temperature
  - (- nacelle anemometer)
- Mean, max, min, standard deviation of each channel preferred
- No wind speed measurement needed!

SCADA Data Needs Detailed Checking

- Double appearance of data
- Synchronisation of data of Test and Reference Turbine
- Plausibility of data
  - plausible range
  - consistency of different data channels of each turbine
  - consistency of same data channels of different turbines
- Consistency of WT settings in Training Period and Testing Period
- Northing, drifting of nacelle position signal

Consistency of Turbine Settings





- Reference Turbine:

  Settings unchanged throughout Training Period and Testing Period
- Test Turbine:

  Settings change between Training and Testing Period, but unchanged within each of the two periods

Data Filtering

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- Test Turbine and Reference Turbine operational, filtering by status code or e.g. by RPM signal
- Test Turbine and Reference Turbine not curtailed, filtering by status signal
- No blade icing, filtering by temperature
- Test Turbine and Reference Turbine free of wakes is often preferable, but no necessary condition
- In Testing Period: use only wind direction ranges and power ranges also covered by Training Period

Wind Direction Measurement

- Direction measurement needed for:
  - filtering of wake conditions
  - application of directional dependent power-to-power relation
- Realisation via nacelle position signal

Northing of Nacelle Position Signal

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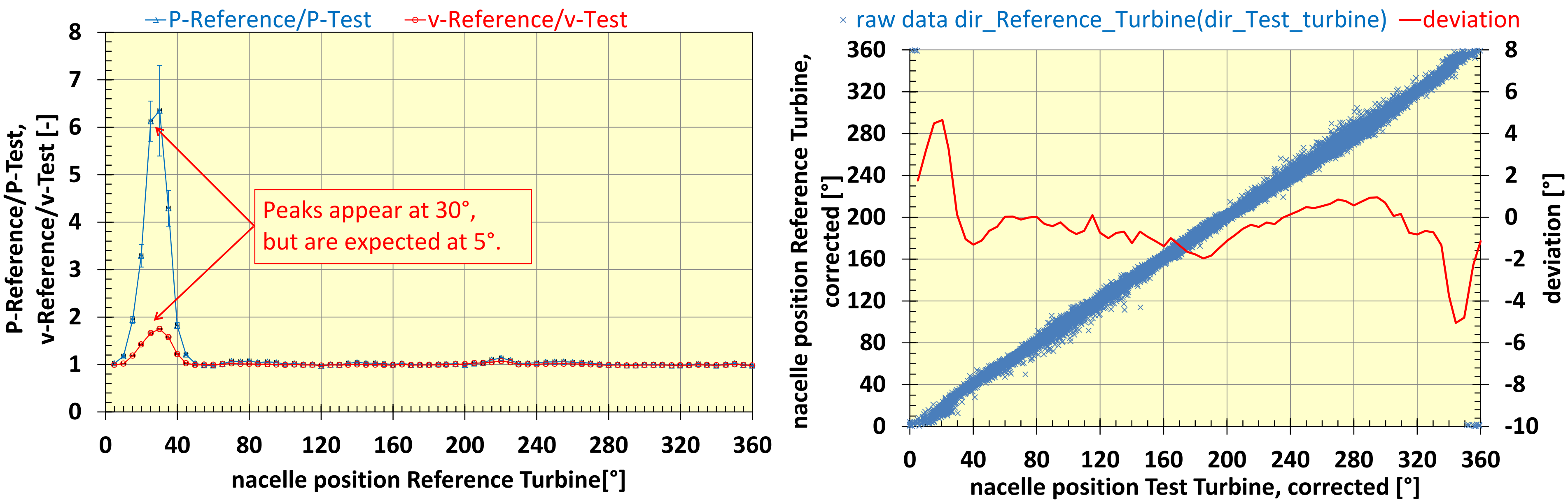
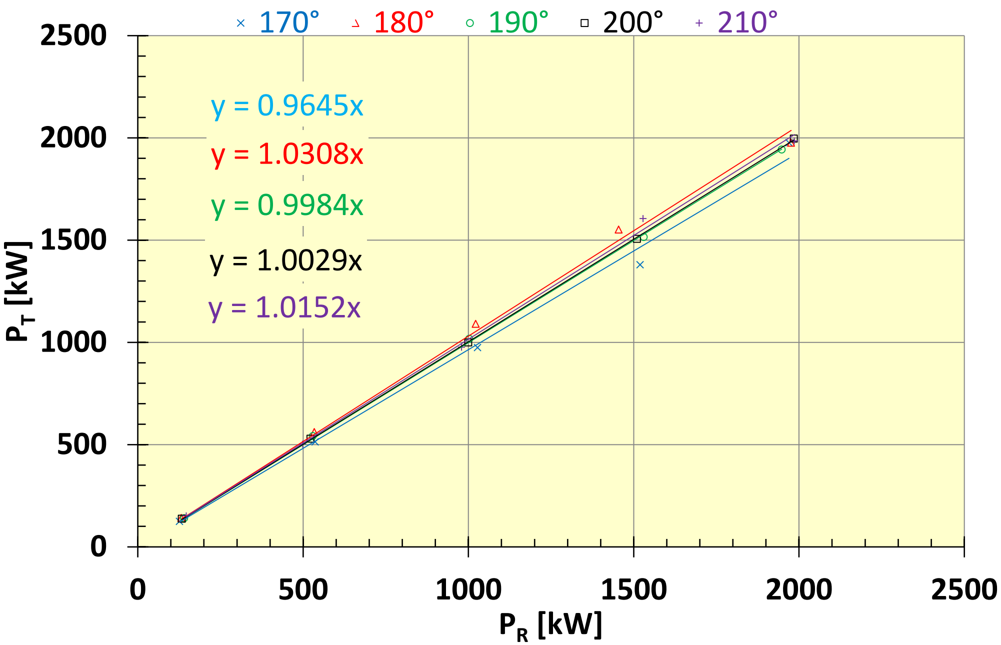


- Northing of nacelle position signals of both turbines against known breakings
- Check of parity of corrected signals
- Warning: nacelle position signal can drift!

