Active Wake Control Validation Methodology

Details on uncertainty quantification methodology

IEA Task 44 Wind Farm Flow Control

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What's on the menu for today?

1. Background and context
2. Overview of validation methodology
3. Brief example on dummy dataset
4. Uncertainty quantification methodology
5. Sensitivity of results
6. Reflections, comments, discussion

Developed for consistent assessment of AWC gains for offshore wind farms

- Developed within the project **Dy**namic robu**s**t wind farm **con**trol (Dyscon). More information here.
- Developed by Dr. Stoyan Kanev and fully detailed and made publicly available here.
- Maintained and further developed internally at TNO, to assess gains at the turbine level, for example. Latest summary of the methodology available here.
- (Some) Initial requirements and goals of methodology when defined:
  - Applicable to large offshore wind farms of any layout.
  - Using only available measurement equipment on site.
  - Makes use of standard SCADA data, ten minute statistics or faster if necessary.

Methodology can be segmented into seven different steps

01 Data rejection

Curtailed, not on grid turbines, measurements taken not using the same sensor throughout the campaign are removed initially from the dataset.

02 Calibration

Wind direction measurements are calibrated. i.e., the possibly existent bias in the wind turbine direction measurements is removed.

03 Consensus

Free stream characteristics of the wind are estimated based on the wind speed and wind direction measurements from leading turbines.
Leading turbines are identified using a wake model (Jensen).

04 Additional filtering

Additional data filtering is applied to ensure maximum quality of the data. Time instants where consensus wind speed and consensus wind direction standard deviation is higher than a certain threshold are removed. Turbines downstream of curtailed or not on grid are removed up a certain threshold.

05 Binning

Data is grouped into bins. Bins are formed if a certain normalized relative standard error of the farm power production within a certain bin is below a certain threshold.

