Quantifying the effect of characteristic turbulence on floating wind turbine fatigue

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What is (characteristic) turbulence?

Definition, measurements, variability, and use according to wind standards

Topic of this work:
What is the effect of considering the actual turbulence distribution instead of the characteristic (P_{90}) turbulence for fatigue of floating wind turbines?

Turbulence intensity (TI) is a measure of the relative variation of wind speed:

$$TI = \frac{\sigma_U}{U}$$

DNV-ST-0437: For site-specific conditions use *characteristic value* of TI.

Characteristic turbulence intensity:

$$TI_C = P_{90}(TI) \overset{*}{=} TI_{\text{mean}} + 1.28\,\sigma_{TI}$$

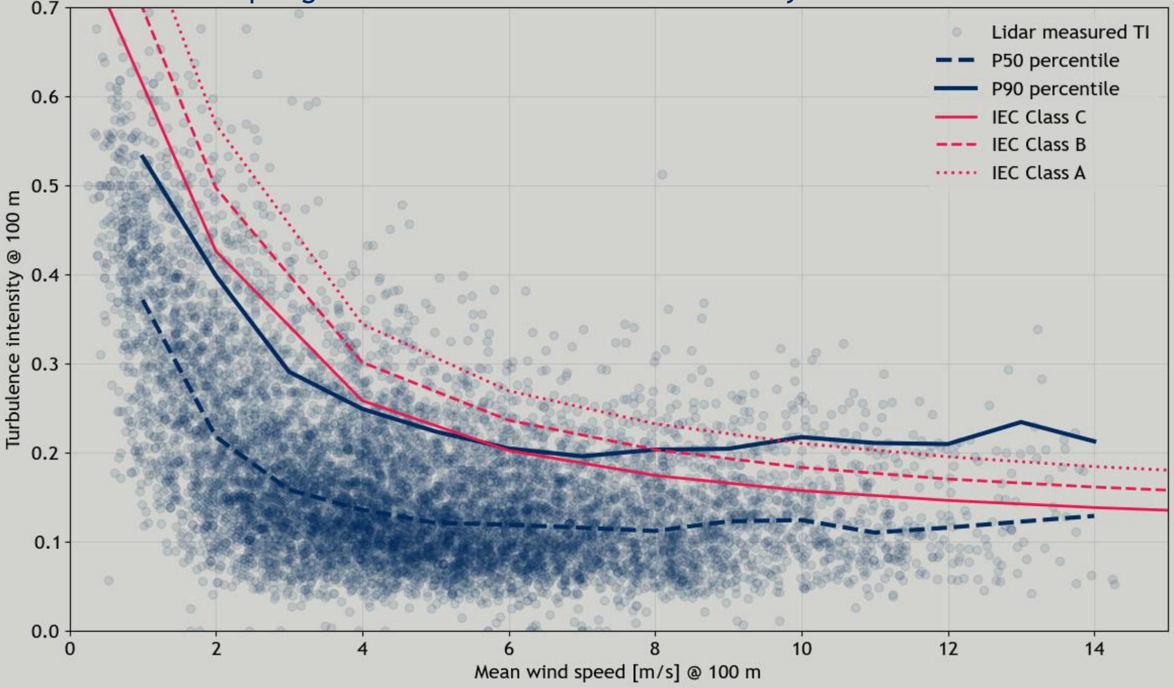
*Assuming Gaussian distribution of TI

(For non-site-specific conditions use an appropriate standardized *Turbulence Class*)

In addition, wake effects from neighbouring turbines shall be considered, e.g. using the *Frandsen* model:

$$I_{\text{eff}} = \frac{1}{U}\left[(1-p_w N)\sigma_c^m + p_w \sum_{i=1}^{N} \sigma_T^m(d_i)\right]^{1/m}$$

Example: Turbulence intensity at Eldøyane, Stord
Measured spring 2017 with WindCube V2 Lidar for Hywind Scotland installation



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Why is this interesting?

And why consider this right now?

- Floating wind turbine systems are largely fatigue governed
- Turbulence is one of the major contributions to fatigue
- For fatigue, other load contributions (e.g. waves and mean wind speed distributions) are based on *expected* values and not augmented to artificially increase level of safety
- For fatigue, partial load factors are not used, but a total safety factor (Design Fatigue Factor, or DFF) is applied to the calculated lifetime at the end.
- Thus, the use of characteristic turbulence deviates from how other *loads* are handled in fatigue analysis
- The use of characteristic turbulence is more akin to the way *capacities* are handled (e.g. SN-curves are defined as $\text{mean} - 2\sigma$ of the experimental data, or $P_{97.7}$ value)
- Is the P_{90} turbulence then accounted for by reducing the DFF from what it would otherwise be? Maybe, but not obviously.
- E.g., mooring chain DFF in DNV-OS-E301 is the same as in DNV-ST-0119, but DNV-OS-E301/DNV-RP-C205 does not explicitly discuss this topic, except stating that it is "common practice" to use conservative turbulence values when site-specific measurements are not available.

Topic of this work:
What is the effect of considering the actual turbulence distribution instead of the characteristic (P_{90}) turbulence for fatigue of floating wind turbines?

The timing of this study is due to the ongoing joint industry effort initiated by DNV to update DNV-ST-0119:

DNV - Energy Systems
136,142 followers
6mo

DNV LinkedIn post

The Floating Wind Reliability JIP has kicked off!

DNV has now officially launched the Joint Industry Project (JIP) on optimizing mooring and dynamic cable design requirements for floating wind.

...

Analysis case

Somewhat arbitrarily chosen…

Floating wind turbine model:

- 15MW 3-column semisubmersible floater, offset turbine
- 15 MW IEA turbine (slightly modified, stiff-stiff tower)
- ROSCO Controller for IEA 15 MW turbine (floating, tuned)

Environment and metocean:

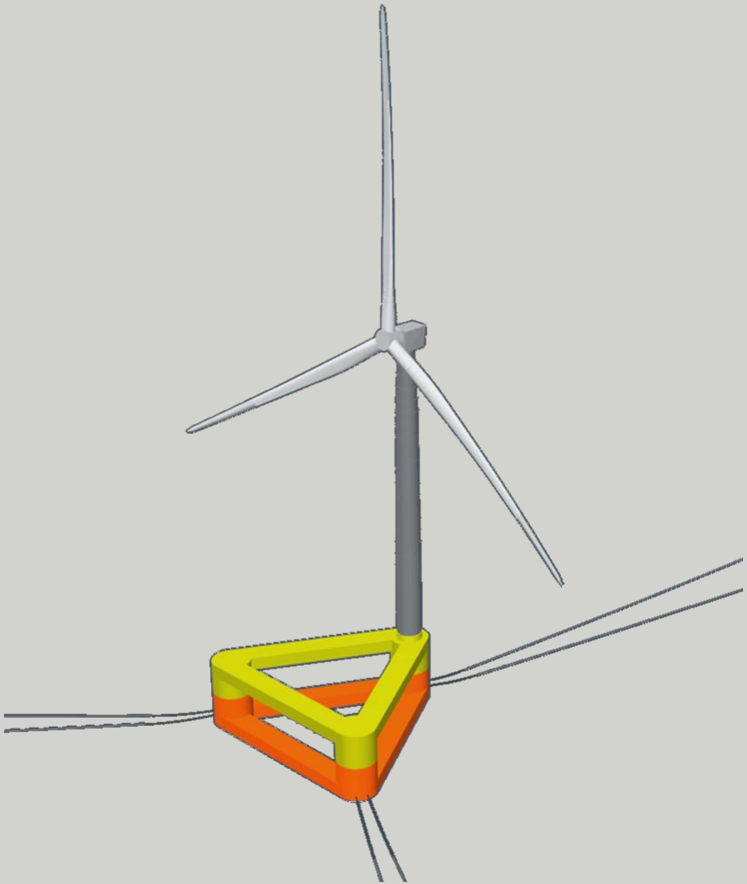
- North Sea wind, wave conditions (Ekofisk area, $\overline{H_S}$ =1.9m, $\overline{U}$=10.2m/s)
- North Sea turbulence model (Tampen area, close to DNV Class OC)
- Water depth 150m (relevant for many locations worldwide)

Two different mooring systems:

- Full chain catenary (max ULS offset 30% of WD)
- Chain/polyester semi-taut mooring (max ULS offset 30% of WD)

Key assumptions for polyester rope:

- 1.5% permanent elongation of fibre rope over lifetime. Full elongation assumed for max ULS offset and half (0.75%) of elongation assumed for fatigue analysis.
- Fibre rope axial stiffness based on dual stiffness approach. Rope stiffness for FLS corresponding to average of upper and lower bound in Bureau Veritas NI 432 (Certification of Fibre Ropes…).

