Wind Europe Technology Workshop 2025

Session: Effects of the atmospheric boundary layer on wind farm performance

Accounting for Mesoscale Flow Features in Offshore Wind Farm Wake Loss Assessments

Jorge Garza[1], Rémi Gandoin[1]

[1]C2Wind

Date 2025-06-20
Author JOG
QC RGA
Doc no. 0-007-06-01
Revision 2

Table of Contents

Take-aways:

ABL dynamics = key drivers of wake effects

Modelling should account for these

WRF + Wind Farm Parametrisation, and LES with actuator disk compare well with measurements

It's feasible to integrate both into EYA workflows

C2WIND

Wake drivers:

- **aerodynamic efficiency** of each turbine (deficit)
- structure of the **atmospheric turbulence** (recovery).

Both **large scale** (0.1-10km) and **small scale** (.01-100m) turbulence motions matter.

Current engineering practice largely relies on analytical **wake deficit** models, however **mesoscale flow features** become increasingly relevant.

Cost-effective commercial tools are available: in this study we used **WakeMap** and **Whiffle Wind**.

WakeMap

- **Fitch WFP parameterization in WRF** + recent WRF WFP correction by Vollmer
- TKE generation factor of 1.0
- Turbulence advection turned on.
- **ERA5 reanalysis as boundary forcing.**
- Innermost domain **at 700 m**, nested by 2.1 km and 6.3 km outer domains.
- Validation period split into separate 3-day simulation periods each with 6-hour spin up, resulting timeseries concatenated in post-processing.

Whiffle Wind

- Built around Whiffle's in-house, GPU-resident atmospheric simulation platform.
- Whiffle Wind's default simulation setup
- **LES domain at 100 m resolution** nested in a 2 km meso-scale model.
- **Boundary conditions provided by ERA5.**
- LES employs an actuator disk-based turbine model, of which the disk-based thrust- and power coefficients are obtained from a separate, offline simulation.

TurbOPark

- Public version in Ørsted's github as per March 2025.
- Site-specific omnidirectional ***TI* as a function of *WS* & *z/L***.
- With- and without free-stream speed-up.

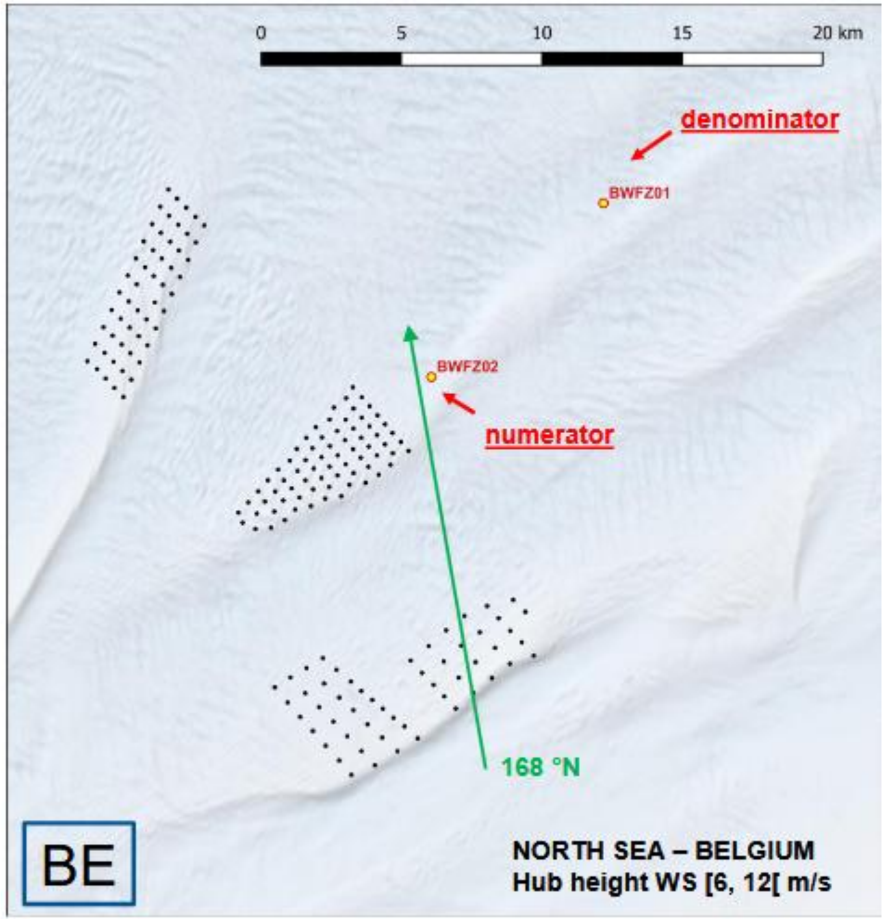
PARK2

- C2Wind **in-house** implementation.
- Site-specific omnidirectional ***k*(*TI*) as a function of WS & z/L**.
- No ground reflection, no boundary layer reflection, with- and without boundary layer height dependency.