Power-to-Power Relation



direction	P_R	P_T	n
[°]	[kW]	[kW]	[-]
170	126.3	124.1	121
170	536.5	513.2	129
170	1027.6	974.6	118
170	1519.4	1379.1	24
170	1969.8	1976.3	61
180	131.9	141.5	95
180	534.0	561.1	179
180	1022.0	1090.2	147
180	1454.6	1551.8	32
180	1976.1	1976.1	43
190	140.1	139.8	118
190	529.3	541.4	271
190	1002.6	1017.4	154
190	1530.4	1515.2	53
190	1947.8	1942.7	50
200	133.1	137.4	180
200	522.5	529.0	279
200	999.6	999.7	130
200	1509.9	1506.3	31
200	1984.6	1996.1	24
210	146.6	151.0	135
210	498.8	501.8	261
210	979.7	976.3	117
210	1528.4	1604.9	24
210	1986.1	1985.3	42

- power-to-power relation is dependent on wind direction and wind speed
- Binning P_T as function of wind direction and P_R in Training Period
- Use 10° wide wind direction bins and 5 power bins from 0kW to rated power

Application of Power-to-Power Relation in Testing Period

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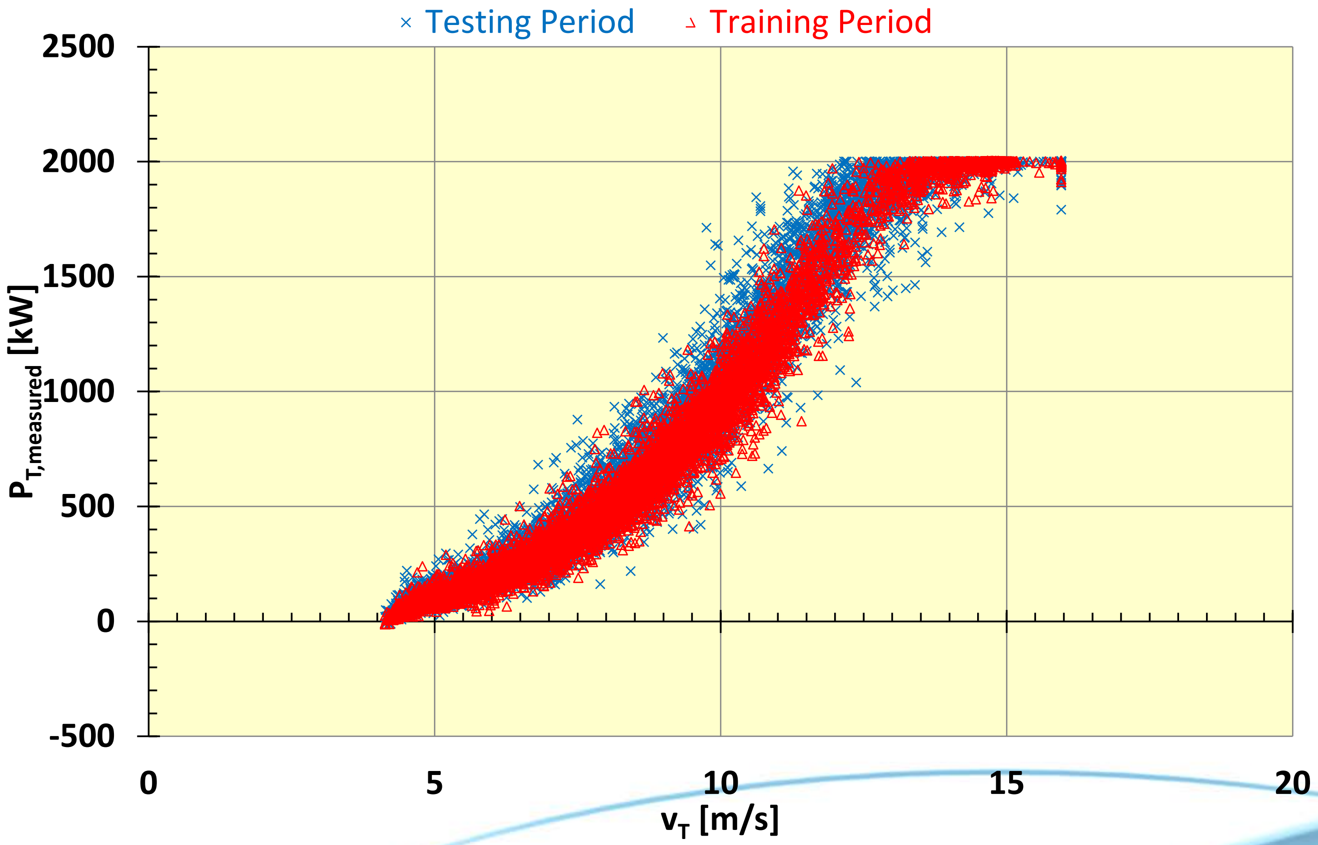
- 1st step: Chose wind direction bin according to nacelle azimuth position of Test Turbine
- 2nd step: Reproduce power output of Test Turbine for case of non-optimised state by piecewise linear fit of correction matrix elements in the relevant direction bin according to measured power at Reference Turbine:

$$P_{T,simulated} = \frac{P_{T,j,i} - P_{T,j,i-1}}{P_{R,j,i} - P_{R,j,i-1}} \left(P_{R,measured} - P_{R,j,i-1}\right) + P_{T,j,i-1}$$