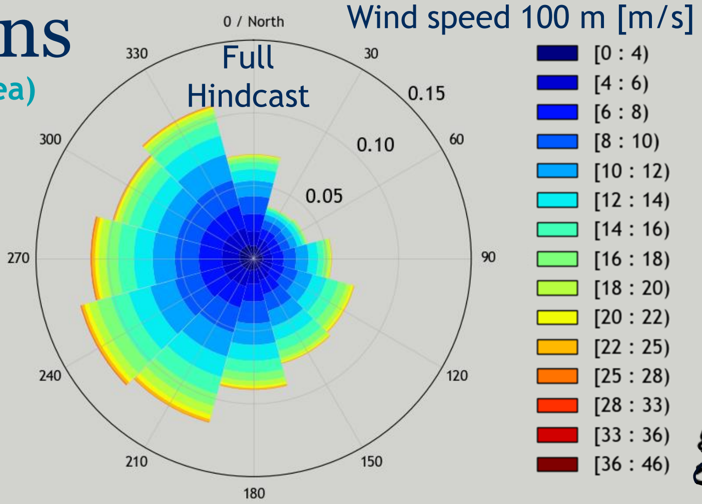


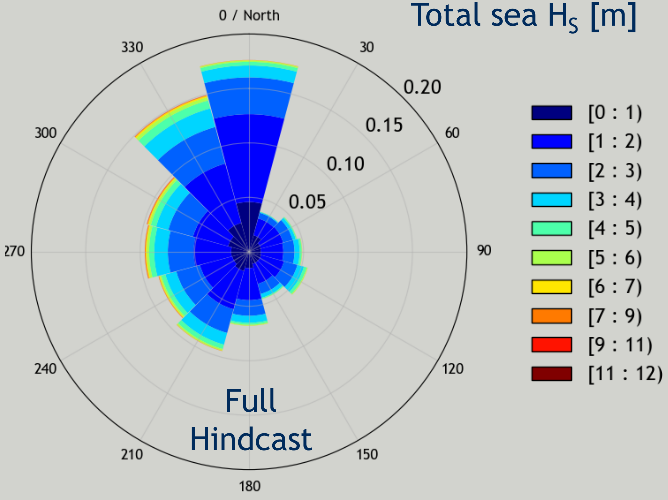
Fully-coupled analysis in OrcaFlex with Kaimal 3D turbulent wind from TurbSim

Metocean conditions

Wind and waves at Ekofisk area (North Sea)

- A hindcast-based approach is used where load cases are sampled directly from the NORA3 hindcast to represent the annual distribution of wind and waves.
- The NORA3 hindcast includes:
  - Wind speed and direction
  - Wind-sea H_S, T_P and direction
  - Swell H_S, T_P and direction





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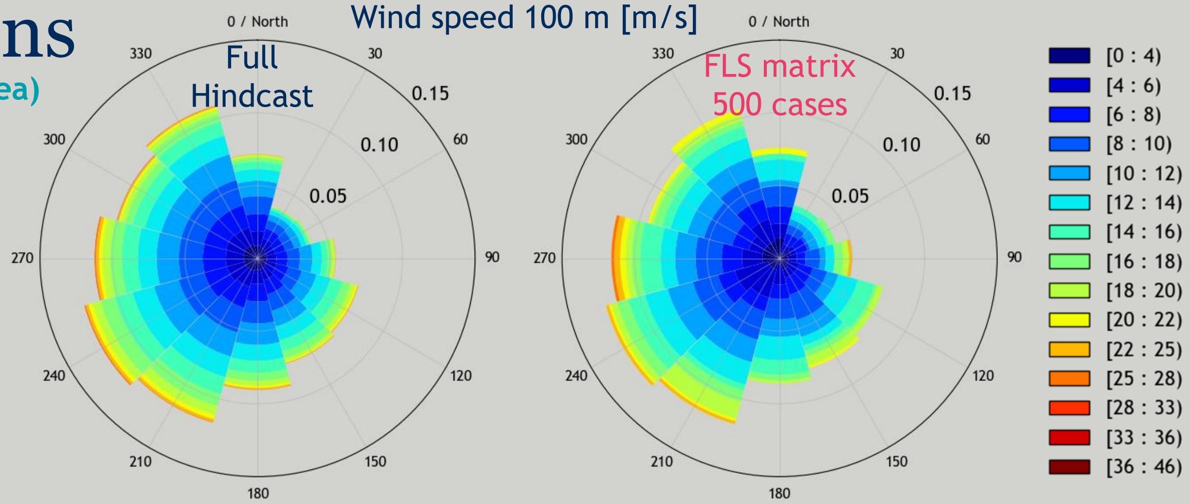
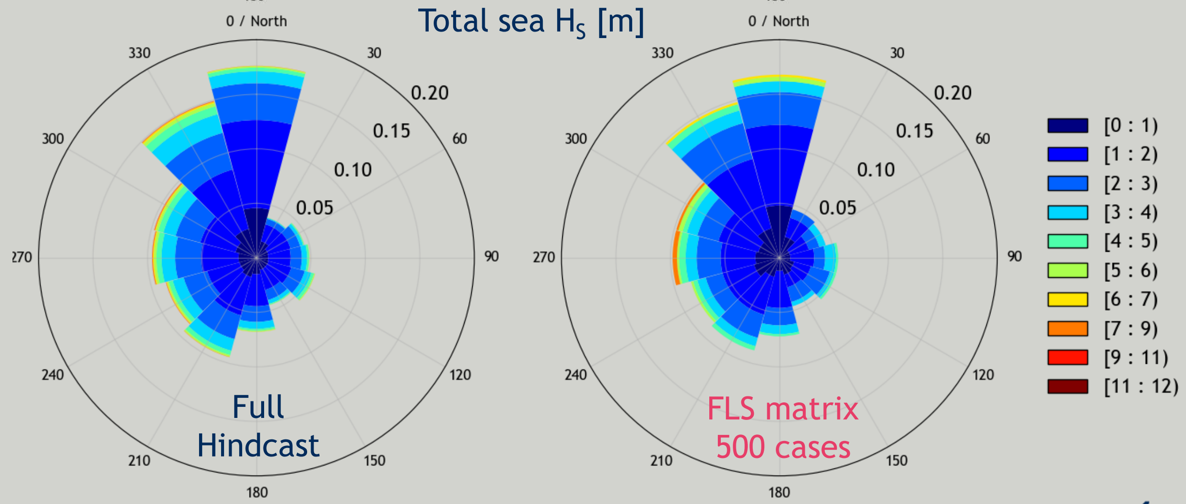
- The NORA3 hindcast includes:
  - Wind speed and direction
  - Wind-sea H_S, T_P and direction
  - Swell H_S, T_P and direction
- 500 cases are chosen for this study, which gives a good but not perfect representation of the actual probability distributions.
- The 500 cases are chosen from 28 years of hourly data = ¼ million seastates
- Only operational wind speeds are simulated (4 m/s to 25 m/s) which reduces the number of cases to 451.