C2Wind ApS | Vesterballevej 5 | 7000 Fredericia | Denmark

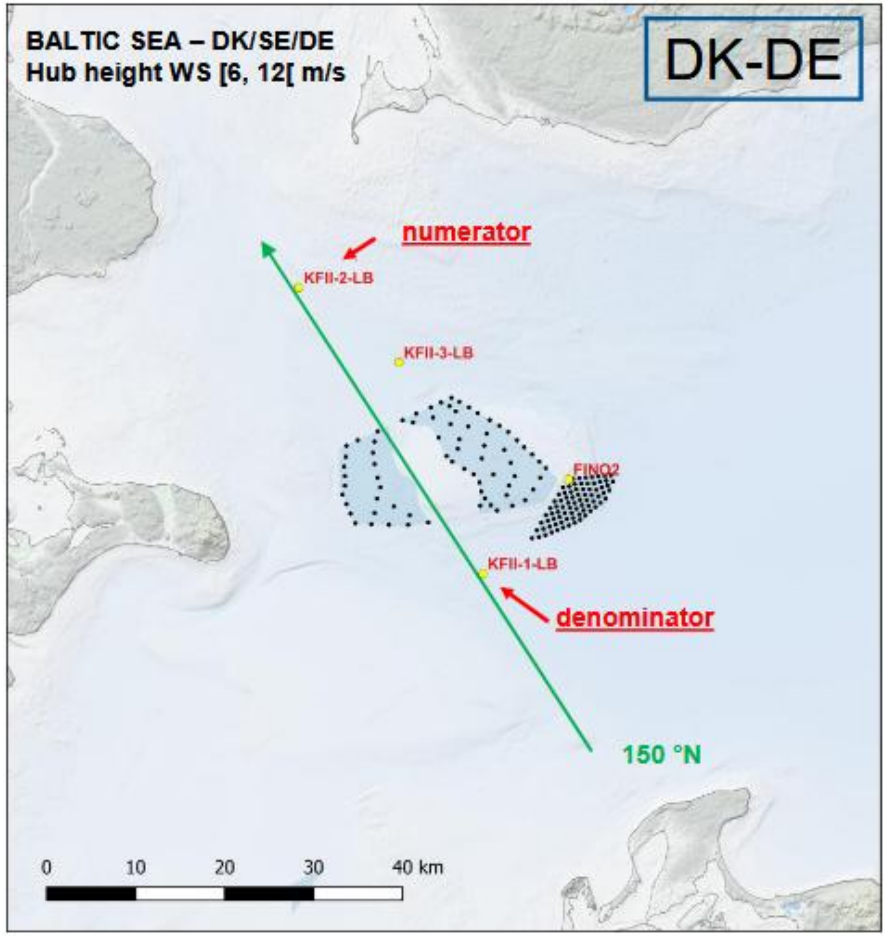
Measurements

Floating lidar measurements from the Southern North Sea and the Baltic + FINO2