- 3rd step: calculate wind speed at Test Turbine by piecewise linear fit of power curve assumed for Training Period according to $P_{T,simulated}$ as gained from step 2:

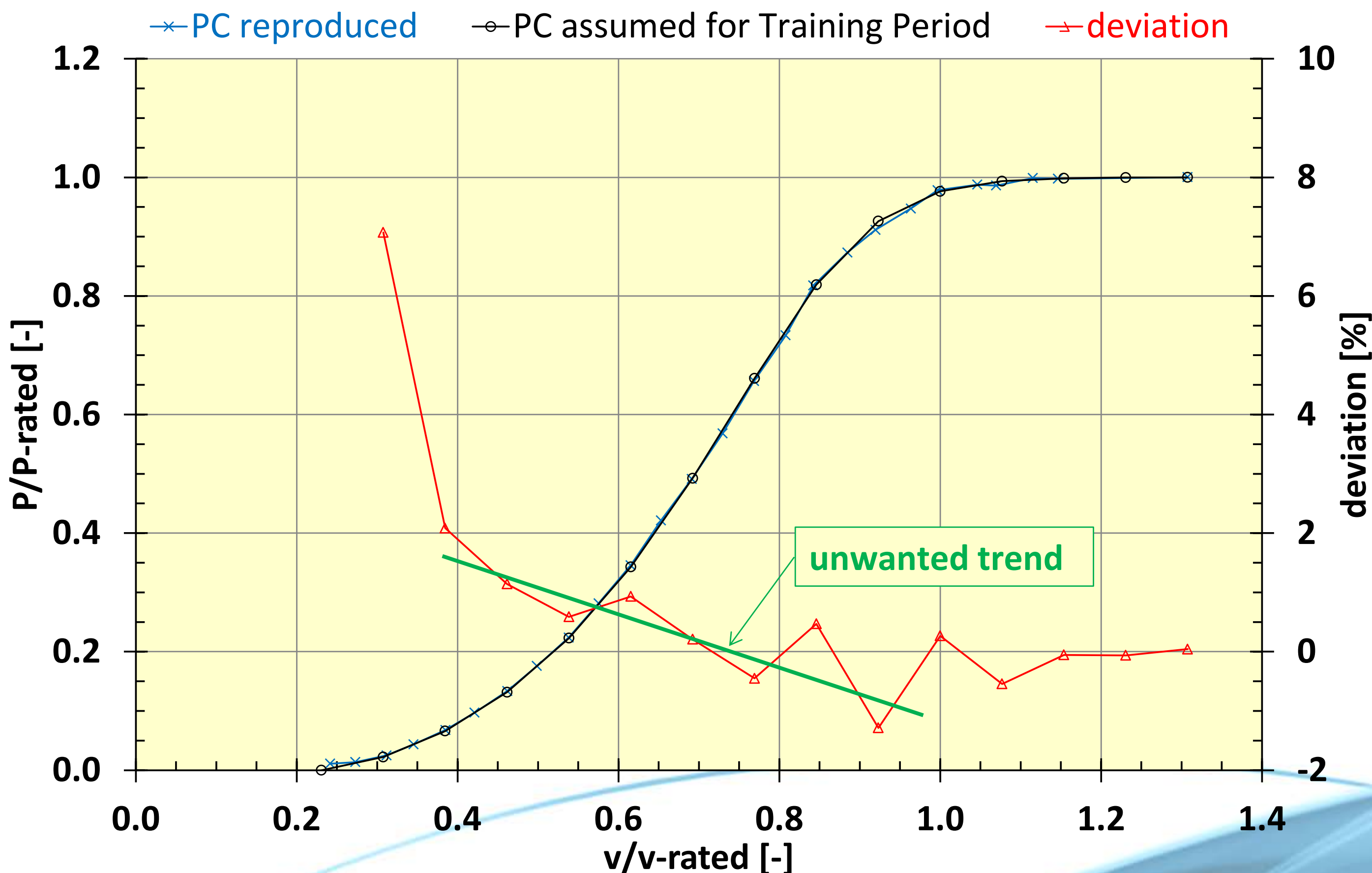
$$v_T = \frac{v_i - v_{i-1}}{P_{non-opt,i} - P_{non-opt,i-1}} \left(P_{T,simualted} - P_{non-opt,i-1}\right) + v_{i-1}$$

Result: Power Curve Raw Data



- v_T from 3rd step combined with measured power output of Test Turbine in Testing Period gives power curve raw data in Testing Period (blue crosses)
- Method can also be applied in Training Period (red triangles)

Power Curve Self-Consistency Test



- Use method in Training Period and compare result with assumed PC for Training Period
- Often unwanted trend due to binning effects