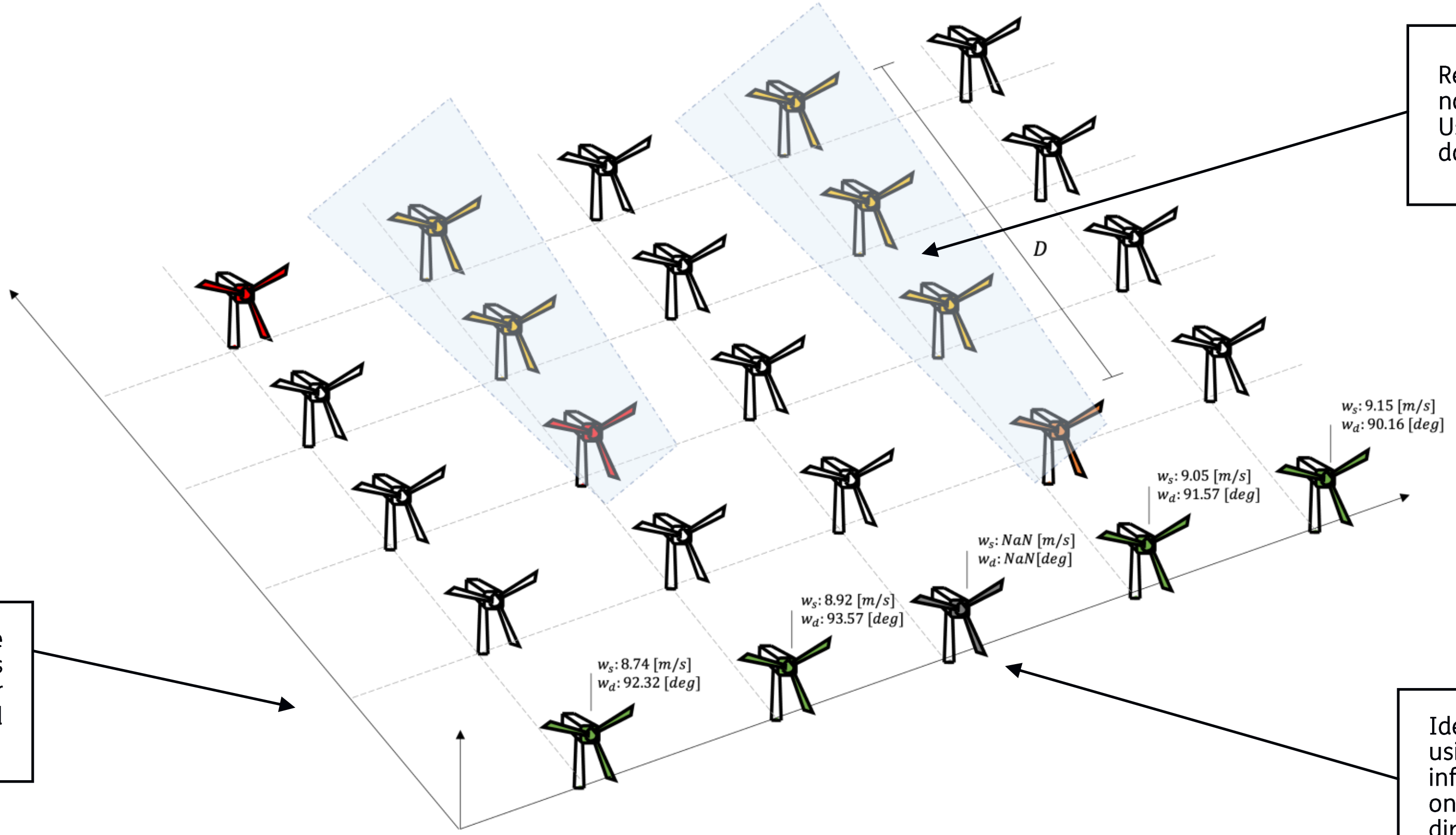
06 Power ratio

Power ratios between Active Wake Control and Nominal operation are quantified per wind direction bin. Annual Energy Production increase is estimated. 95% confidence intervals of the estimated mean values are provided.

07 Turbine analysis

Energy gains at the wind turbine level are also assessed by evaluating the weighted turbine energy gain considered a certain wind speed interval.

Consensus characteristics are estimated and an additional filtering procedure is applied



Removing turbines downstream of not on grid or curtailed turbines. User can choose distance up until downstream turbines are removed.

For a more conservative assessment, 10 minute instants where the consensus wind speed or wind direction have high standard deviations can be removed.

Identification of leading turbines using a wake model to estimate inflow (consensus) characteristics: one unique wind speed and wind direction

Bins are only formed if the uncertainty within it is below a certain threshold

- Hard and soft thresholds (black and red lines, respectively).
- Size of bins is then optimised, based on maximum size allowed and first iteration prescribed.
- Uncertainty quantified through the normalised standard error of the farm power production.

Maximum allowed uncertainty in a certain bin and ideal level of uncertainty so that the bin is formed. Otherwise, data will not be grouped and not be used for the assessment of AWC gains.

Size of bins changes iteratively until it converges to a final solution and meets all defined requirements by the user.