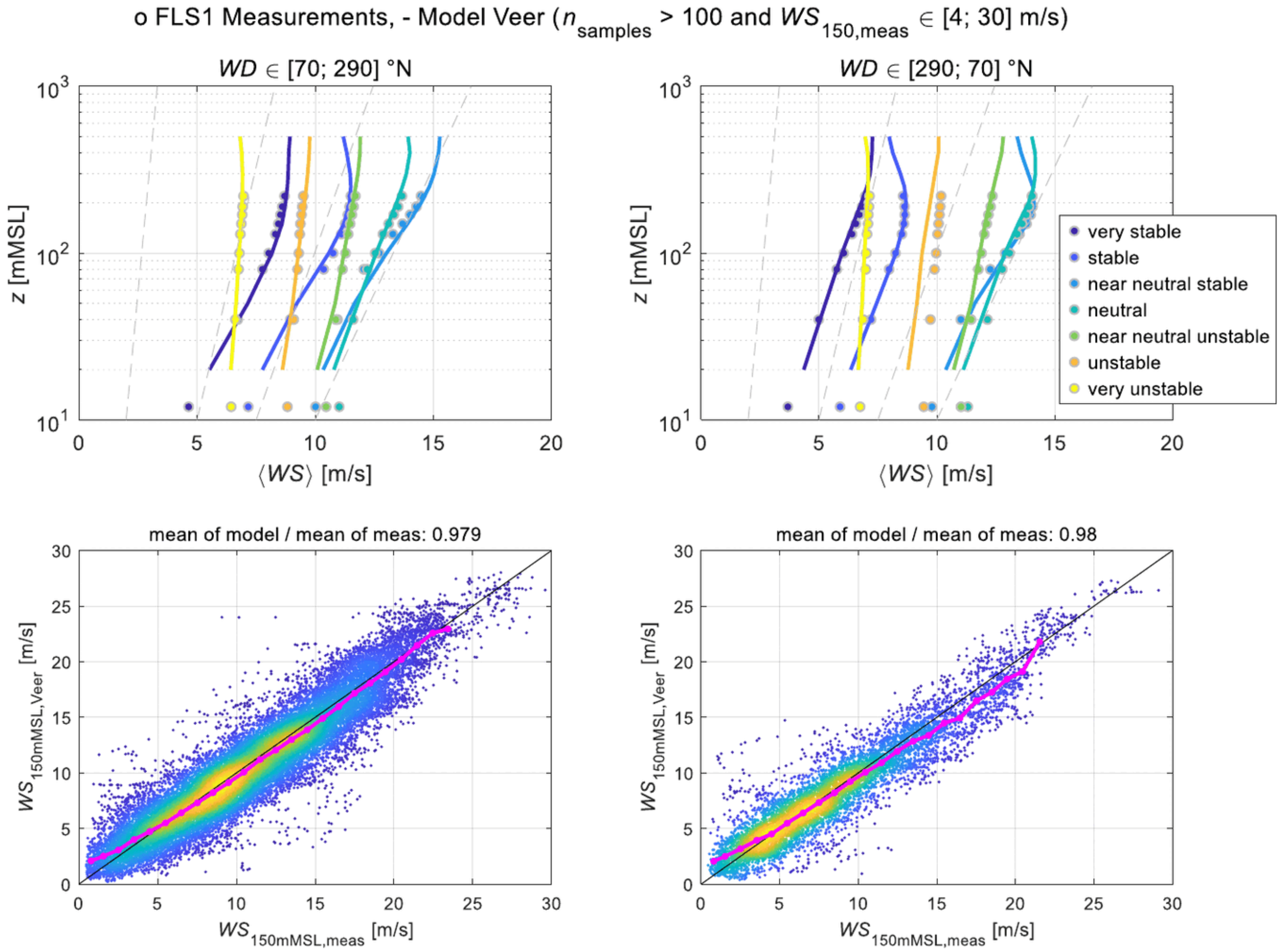
Models

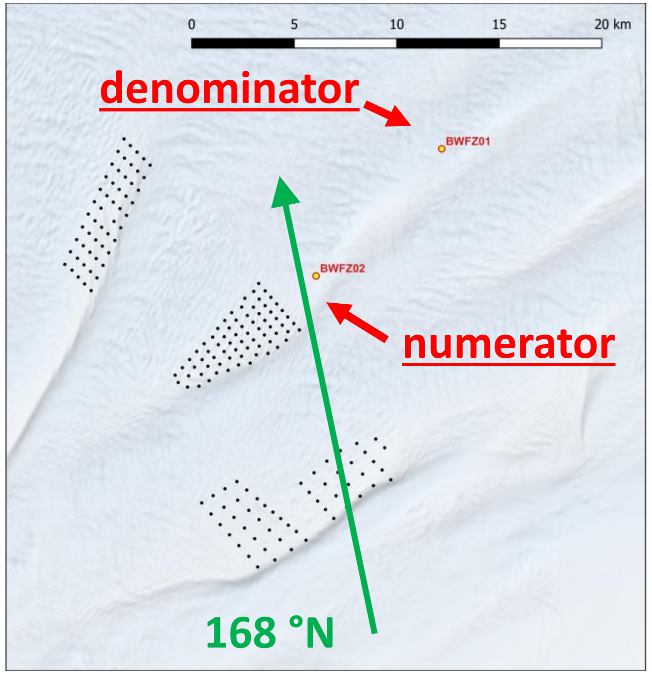
6 months of simulations for North Sea; 1 full year for Baltic Sea