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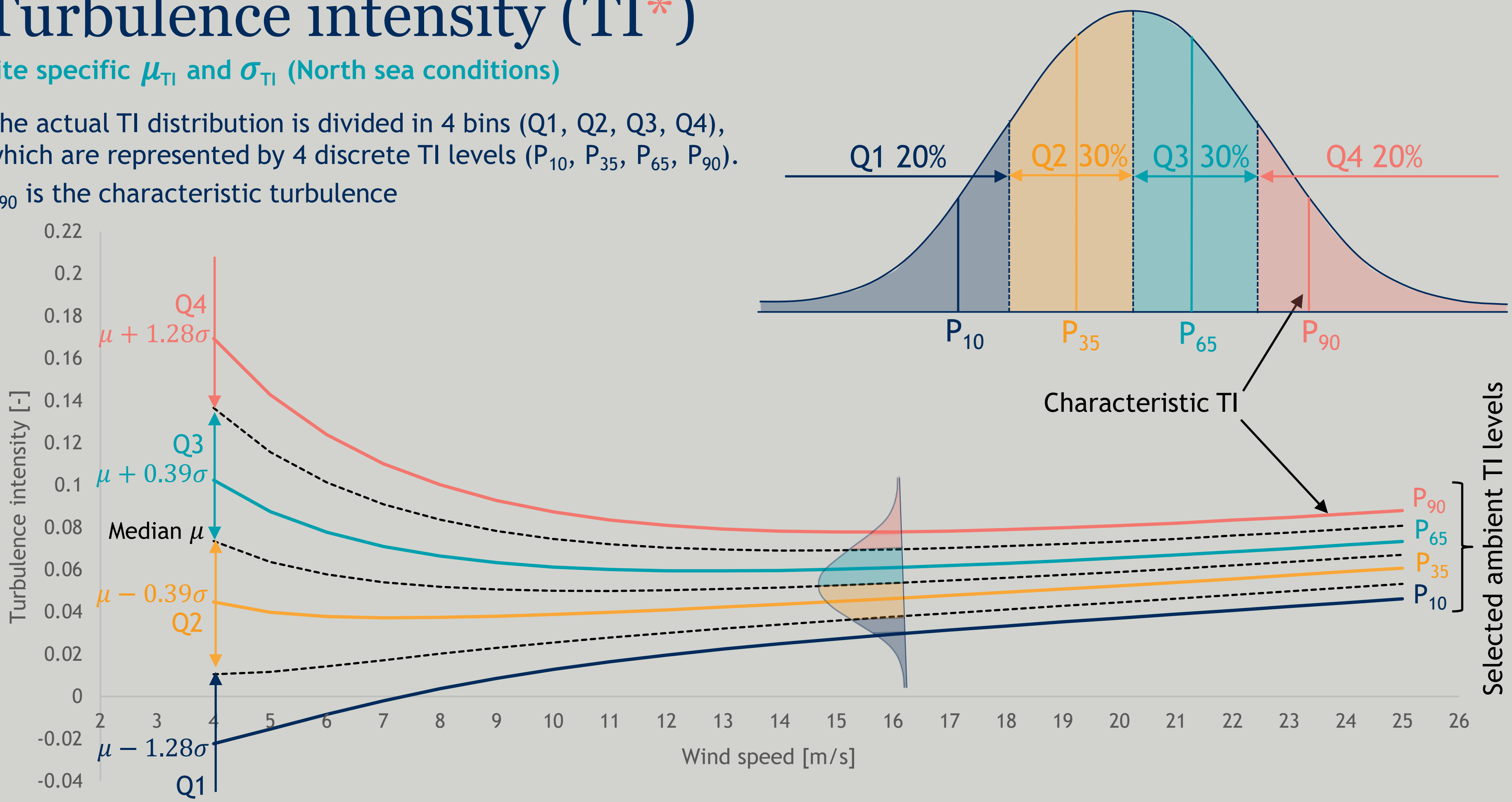
Turbulence intensity (TI*)

Site specific μ_{TI} and σ_{TI} (North sea conditions)

The actual TI distribution is divided in 4 bins (Q1, Q2, Q3, Q4), which are represented by 4 discrete TI levels (P_{10}, P_{35}, P_{65}, P_{90}).
P_{90} is the characteristic turbulence



*TI = Ambient TI (without park wake effects)

Park wake effects (TI*)

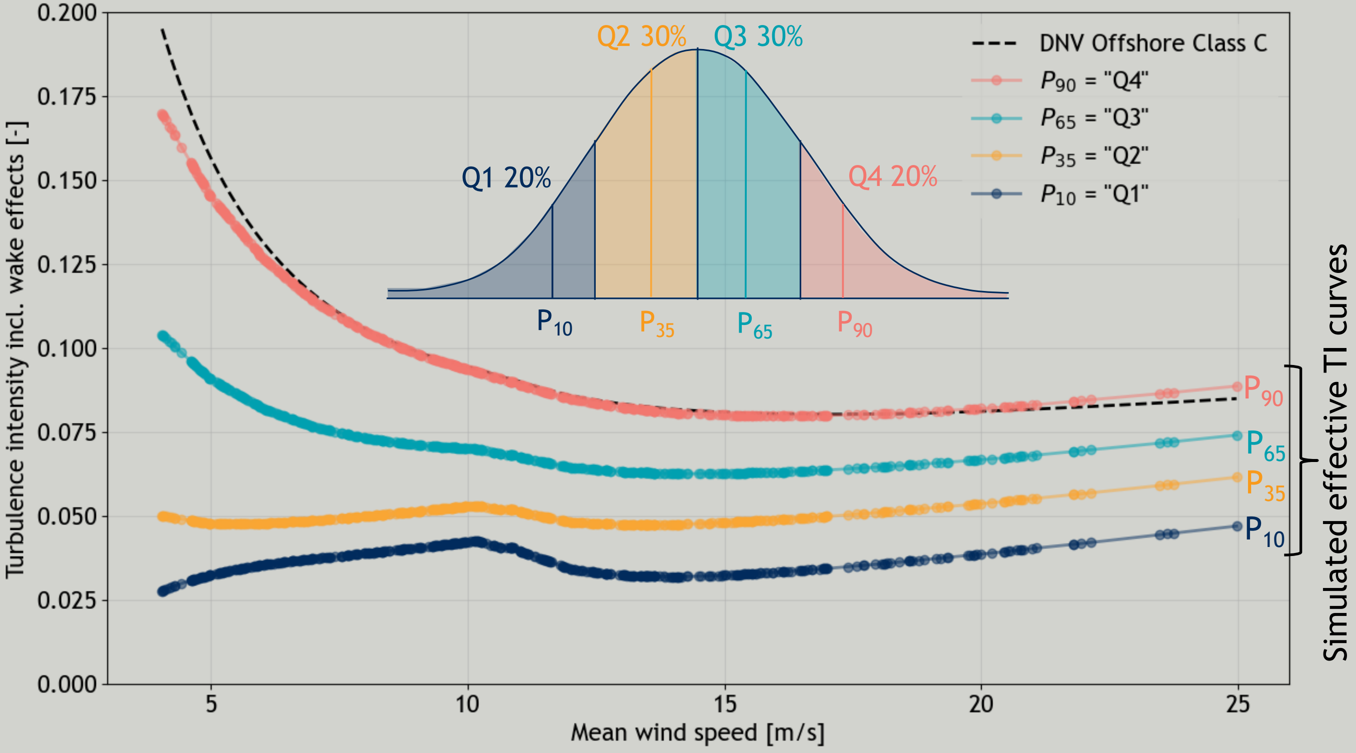
Frandsen method on assumed wind farm layout

Effective wind farm turbulence:
TI for each of the 4 selected turbulence levels is augmented using Frandsen method based on WTG thrust curve and wind farm layout assumptions.