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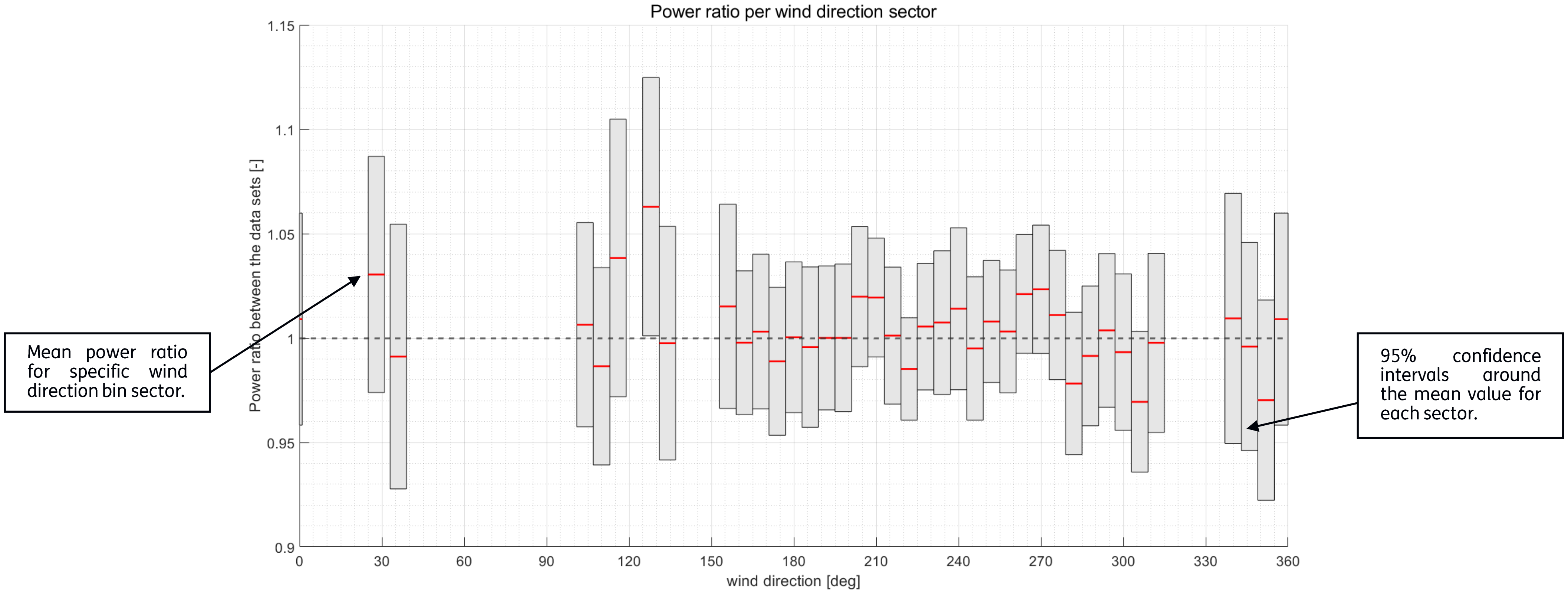
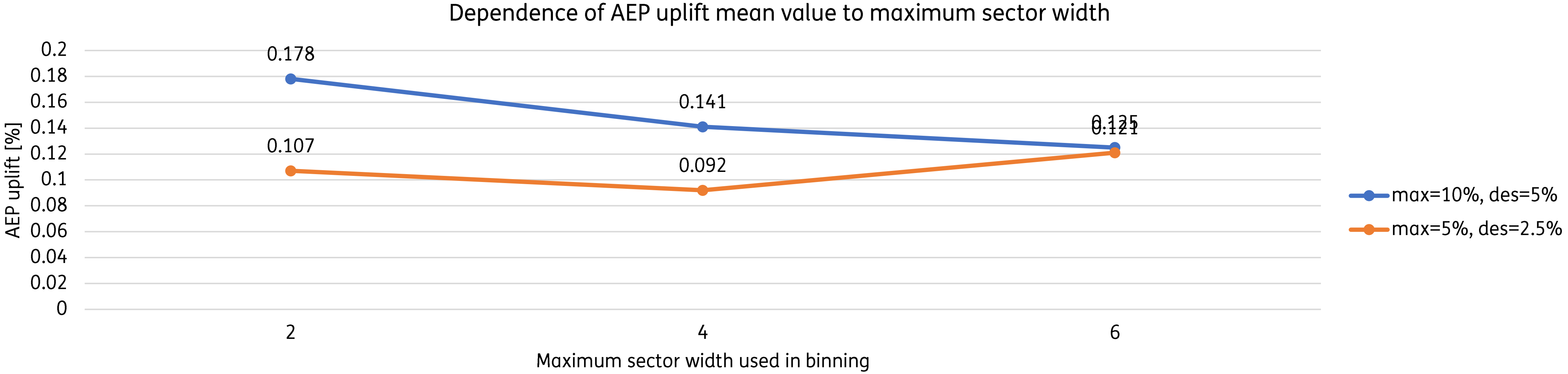
Gains are assessed through the power ratio of each wind bin

- The mean power ratio for each wind sector is assessed. This is represented with a red line.
- Grey bars represent the 95% confidence intervals, i.e., mean value ± 2 standard errors.



Final result corresponds to the estimate of the AEP ratio and corresponding 95% confidence intervals

- AEP ratio estimate is sensitive to the criteria used for filtering and binning. Mean values still within confidence bounds.



Test	WSstdMax	WDstdMax	WindSpdBins	desPSTEperSec	maxPSTEperSec	maxSectorWidth	Wake influence	Average bin size	AEP Ratio	95% CI
	[m/s]	[deg]	[m/s]	[%]	[%]	[deg]	RD [-]	[-]	[-]	[-]
#1	2.5	10	1	5%	10%	2	25	2.00	1.00178	±0.00296
#2	2.5	10	1	5%	10%	4	25	3.75	1.00141	±0.00266
#3	2.5	10	1	5%	10%	6	25	4.56	1.00125	±0.00262
#4	2.5	10	1	2.5%	5%	2	25	2.00	1.00107	±0.00583
#5	2.5	10	1	2.5%	5%	4	25	4.00	1.00092	±0.00304
#6	2.5	10	1	2.5%	5%	6	25	6.00	1.00121	±0.00283

Turbine statistics are calculated prior to farm statistics and from there propagated

- Wind turbine statistics are first calculated for a certain wind speed and direction bin *b*, for turbine *t* and dataset *s*.