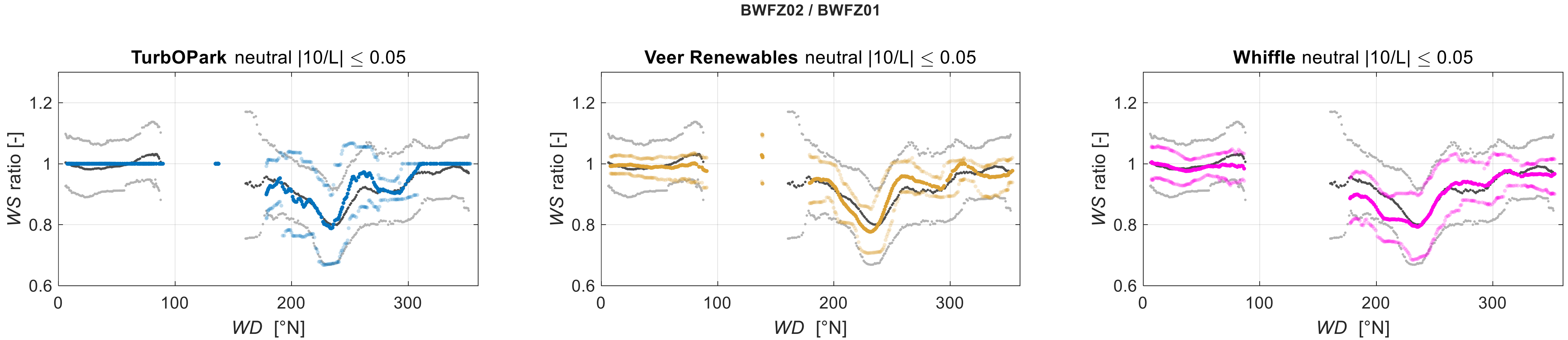


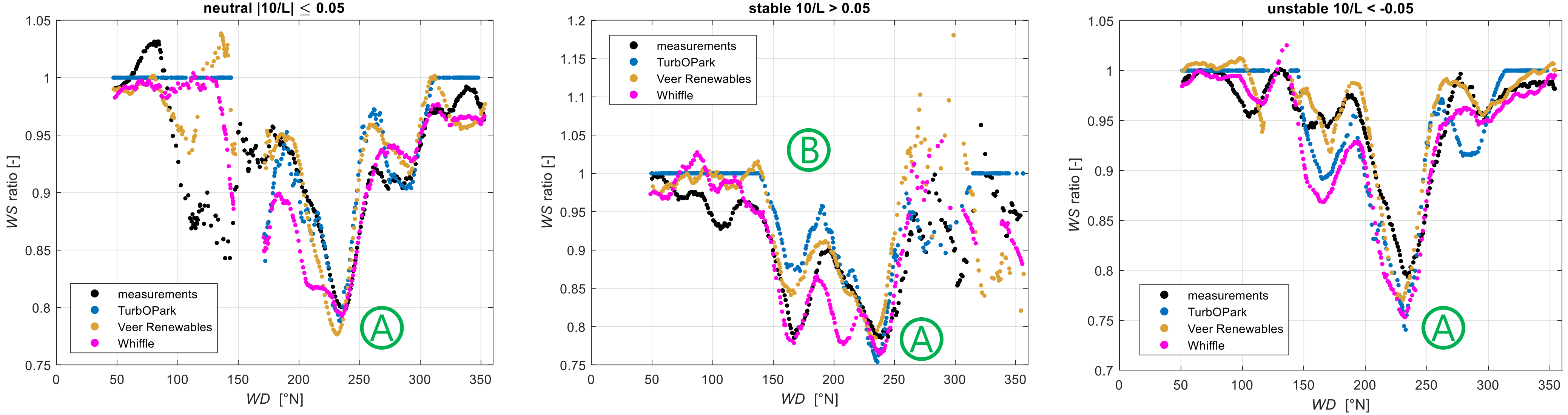
Free-stream

- Good performance on mean wind speed, within [0.98; 1.005]
- Differences in stability, *TI* and boundary layer height between models; some due to internal model workings, some due to ERA5 input.