Wind farm layout assumptions:

- Large wind farm (WTGs in the interior surrounded on all sides)
- 9D spacing (9 x rotor diameter)
- 6 neighboring WTGs around each WTG (scattered grid)
- SN-curve slope m = 3

DNV Class Offshore C turbulence curve is included for comparison (including park wake effects)

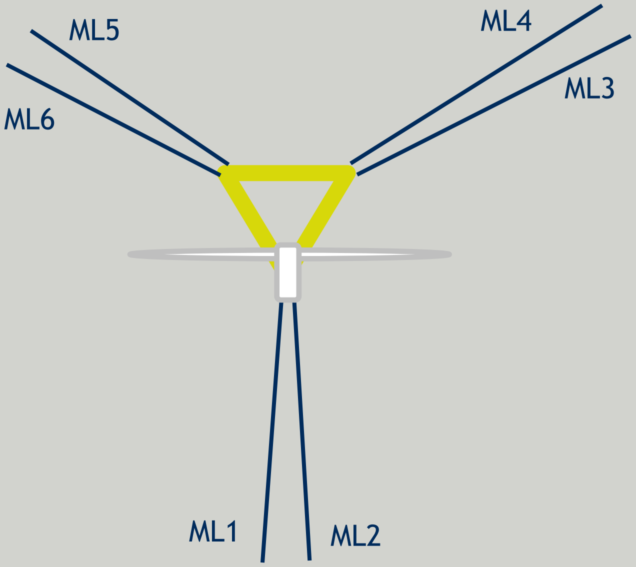


*TI = Effective TI (with park wake effects)

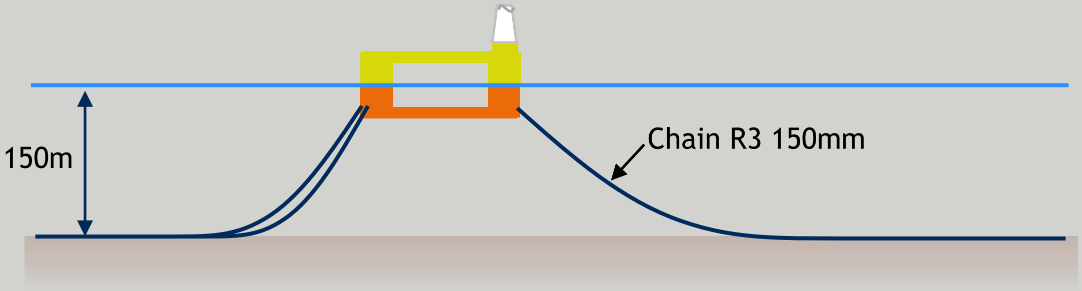
Mooring configurations

Semi-taut and catenary systems - Overview

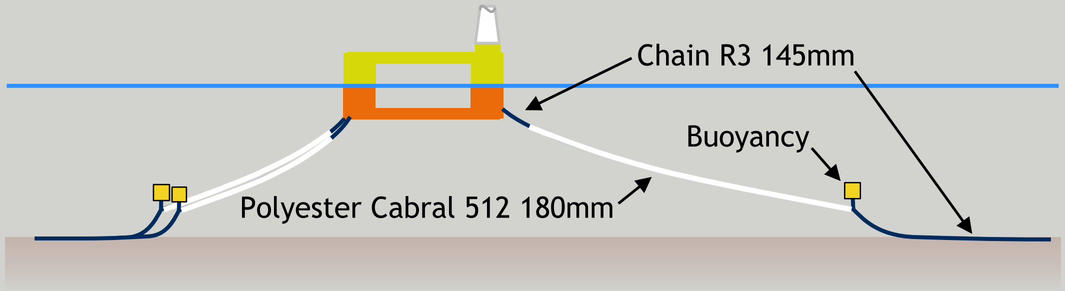
Schematic top-view



Schematic side-view - Catenary



Schematic side-view - Semi-taut



451 load cases x 4 TI levels x 2 mooring systems = 3608 fatigue simulations

Note: Illustrations not to scale

Analysis verification

Generator power (WTG controller performance)

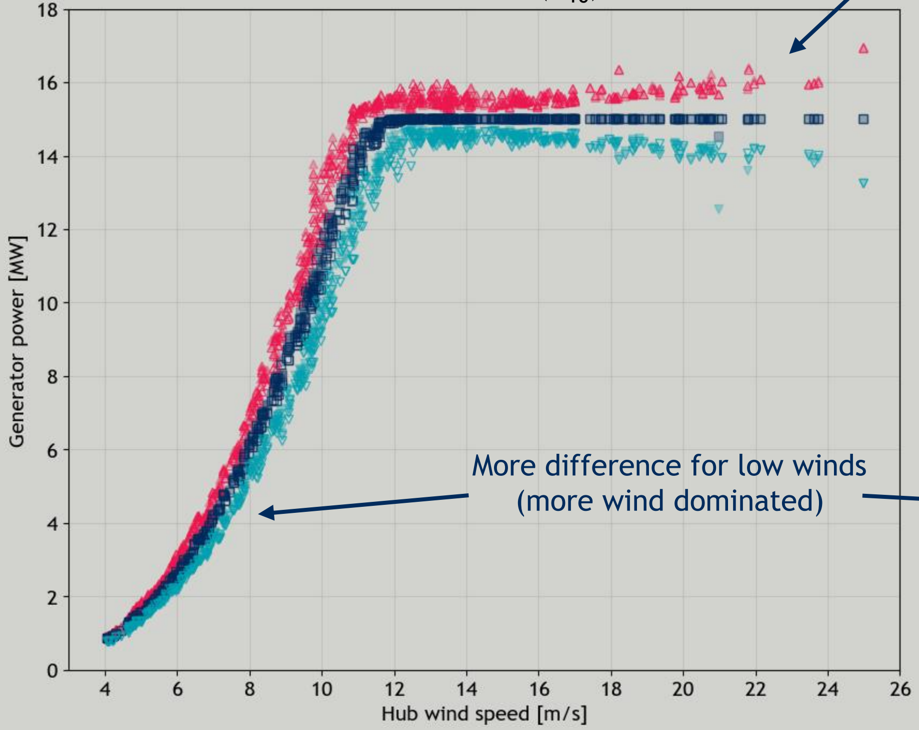
Maximum
Average
Minimum
Per FLS load case

Larger variation (range) for the higher turbulence level Q4 compared to Q1

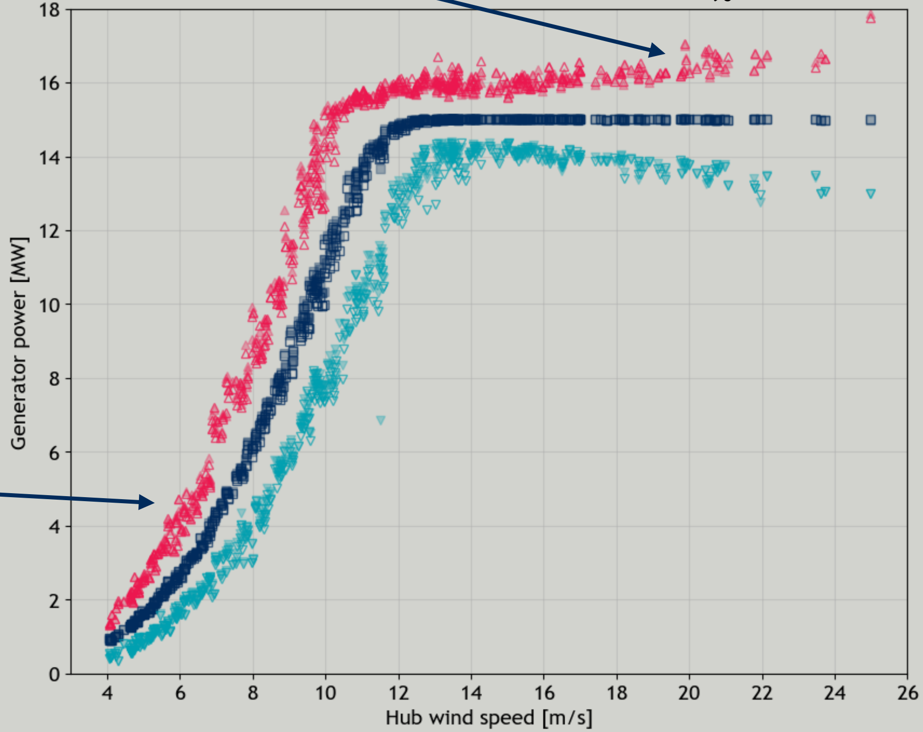
Less difference for high winds (more wave dominated)