Mean turbine *t* power production for a certain wind speed and direction bin *b* for each of the two data sets *s*. Considers all the time instants *i* in this calculation.

$$\bar{P}_{b,t}^{(s)} = \frac{1}{N_{b,t}^{(s)}} \sum_{i=1}^{N_{b,t}^{(s)}} P_{b,t,i}^{(s)},$$

Variance of the turbine *t* power production for each bin *b* in the two data sets *s*.

$$\hat{\sigma}^2\left(P_{b,t}^{(s)}\right) = \frac{1}{N_{b,t}^{(s)}-1} \sum_{i=1}^{N_{b,t}^{(s)}} \left(P_{b,t,i}^{(s)} - \bar{P}_{b,t}^{(s)}\right)^2,$$

Variance of the mean turbine *t* power production value to compute the standard error.

$$\hat{\sigma}^2\left(\bar{P}_{b,t}^{(s)}\right) = \frac{1}{N_{b,t}^{(s)}} \hat{\sigma}^2\left(P_{b,t}^{(s)}\right).$$

- Wind farm statistics are then calculated. Standard propagation of uncertainties are used.

Mean wind farm power production for bin *b*, resulting from summing the mean turbine power productions for same bin *b*.

$$\bar{P}_{b,farm}^{(s)} = \sum_{t=1}^{N_t} \bar{P}_{b,t}^{(s)}$$

$$\hat{\sigma}^2\left(P_{b,farm}^{(s)}\right) = \sum_{t_1=1}^{N_t} \left(\hat{\sigma}^2\left(P_{b,t_1}^{(s)}\right) + \sum_{t_2=1}^{N_t} \hat{\sigma}^2\left(P_{b,t_1}^{(s)}, P_{b,t_2}^{(s)}\right)\right);$$

$$\hat{\sigma}^2\left(\bar{P}_{b,farm}^{(s)}\right) = \sum_{t_1=1}^{N_t} \left(\hat{\sigma}^2\left(\bar{P}_{b,t_1}^{(s)}\right) + \sum_{t_2=1}^{N_t} \hat{\sigma}^2\left(\bar{P}_{b,t_1}^{(s)}, \bar{P}_{b,t_2}^{(s)}\right)\right),$$

Law of propagation of uncertainties dictates the propagation of both the turbine power production variances on each bin **but also the covariance terms.**

The variance of a wind farm bin is sensitive to the covariance terms considered

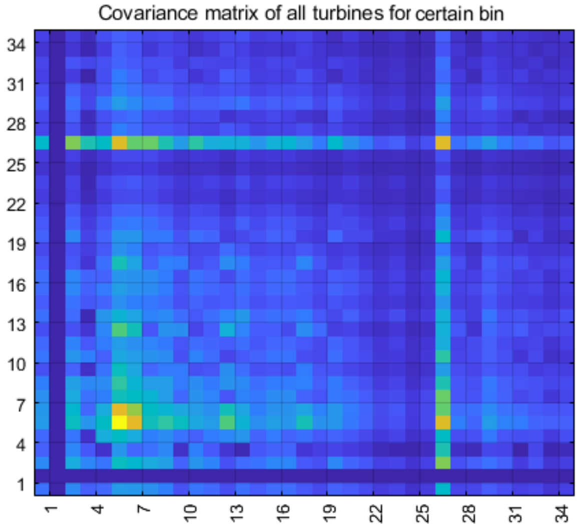
- For the quantification of uncertainty, the user can choose the covariance terms to be included in the analysis.