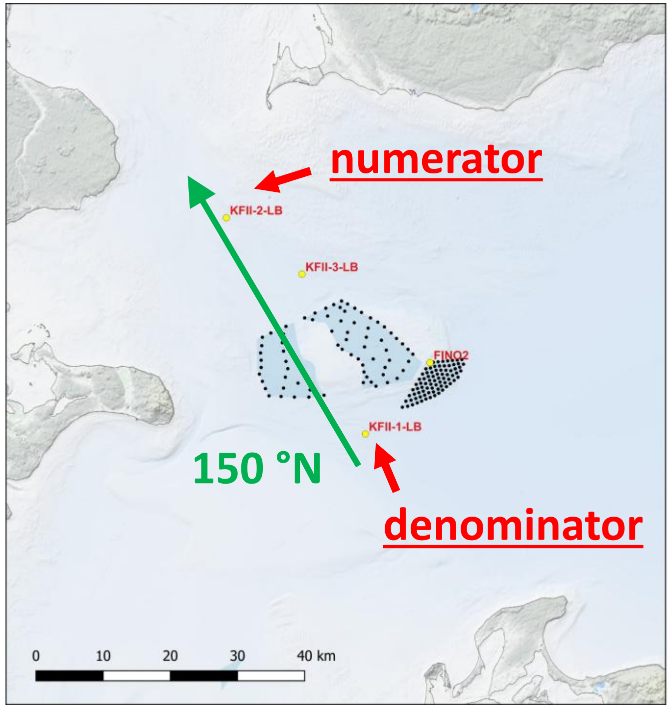


NORTH SEA – BELGIUM
Hub height WS [6, 12[m/s

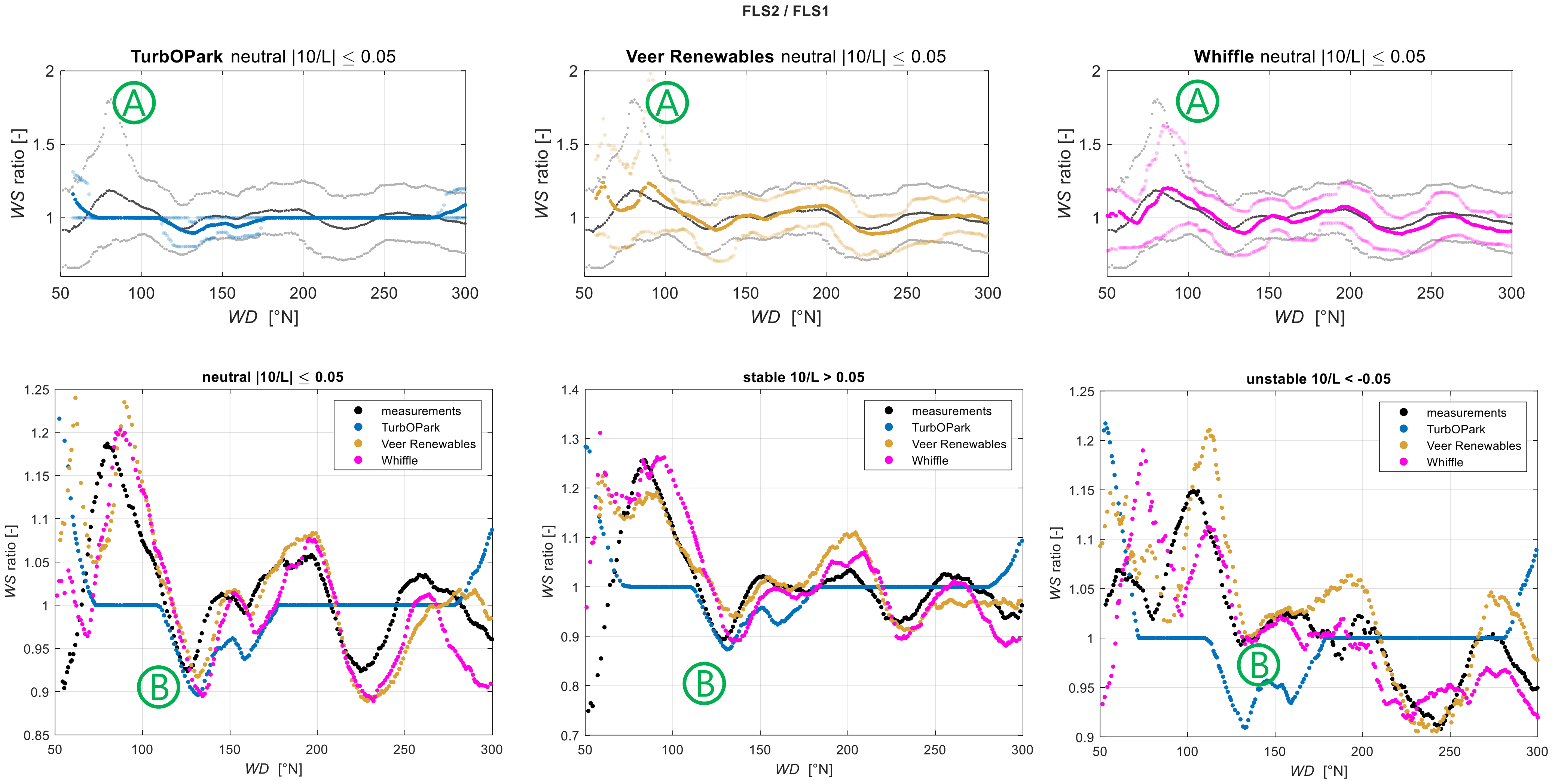
C2WIND

Ⓐ all models perform well

Ⓑ Veer and Whiffle better capture stable conditions



BALTIC SEA – DK/SE/DE
Hub height WS [6, 12[m/s



C2WIND

Ⓐ large mesoscale variations

Ⓑ Veer and Whiffle capture stability + mesoscale effects

Wind speed in wake

- All models perform well in simple flow cases, ie. short- to medium distance wakes, neutral conditions, high wind speed.
- **WakeMap** and **Whiffle Wind** are better able to capture stability and mesoscale effects, including variance.