More difference for low winds (more wind dominated)

Turbulence Q1 (P_{10})



Turbulence Q4 (P_{90})



Note: No significant impact on annual energy production

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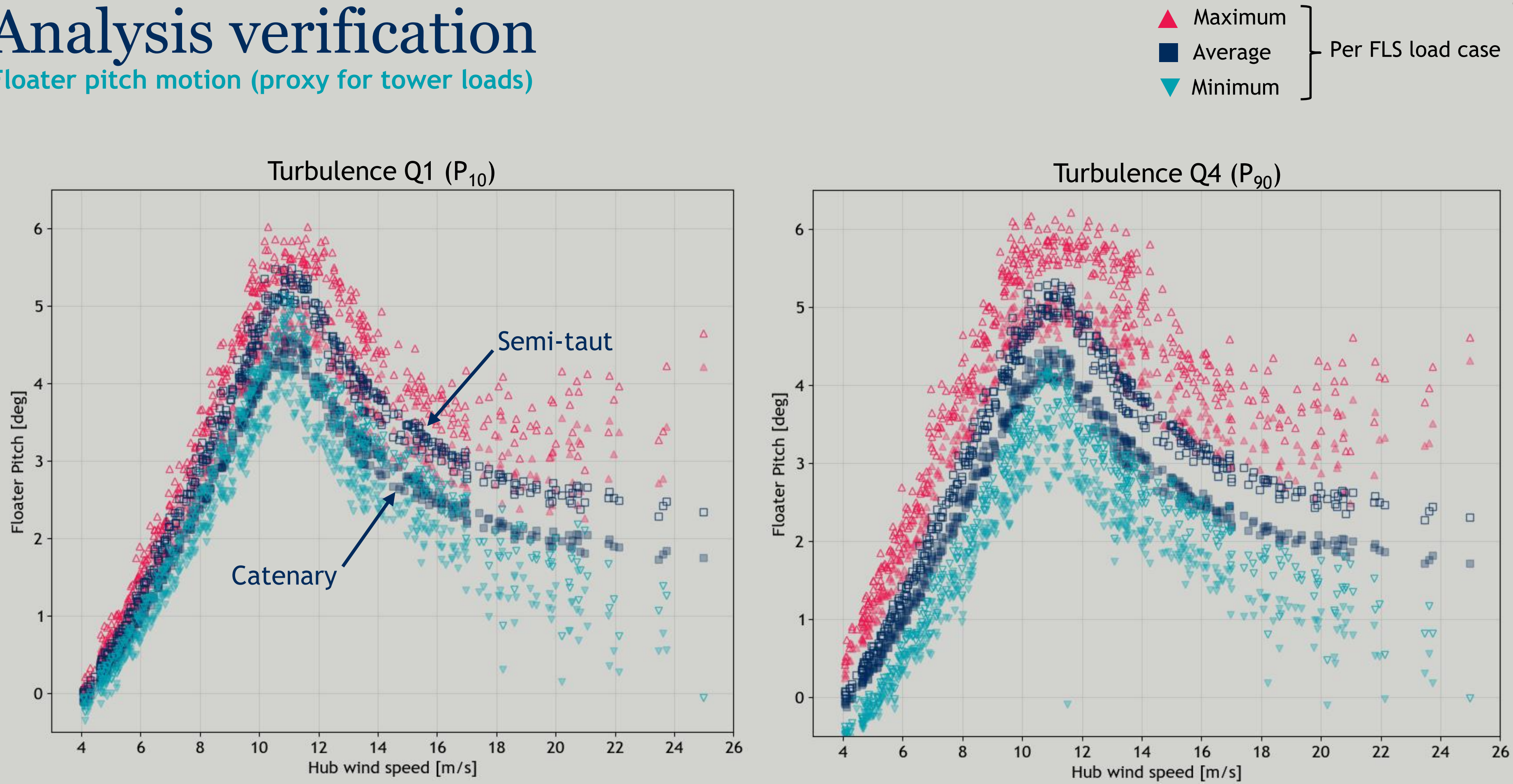
Analysis verification

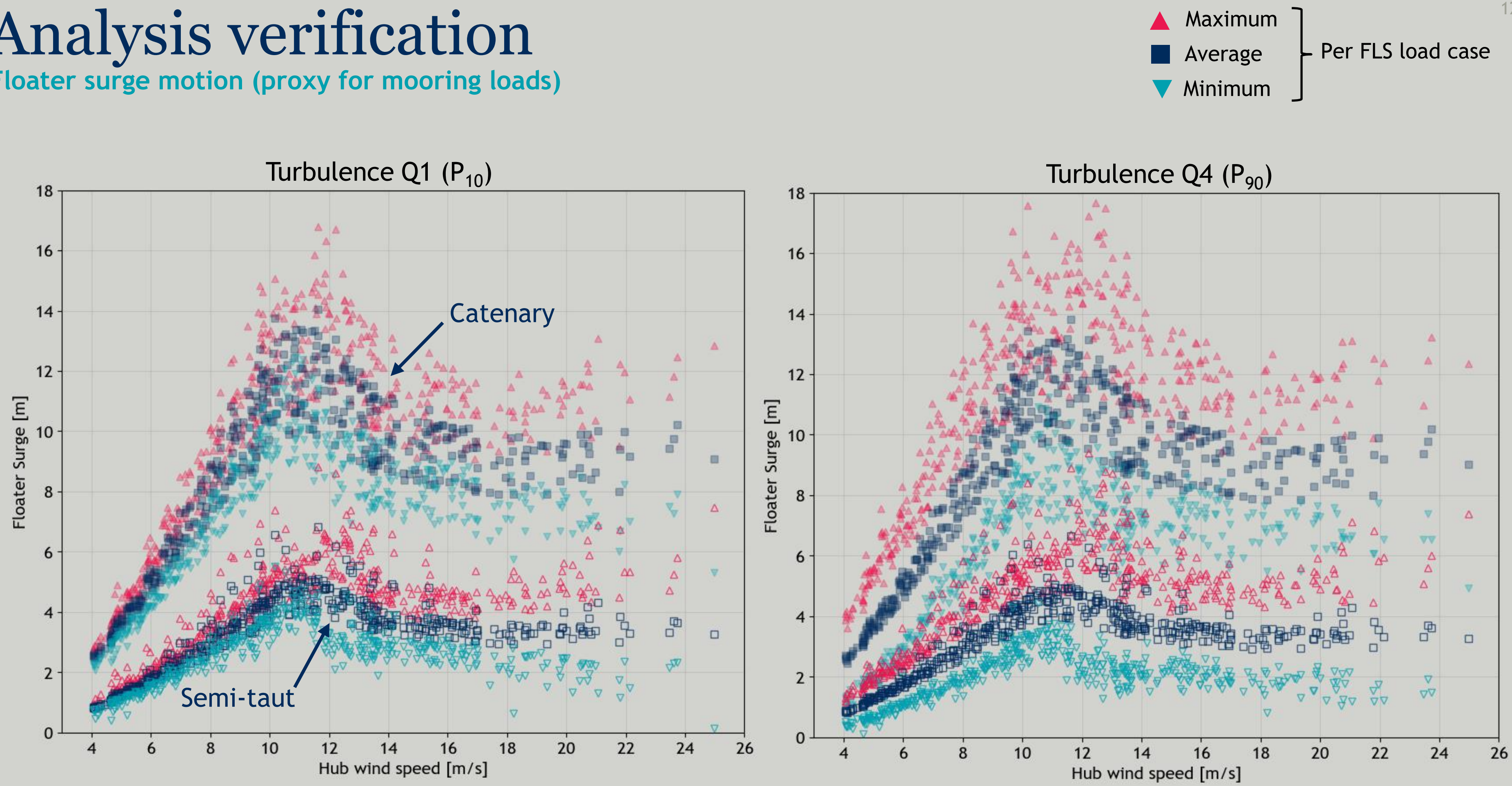
Floater pitch motion (proxy for tower loads)



Note: Catenary system is more vertical which gives higher pitch restoring moment / smaller mean pitch angle