Solution to Overcome Binning Effects

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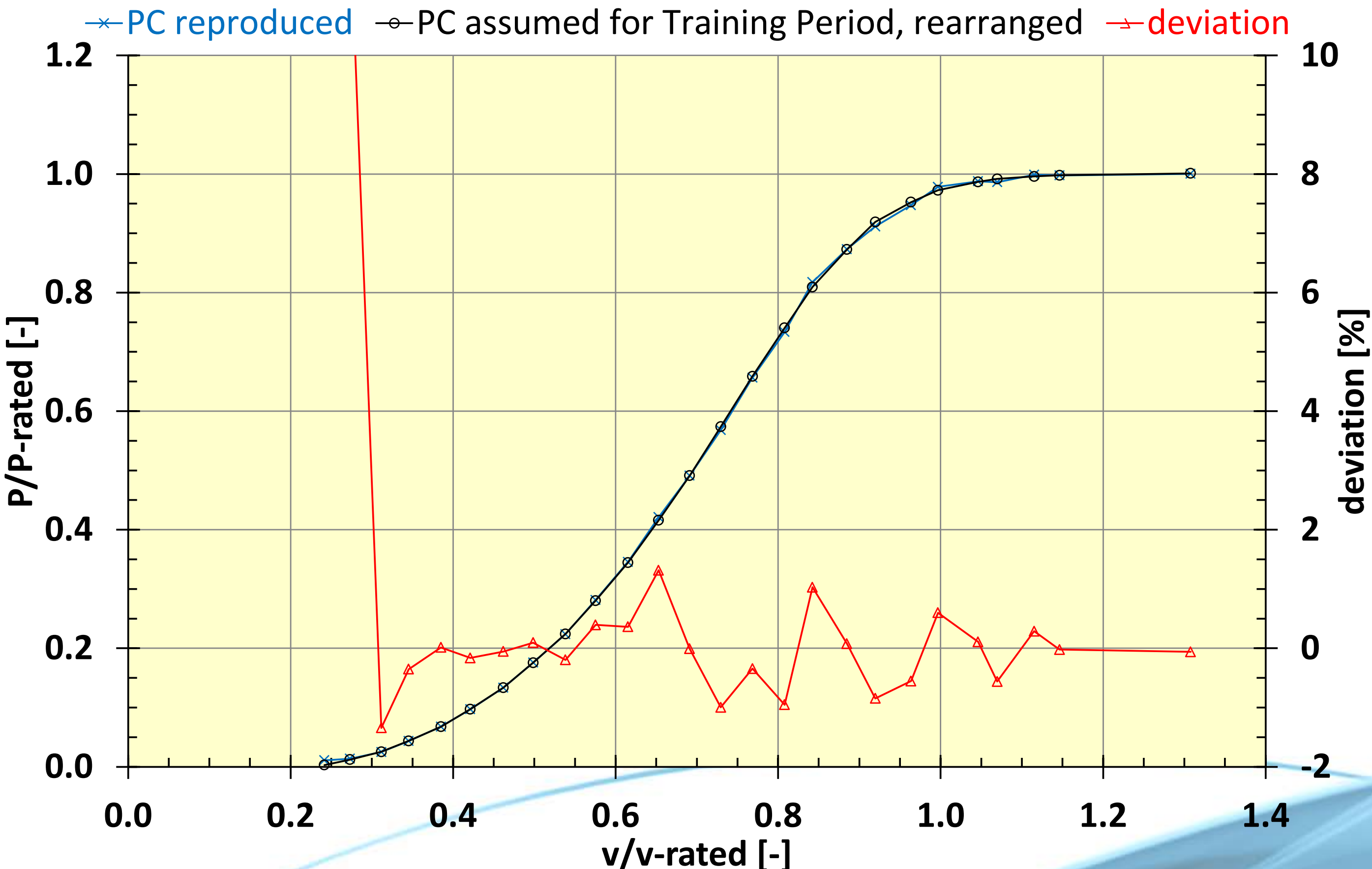
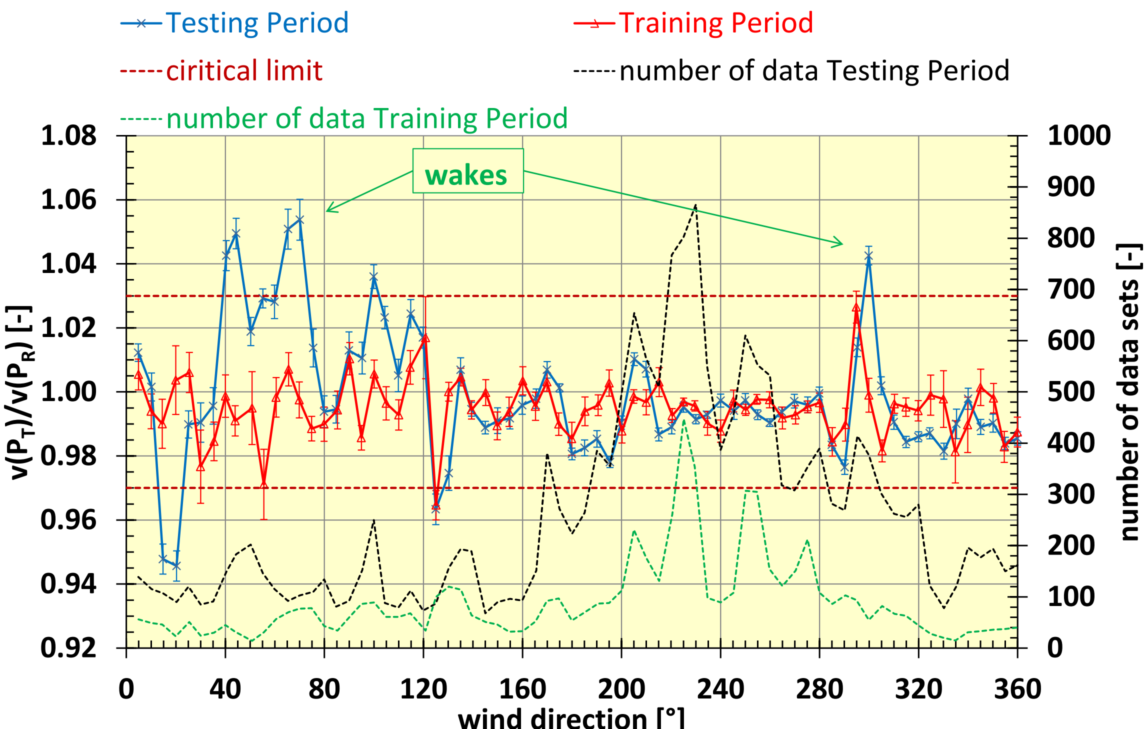