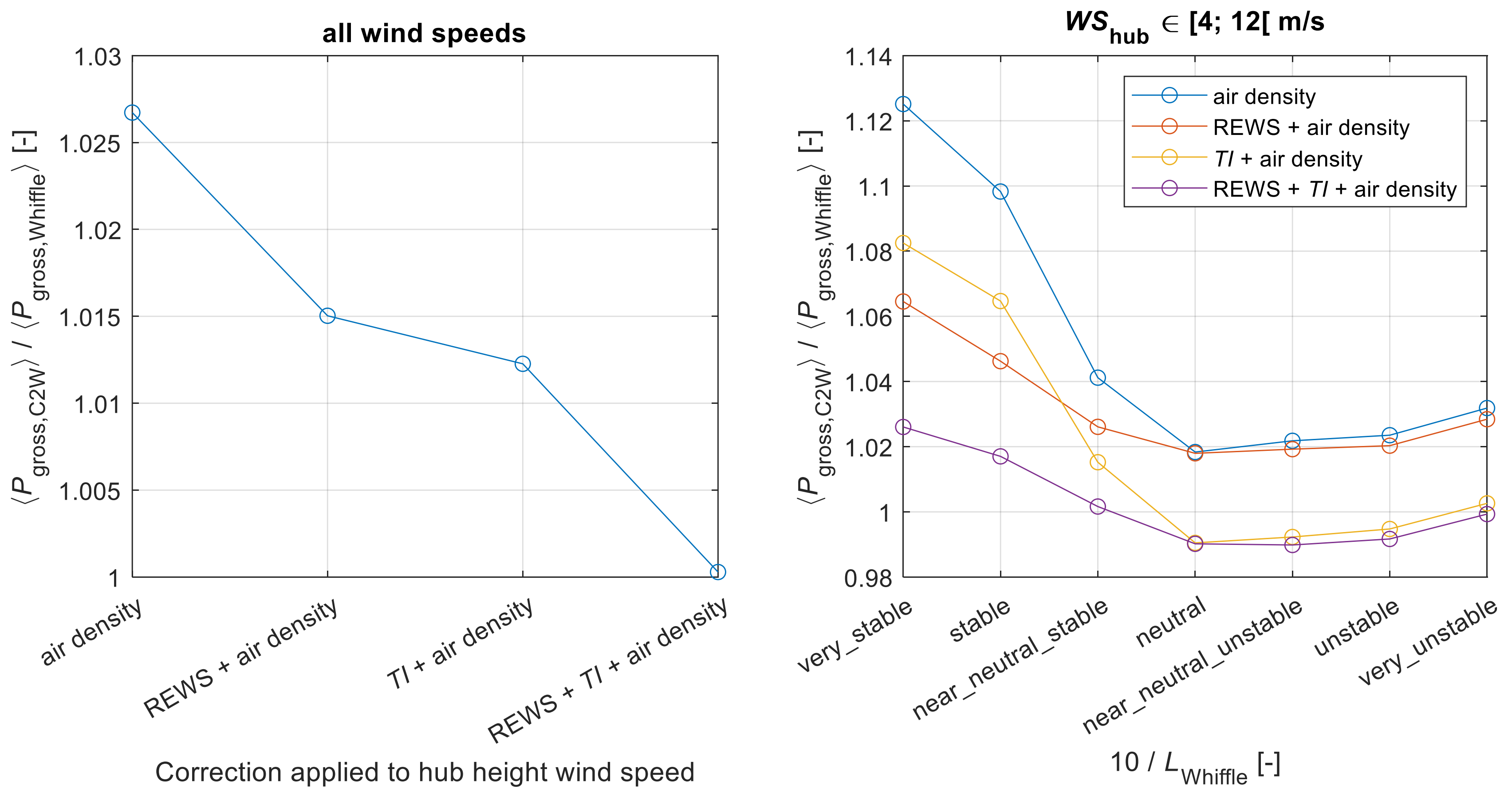
mean deficits [%] – all stab.		
	BE	DK-DE
Wind dir. [°N]	*[200;270[*	*[120;150]*
Meas.	15.7	4.4
TurbOPark	13.6	6.5
Veer	14.0	2.7
Whiffle	17.0	4.3

C2WIND

Gross power

- ➢ Understanding which model-specific adjustments (ie. *TI*, *REWS*, *ρ*) are necessary is key.
- ➢ For seamless integration into EYA workflows, a wake-free and a waked simulation are optimum.