Analysis verification

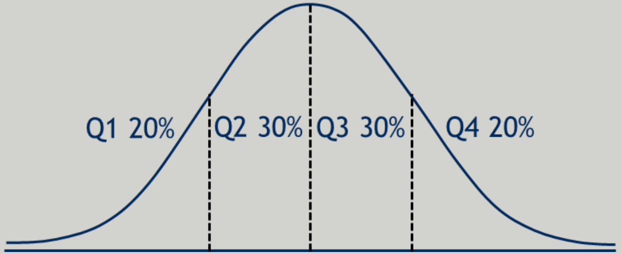
Floater surge motion (proxy for mooring loads)



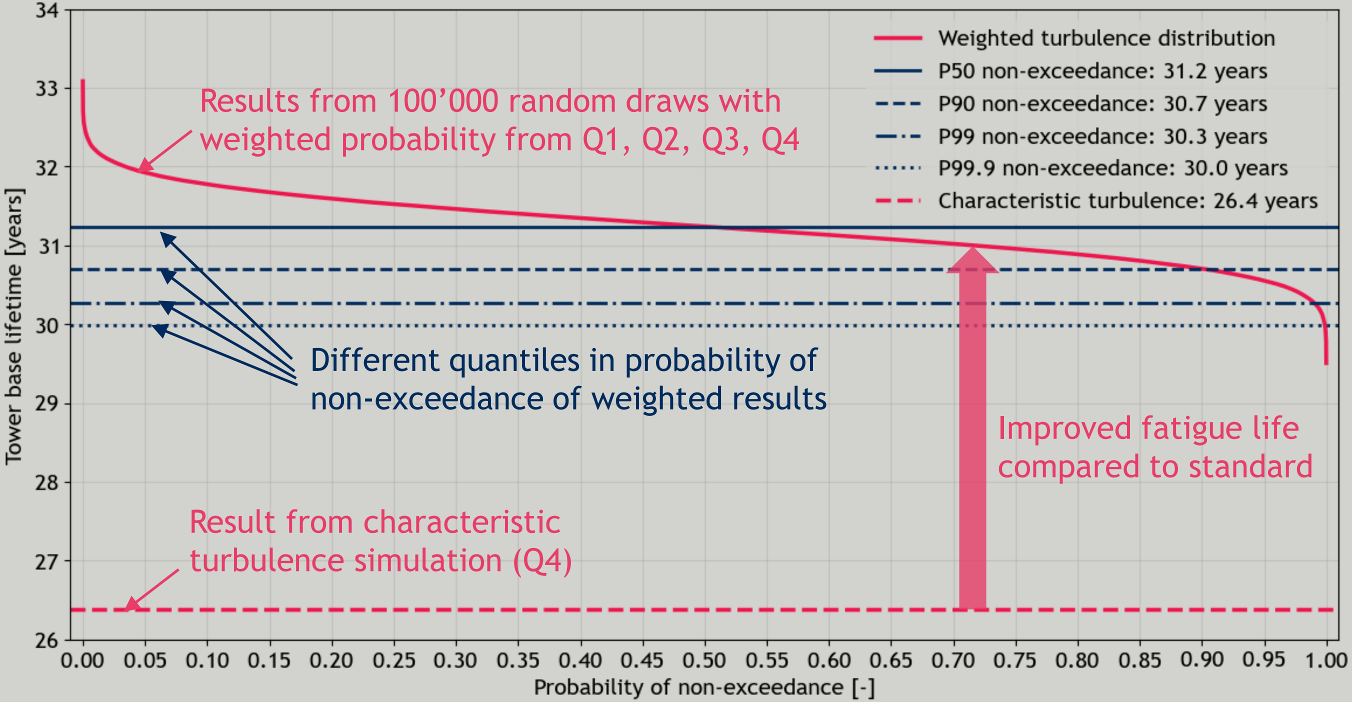
Note: Semi-taut run with half of rope permanent elongation which results in a stiffer system / less horizontal motion

Fatigue comparison method

A quasi-probabilistic / Monte Carlo approach



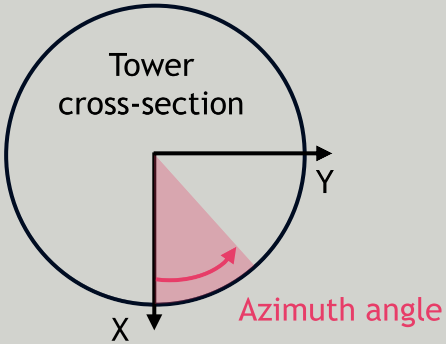
- Treating the turbulence as a stochastic variable gives a probability distribution for the non-exceedance of the fatigue results
- The change of lifetime depends on the level of safety (non-exceedance quantile) selected
- On the following slides lifetime values are given for P_{50} non-exceedance only, for simplicity
- Results shown for the most utilized tower azimuth and the two most utilized mooring lines

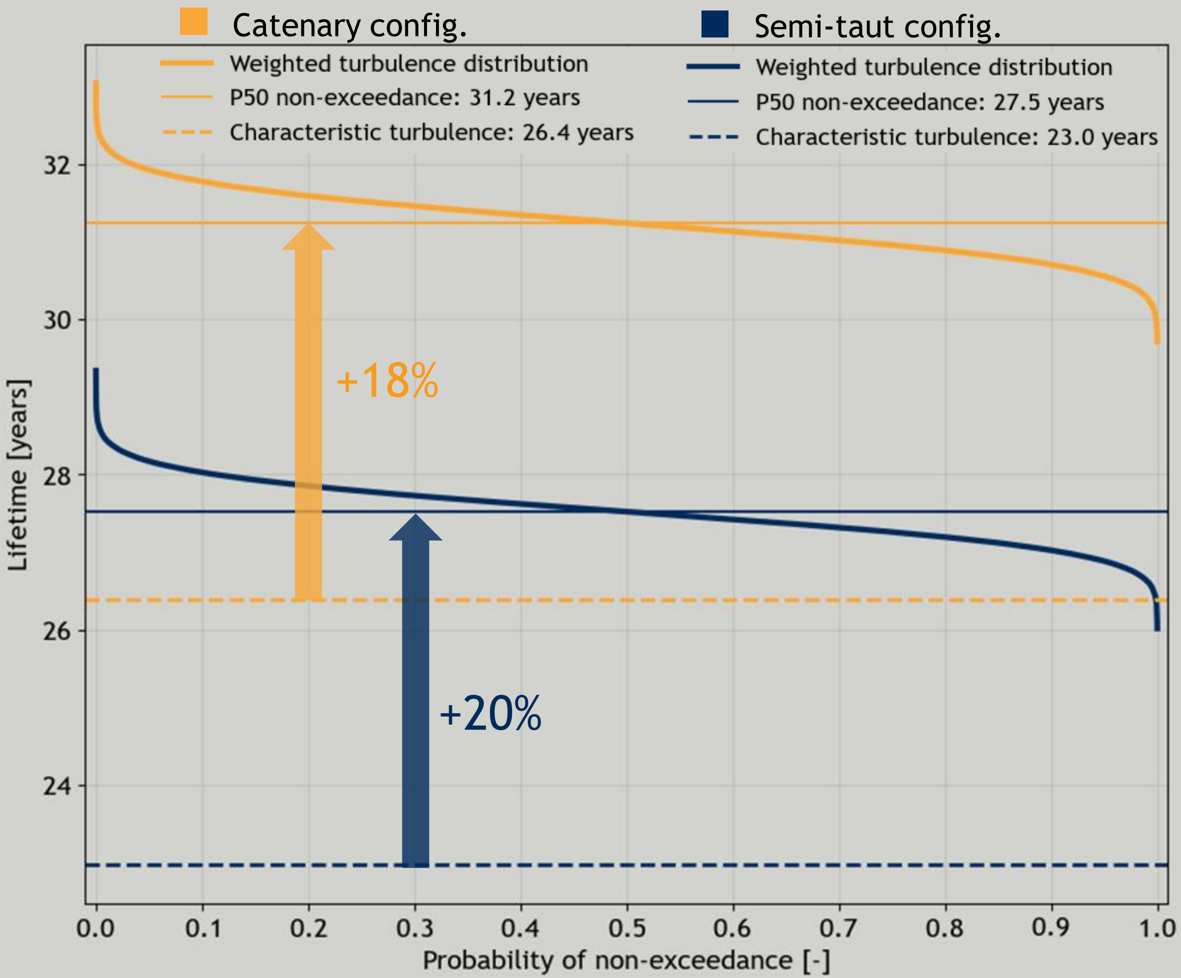


Fatigue comparison

Tower base (most utilized azimuth angle)

- The change from characteristic turbulence to weighted turbulence distribution leads to 18 - 20% increase of the tower base fatigue lifetime (50% prob. of non-exceedance).
- This corresponds to 4 mm reduction of wall thickness on the tower assumed (stiff-stiff tower, 10m base diameter)
- The expected impact will be larger for a smaller diameter tower or a soft-stiff tower.