- Rearrange assumed PC to identical bins as reproduced power curve by directly binning $P_{T,simulated}$ versus v_T (black circles)
- Note: PC reproduced is binning $P_{T,measured}$ versus v_T (blue crosses)

Sector Self-Consistency Test



- Calculate v from power measured at Test Turbine and evaluated power curve: $v(P_T)$
- Calculate ratio of $v(P_T)$ and v evaluated from power measured at Reference Turbine $v(P_R)$ (for position at Test Turbine)
- Bin average ratio as function of wind direction
- Take out sectors where critical limit exceeded

Self-Consistency Test after Sector Reduction

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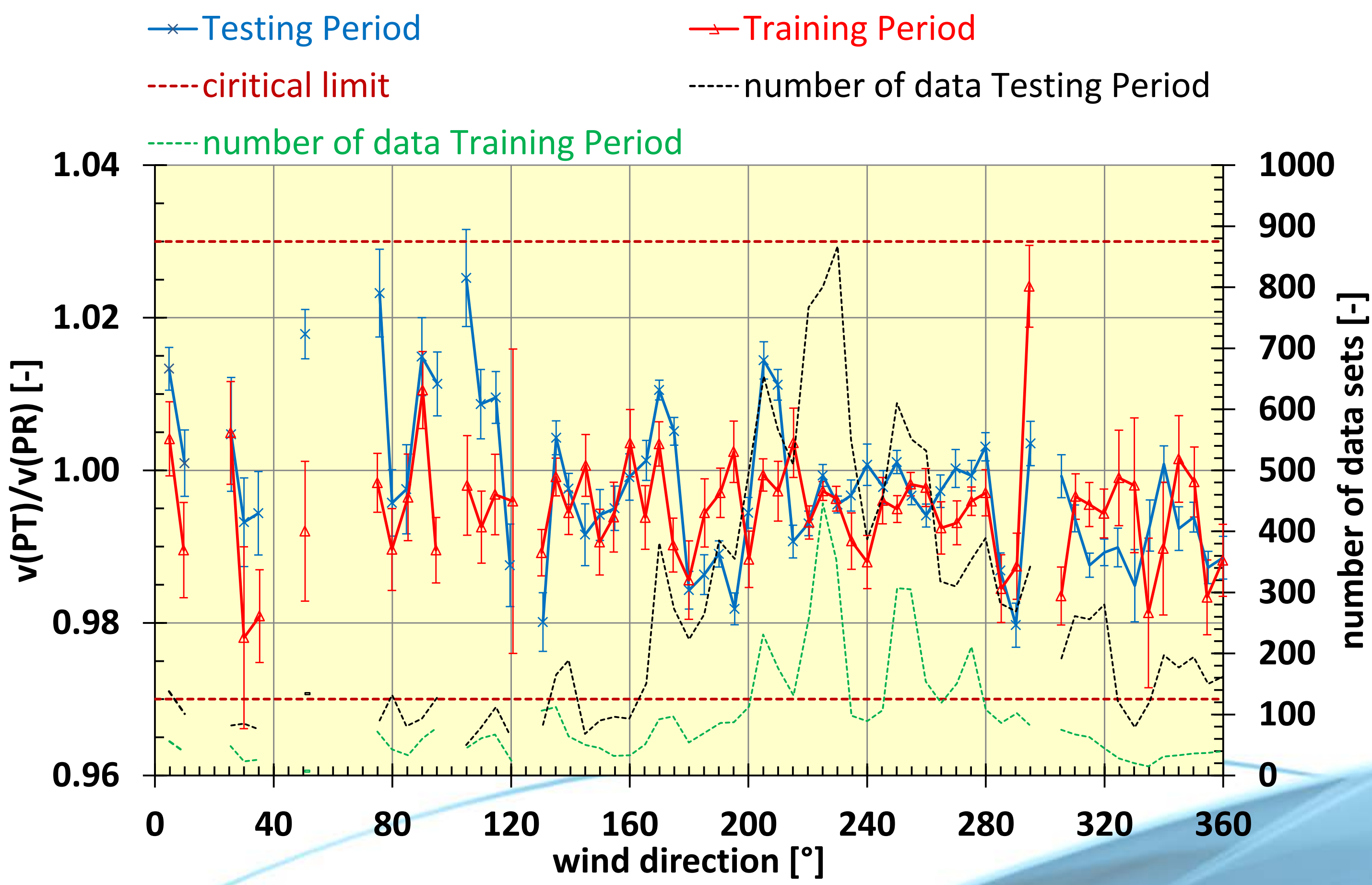
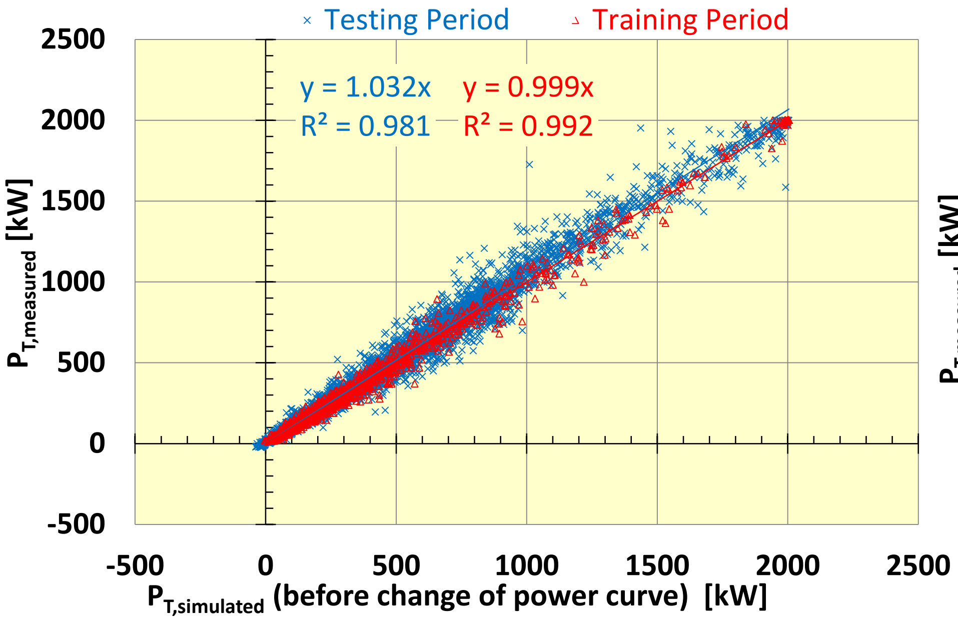
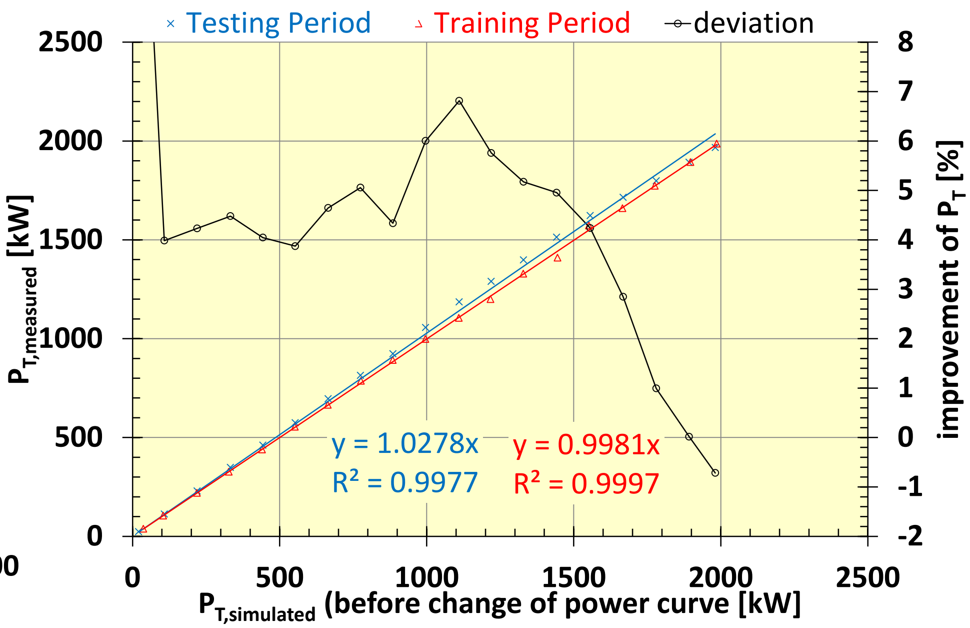