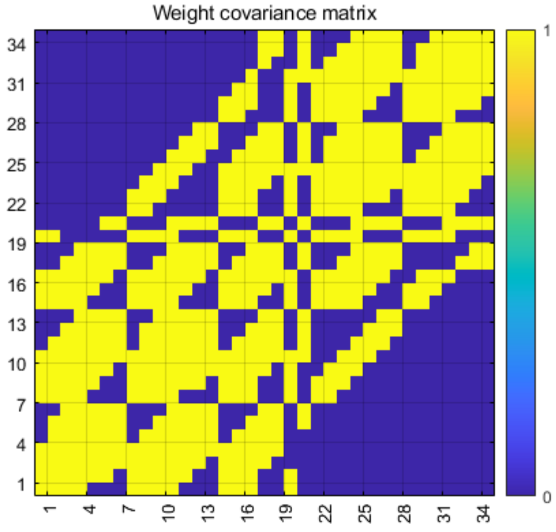
$$\hat{\sigma}^2\left(P^{(s)}_{b,t_1}, P^{(s)}_{b,t_2}\right) = \frac{1}{N^{(s)}_{b,t_1,t_2}-1} \sum_{i=1}^{N^{(s)}_{b,t_1,t_2}} \overbrace{\left(P^{(s)}_{b,t_1,i} - \bar{P}^{(s)}_{b,t_1}\right)\left(P^{(s)}_{b,t_2,i} - \bar{P}^{(s)}_{b,t_2}\right)},$$

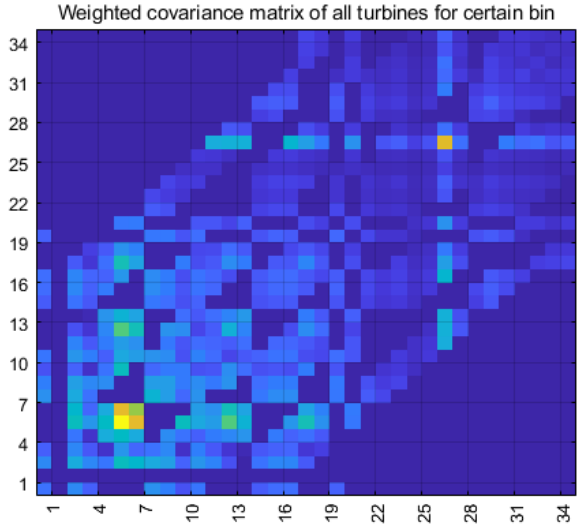
$$\hat{\sigma}^2\left(\bar{P}^{(s)}_{b,t_1}, \bar{P}^{(s)}_{b,t_2}\right) = \frac{1}{N^{(s)}_{b,t_1,t_2}} \hat{\sigma}^2\left(\bar{P}^{(s)}_{b,t_1}, \bar{P}^{(s)}_{b,t_2}\right),$$

Considering all covariance terms in the covariance matrix to estimate the wind farm bin variance.

Designing a weight covariance matrix to only account for covariance terms of turbines placed within a certain number of rotor diameters.