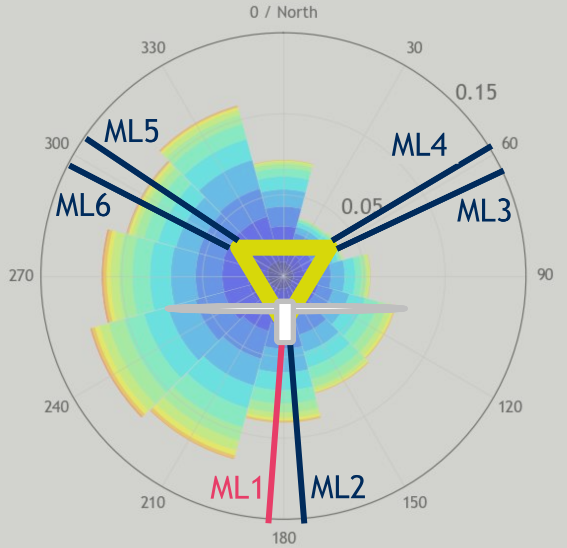


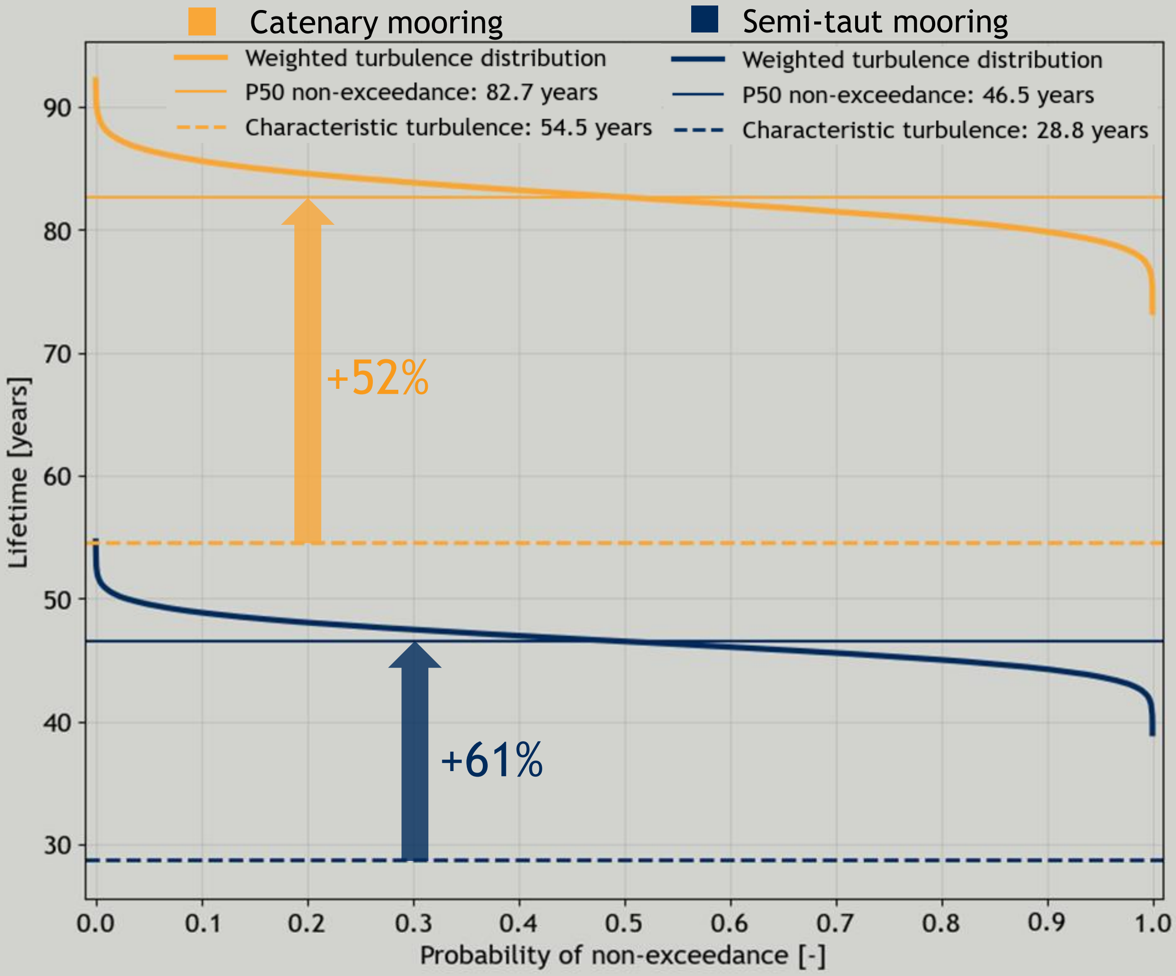


Fatigue comparison

Mooring line 1 (most utilized line)

- The change from characteristic turbulence to weighted turbulence distribution leads to 52 - 61% increase of the mooring chain fatigue lifetime for ML1 (50% prob. of non-exceedance).
- This corresponds to 10 - 20mm reduction of chain bar dimeter.