- Difference of result for Testing Period and Training Period is measure of change of power-to-power relation

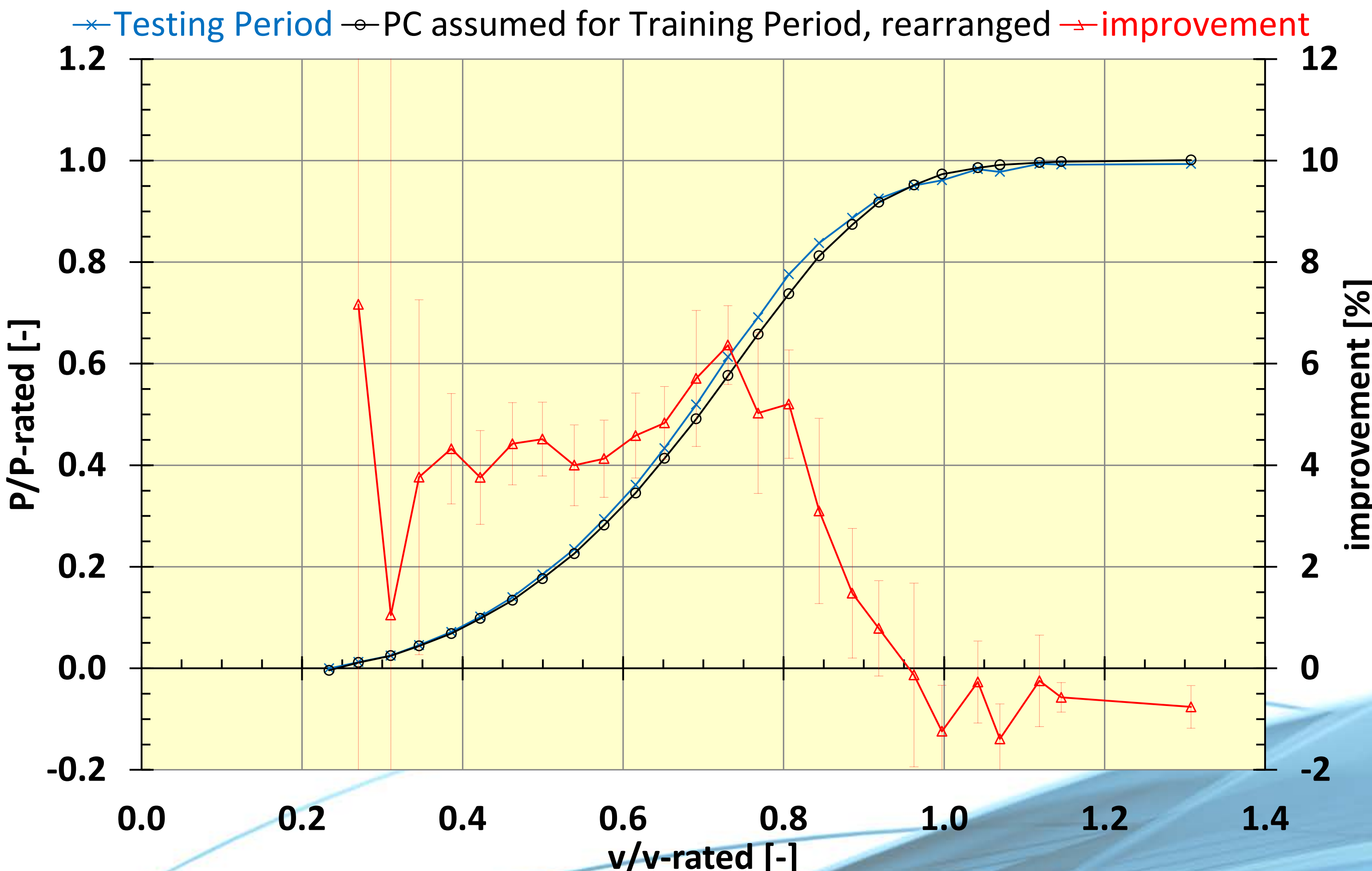
Result: Improvement of Power





- Don't use P_R on x-axis! (too many assumptions)
- Use $P_{T,simulated}$: power simulated for Test Turbine for non-optimised case on basis of measured power of Reference Turbine and power-to-power matrix

Result: Improvement of Power Curve



Result: Improvement of AEP

v-average	AEP measured	uncertainty AEP		AEP extrapolaed	AEP assumed PV before change	improvement of AEP
[m/s]	[MWh]	[MWh]	[%]	[MWh]	[MWh]	[%]
4.0	1333	11	0.8	1333	1271	**4.9**
4.5	1952	12	0.6	1952	1867	**4.6**
5.0	2665	13	0.5	2667	2557	**4.3**
5.5	3436	15	0.4	3446	3315	**3.9**
6.0	4227	17	0.4	4260	4113	**3.6**