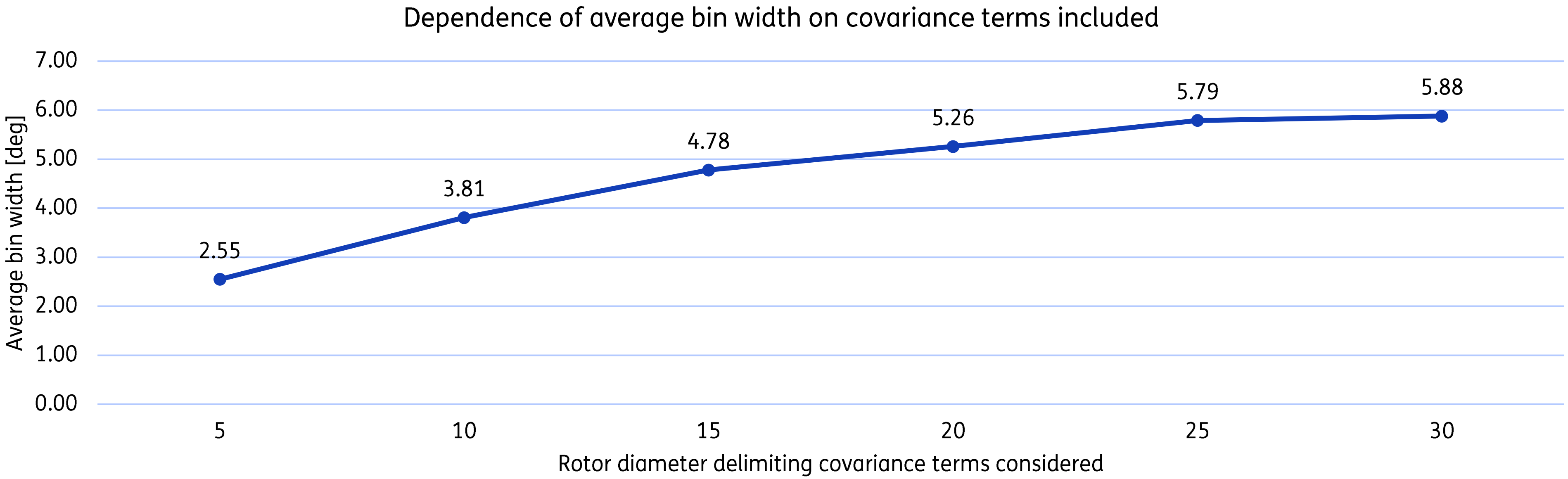






Uncertainty estimate is sensitive to the covariance terms considered

- Bin width will increase (within boundaries) to accommodate higher conservativism in uncertainty quantification.



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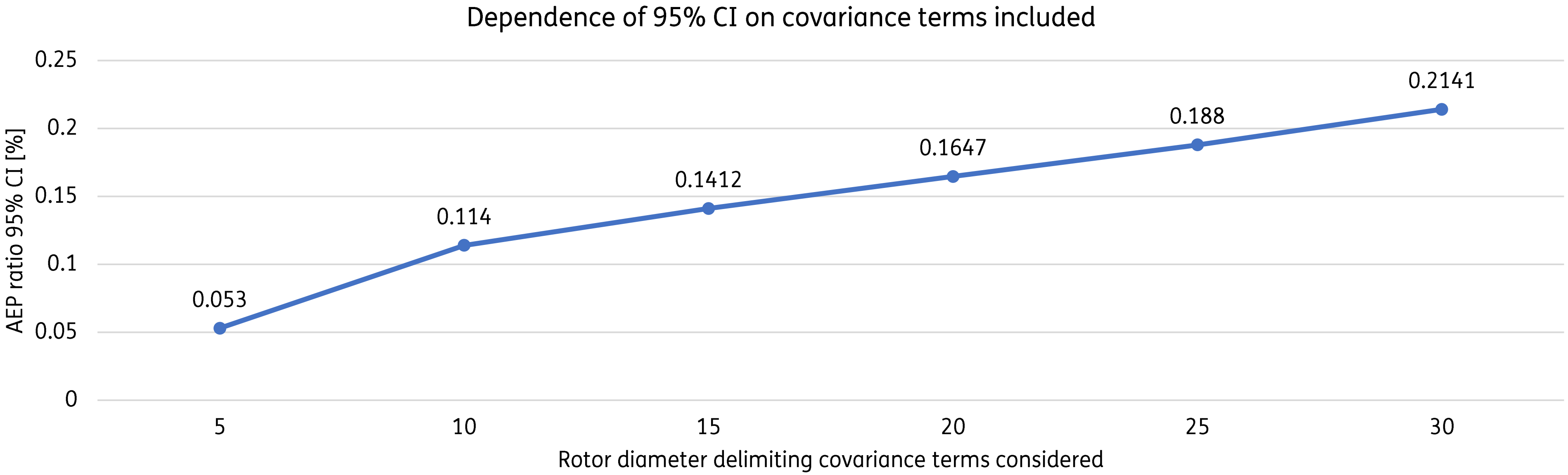
	[m/s]	[deg]	[m/s]	[%]	[%]	[deg]	RD [-]	RD [-]	[-]	[-]	[-]
#1	2.5	10	1	2.5	5	6	25	5	2.55	1.00180	0.00053
#2	2.5	10	1	2.5	5	6	25	10	3.81	1.00159	0.00114
#3	2.5	10	1	2.5	5	6	25	15	4.78	1.00138	0.001412
#4	2.5	10	1	2.5	5	6	25	20	5.26	1.00121	0.001647
#5	2.5	10	1	2.5	5	6	25	25	5.79	1.00089	0.00188
#6	2.5	10	1	2.5	5	6	25	30	5.88	1.00109	0.002141

Uncertainty estimate is sensitive to the covariance terms considered

- Uncertainty bounds can increase by a factor of 4 from the lowest to a more conservative approach.