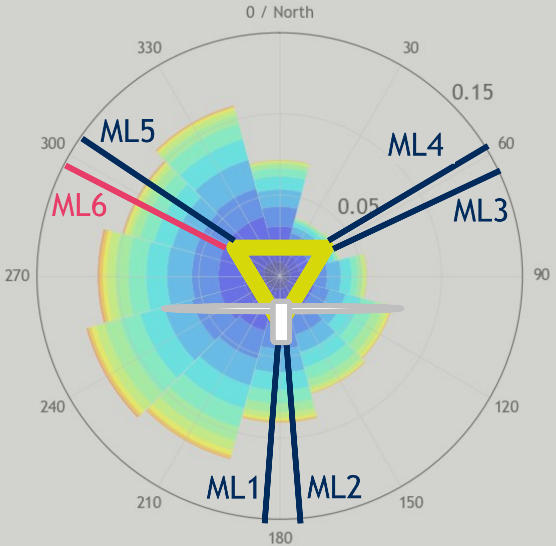


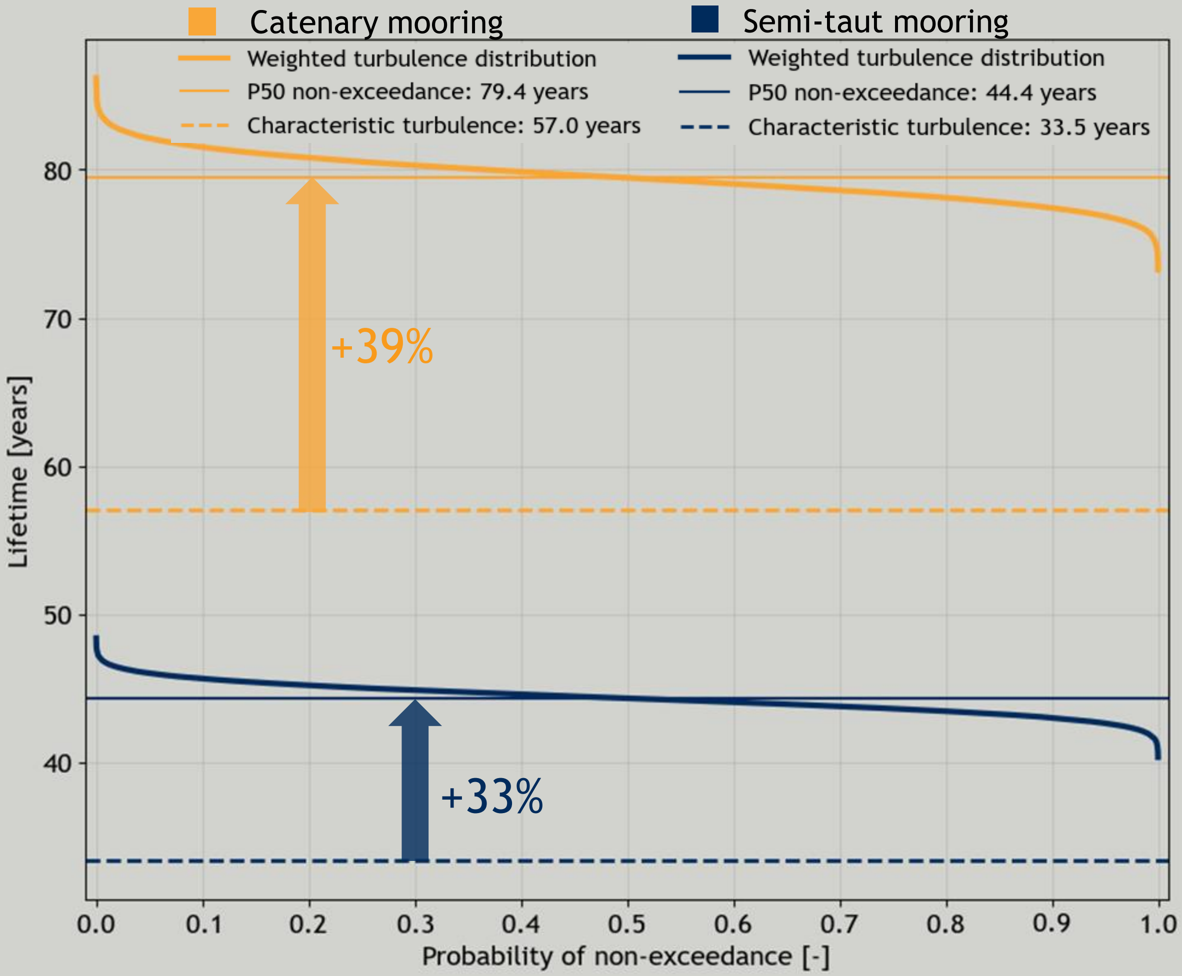


Fatigue comparison

Mooring line 6 (2nd most utilized line)

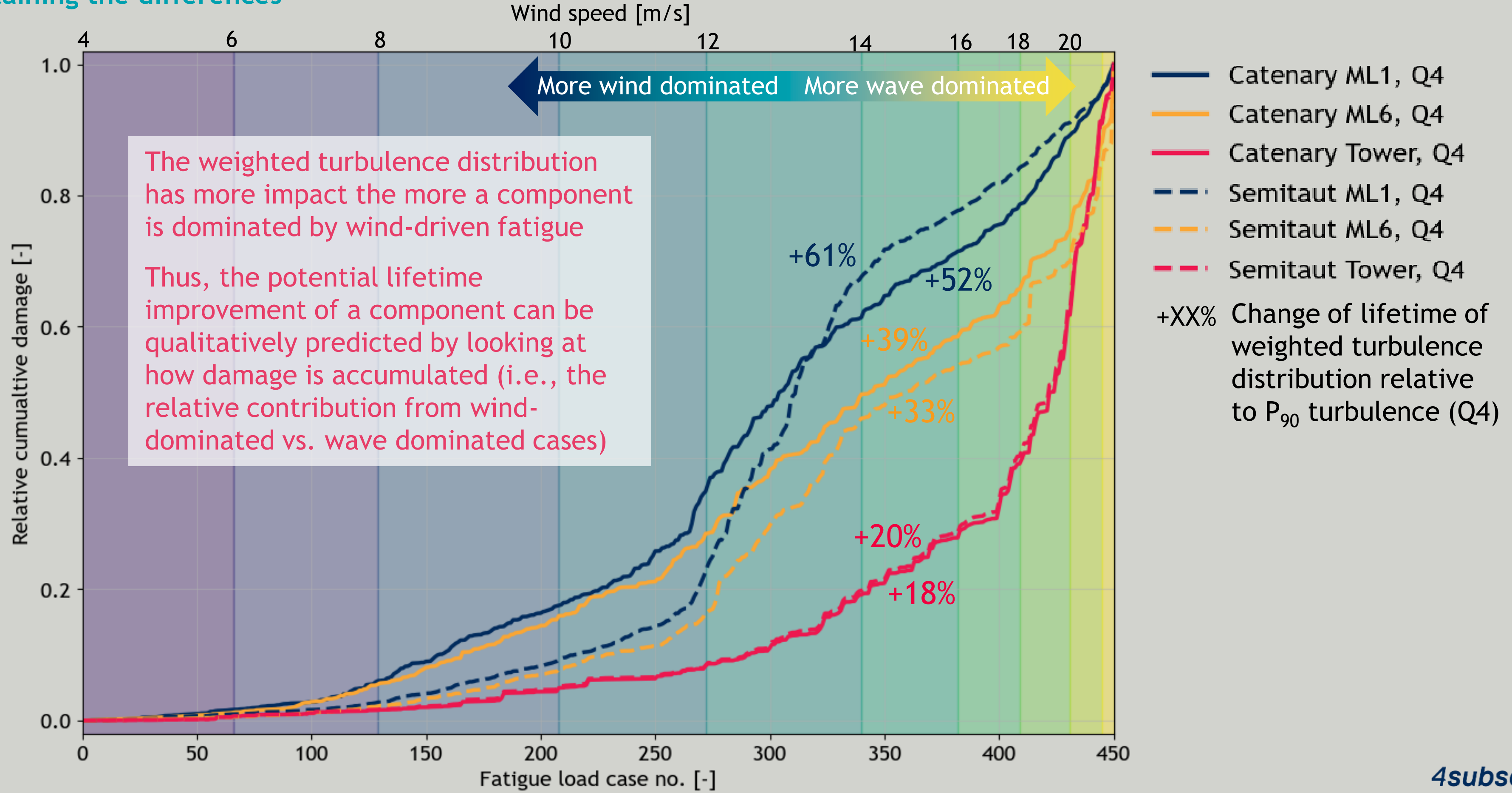
- The change from Characteristic turbulence to weighted turbulence distribution leads to 33 - 39% increase of the mooring chain fatigue lifetime for ML6 (50% prob. of non-exceedance).
- This corresponds to 7 - 8mm reduction of chain bar diameter.





Fatigue summary

Explaining the differences



Conclusion

Summary, discussion, and recommendations

Use of turbulence distribution instead of characteristic turbulence resulted in :

- 30-60% increase of mooring chain fatigue lifetime, depending on mooring system being chain catenary or semi-taut chain/polyester and orientation of mooring lines
- 20% increase of tower base fatigue lifetime

The behavior seems to be general, but the actual values could depend on key assumptions:

- Floater type and motion characteristics
- Wind turbine controller characteristics and efficiency
- Stiff-stiff tower (less influenced by 3P loading than soft-stiff tower)
- Selected metocean conditions (mostly wind-driven waves) and water depth (moderate)
- Selected mean and standard deviation of turbulence intensity
- Fibre rope stiffness and elongation characteristics (semi-taut mooring)

The present work says nothing about:

- RNA and blade fatigue (but logically should improve as well)
- Power cable fatigue (but logically should improve as well)

Recommendations:

- For floating wind Certification / Standardization Agencies (e.g. DNV):
  Evaluate the consequences of allowing a more granular approach to TI in the standards
- For Project Developers:
  Discuss this topic with the relevant Certification Agency for your project

Thank you!

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