6.5	4998	19	0.4	5081	4923	**3.2**
7.0	5715	21	0.4	5889	5725	**2.9**
7.5	6354	22	0.3	6667	6503	**2.5**
8.0	6897	23	0.3	7405	7243	**2.2**
8.5	7339	24	0.3	8093	7936	**2.0**
9.0	7680	24	0.3	8724	8575	**1.7**
9.5	7926	24	0.3	9296	9155	**1.5**
10.0	8086	24	0.3	9804	9672	**1.4**
10.5	8170	24	0.3	10246	10124	**1.2**
11.0	8190	24	0.3	10623	10511	**1.1**

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Relevant Uncertainties:

- A1: statistical uncertainty of PC in Testing Period
- A2: statistical uncertainty of power-to-power relation
- B1: power curve reproduction capability (how well can the power curve assumed for the Training Period be reproduced with the method?)
- B2: possible shift of power-to-power relation with time

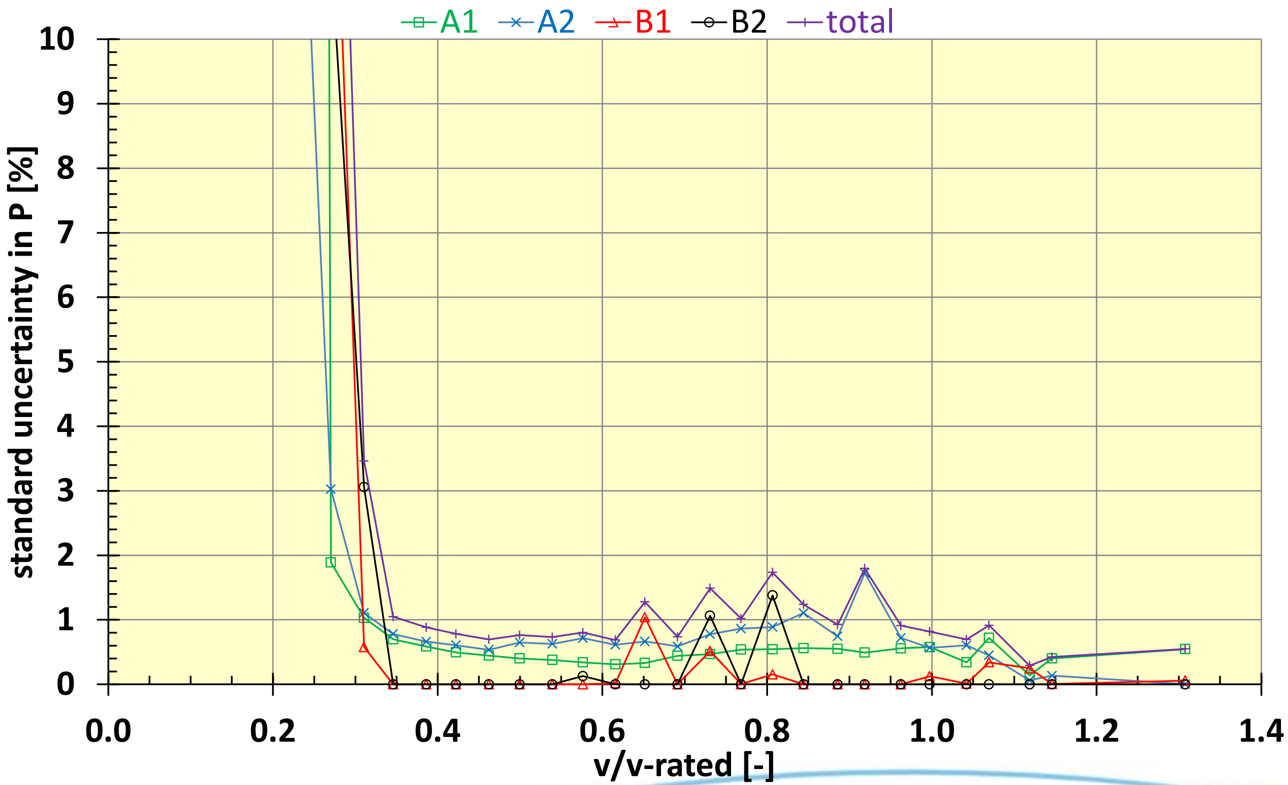
Irrelevant Uncertainties:

- Uncertainty of power measurements: evaluation process designed such that uncertainty almost entirely cancels out!
- Uncertainty due to influence of air density, turbulence intensity, wind shear, wind veer on power curve: change of influence between Training Period and Testing Period is nearly the same at Test Turbine and Reference Turbine and cancels out **(big advantage over methods based on wind measurements!)**

Assessment of Uncertainties

- A1: statistical uncertainty of PC in Testing Period
  - by variation of power values in wind speed bin as in IEC 61400-12-1
- A2: statistical uncertainty of power-to-power relation
  - equals statistical uncertainty of power curve reproduced for Training Period (scaled by change of power curve)
- B1: power curve reproduction capability
  - by deviations of assumed and reproduced power curve in Testing Period as gained from Power Curve Self-Consistency Test (reduced by statistical unc.)
- B2: possible shift of power-to-power relation with time
  - split Testing Period in two sub periods, or
  - evaluate change of sector self-consistency test from Training to Testing Period, or
  - assess how power relation of two unchanged Reference Turbines varies from Training to Testing Period

Magnitude of Uncertainties



- Typical standard uncertainty in single bins: 1% to 2% of P
- Typical standard uncertainty in AEP: 0.2% to 1%
- Uncertainty in AEP much lower than in P because dominating statistical uncertainties A1 and A2 are uncorrelated across wind speed bins

Minimisation of Uncertainties by Weighting Results of Different Tests

- L power curve tests:
  - same Test Turbine, different Reference Turbines
  - same Test Turbine, different direction sectors
  - different Test Turbines
- Weighting of L power curves in wind speed bin i:

$$P_i = \sum_{m=1}^{L} t_{i,m} \cdot P_{i,m} \quad v_i = \sum_{m=1}^{L} t_{i,m} \cdot v_{i,m} \quad \sum_{m=1}^{L} t_{i,m} = 1$$

- Uncertainty component j in wind speed bin i of weighted power curve:

$$u_{i,j} = \sqrt{\sum_{m=1}^{L} \sum_{l=1}^{L} t_{i,m} u_{i,j,m} t_{i,m} u_{i,j,l} \rho_{i,j,m,l}}$$

- Selection of weighting factors $t_{i,m}$ such that total uncertainty of weighted power curve in bin i is minimised:

$$u_{i,total} = \sqrt{\sum_{j=1}^{M} u_{i,j}^2} = Min$$

Uncertainty Reduction by Weighting

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v-average	unc. AEP 1	unc. AEP 2	unc. AEP 3	unc. AEP 4	unc. AEP weighted PC
[m/s]	[%]	[%]	[%]	[%]	**[%]**
4.0	1.1	0.9	0.8	0.5	**0.3**
4.5	0.9	0.8	0.6	0.4	**0.3**
5.0	0.8	0.7	0.5	0.4	**0.3**
5.5	0.8	0.7	0.4	0.3	**0.3**
6.0	0.8	0.7	0.4	0.3	**0.3**
6.5	0.7	0.7	0.4	0.3	**0.2**
7.0	0.7	0.7	0.4	0.3	**0.2**
7.5	0.7	0.7	0.3	0.3	**0.2**
8.0	0.7	0.7	0.3	0.3	**0.2**
8.5	0.7	0.7	0.3	0.3	**0.2**
9.0	0.7	0.7	0.3	0.3	**0.2**
9.5	0.7	0.7	0.3	0.3	**0.2**
10.0	0.7	0.7	0.3	0.3	**0.2**
10.5	0.7	0.7	0.3	0.3	**0.2**
11.0	0.7	0.7	0.3	0.3	**0.2**

- Strong uncertainty reduction possible by weighting due to high content of statistical uncertainties (often highly uncorrelated across tests)

Requirements on Test Site

- Good correlation of wind conditions at Test Turbine and Reference Turbine
  - distance up to 10D
  - maximum distance dependent on terrain complexity (lower distance in complex terrain)
  - sufficient correlation reflected by acceptable statistical uncertainty (A1 and A2)
- Applicability in complex terrain possible only by use of directional dependent power-to-power relation (otherwise only small direction sector applicable in complex terrain)
- Applicability in wakes possible only by use of directional dependent power-to-power relation

Advantages Side-by-Side Testing

- Cheap: only SCADA-data needed, no additional measurements
- No relevant sensor uncertainties
- Large wind direction sector applicable, shorter measurement period
- No air density normalisation needed (self normalising to reference air density of power curve assumed for Training Period)
- Results hardly influenced by turbulence intensity, wind shear or wind veer as Test Turbine influenced in the same way as Reference Turbine
- Hardly influenced by site effects and effects of vertical flow inclination due to directional dependent power-to-power relation
- Often strong uncertainty reduction possible by weighting results gained with different Reference Turbines

Disadvantages Side-by-Side Testing

- No information on wind speed above rated power of Reference Turbine: often not applicable for tracking change of power curve by increase of rated power
- Application requires presence of Reference Turbine
- Loss of wind data correlation at larger distances of Test Turbine and Reference Turbine

Conclusions

- Side-by-side testing is inexpensive and accurate
- Ideal for tracking changes of power curves
- Ideal for investigating success of optimisation measures
- Fully repeatable method with complete description of uncertainties has been developed

Thank you

Contact: a.albers@windguard.de