Whiffle Wind



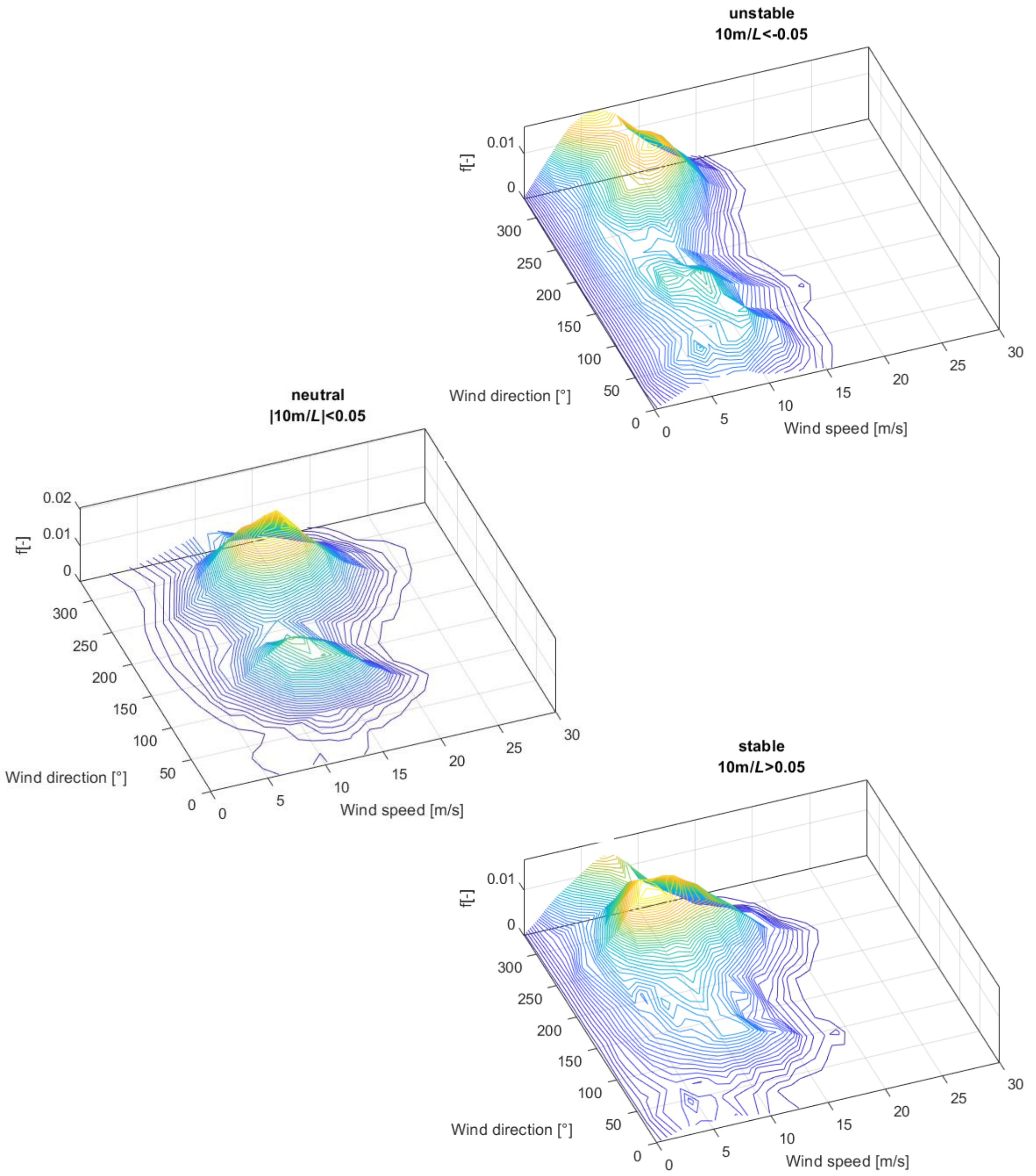
C2WIND

Challenges

- Dozens of WTG / layout scenarios: **not realistic**
- CFD models have nonzero bias in free stream and require adjustments to align with WRA & EYA.