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#1	2.5	10	1	0.025	0.05	6	25	5	2.55	1.00180	0.00053
#2	2.5	10	1	0.025	0.05	6	25	10	3.81	1.00159	0.00114
#3	2.5	10	1	0.025	0.05	6	25	15	4.78	1.00138	0.001412
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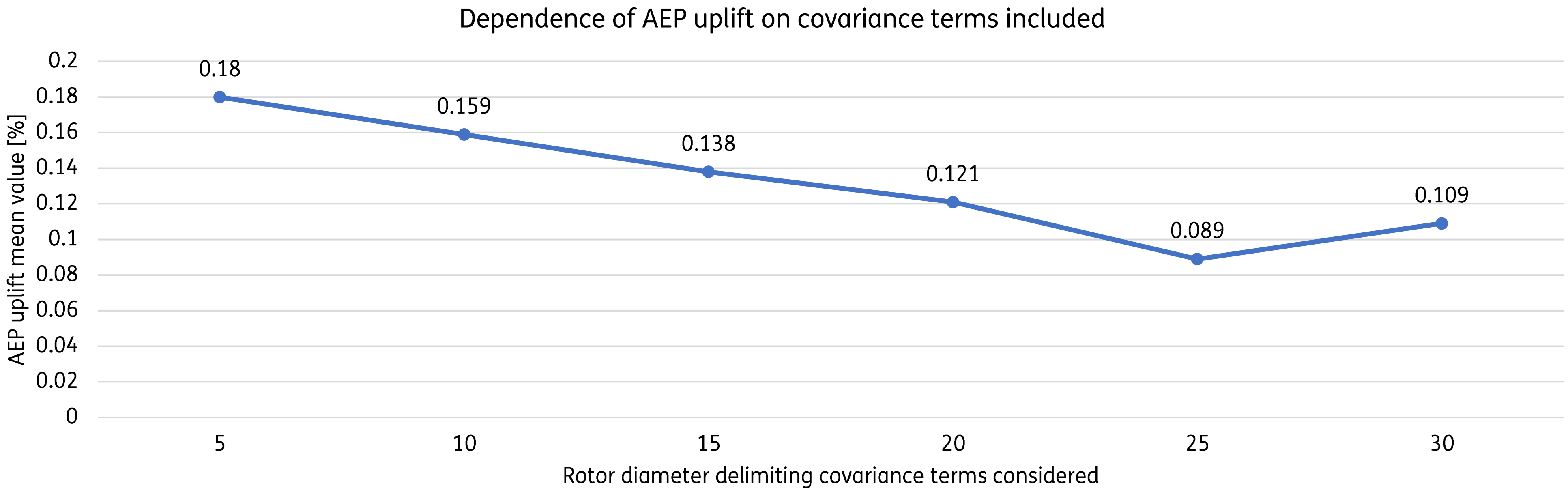
Uncertainty estimate is sensitive to the covariance terms considered

- AEP ratio appears to decrease, perhaps due to wider and more bins homogenizing the ratio.



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Key messages to take from this presentation

- TNO has developed a **methodology to validate benefits from using Active Wake Control** in offshore wind farms.
- Methodology requires **instruments already available** in wind farms. In addition, it makes use of **SCADA data** (10 minute statistics or faster if necessary).
- Thorough analysis is made possible through the use of unique techniques such as **measurement offsets removal** through direct calibration and **optimising the wind direction bins** based on user defined criteria.
- Uncertainty quantification methodology uses the **frequentist approach**, as opposed to other Bayesian approaches. It calculates 95% confidence intervals based on the standard error, which considers the number of points.
- The final outcome is **the calculation of the AEP uplift** (or AEP ratio) and the corresponding 95% confidence interval propagated from the turbine statistics.
- Final **results are sensitive to user defined criteria**, however this small example shows various mean values tends to fall within 95% confidence interval.
- Final quantification of uncertainty is **influenced by the covariance terms** which are included in the analysis. The decision is up to the judgment and **conservatism level** of the user.
- There is more information on the quantification of **deterministic uncertainties** in the methodology.

Thoughts, comments, reflections, questions?

- What other approaches to quantify uncertainty could be used? For example, NREL in FLASC uses bootstrapping to quantify uncertainties in the energy ratio. Are such methods comparable to this frequentist approach taken? Does it consider number of points? What are the implications of using different Uncertainty Quantification (UQ) methods?
- Results can be sensitive to options used as seen in the examples. Should experts agree on rules of thumb and best practices to be used for validating campaigns and assessing gains?
- What other developments would be of interest to see to support ongoing campaigns? Quantification through the energy ratio, for example?

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