Solution

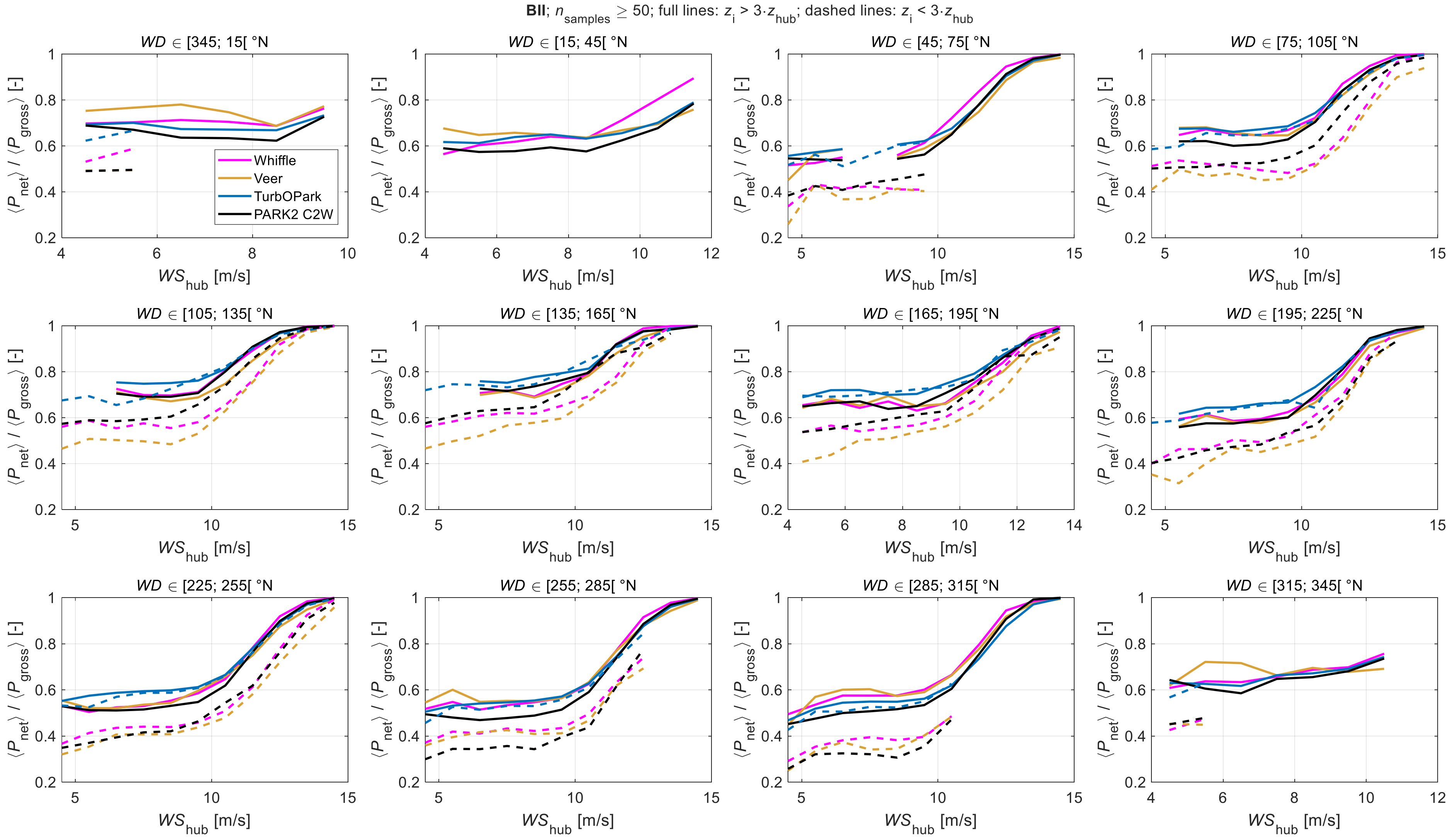
- **3D wind climate**: Long-term representative wind climate at the site in terms of f(v, Θ, z/L)
- **Site-specific binning strategy for all 3 dimensions**: Some sites may require 10° wind direction bins, having 7 stability classes may be too ambitious, etc.
- **Selection of representative period for simulation**: Inspiration from the "complete database" concept in IEC 61400-12, prioritizing important bins in the 3D wind climate → **significantly reduced simulation time and cost**
- **Two simulations**: waked- and wake-free to isolate wakes, mitigate free-stream bias and retain control over gross power adjustments.
- **Power time series**: inherently accounting for variability and facilitating uncertainty assessment.



Example results

PARK2 can be tuned to account for boundary layer height (besides *k* as a function of WS & z/L through turbulence), greatly improving its performance for simple- and not-so-simple flow cases.

Very complex flow cases remain outside the capabilities of engineering wake deficit models.



Using **high quality wind measurements:**

- CFD models work **satisfactorily**
- CFD models capture variations in atmospheric turbulence which drive wake effects, which engineering models do not.

The approach presented allows for:

- Incorporating CFD wake models into traditional EYA workflows
- ... at low cost and quick turnaround
- ... allowing for a more quantitative uncertainty assessment

- More validations.
- Validations against SCADA.
- Fine-tuning what makes a representative wind climate.
- Fine-tuning boundary layer height as input.

Big thanks to Mike Optis from Veer and Pim Van Dorp from Whiffle for fruitful discussions, helping us better understand their models.

References:

Veer Renewables. WakeMap: The Next Generation in Wind Resource Modelling. Link: https://sway.cloud.microsoft/xXNw4LesRPw80JB9

Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., and Barstad, I.: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model, Mon. Weather Rev., 140, 3017–3038 (2012). Link: https://doi.org/10.1175/MWR-D-11-00352.1

Baas, P., Verzijlbergh, R., van Dorp, P., and Jonker, H.: Investigating energy production and wake losses of multi-gigawatt offshore wind farms with atmospheric large-eddy simulation, Wind Energ. Sci., 8, 787–805, https://doi.org/10.5194/wes-8-787-2023, 2023.

Postema, B., Verzijlbergh, R., van Dorp, P., Baas, P., and Jonker, H.: Estimating Long-Term Annual Energy Production of a Large Offshore Wind Farm from Large-Eddy Simulations: Methods and Validation with a 10-Year Simulation, Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2024-54, in review, 2024.

Vollmer, L., Sengers, B. A. M., and Dörenkämper, M.: Brief communication: A simple axial induction modification to the Weather Research and Forecasting Fitch wind farm parameterization, Wind Energ. Sci., 9, 1689–1693 (2024). Link: https://doi.org/10.5194/wes-9-1689-2024

Ørsted. TurbOPark Gitub repository https://github.com/OrstedRD/TurbOPark. Last fetched: 2025-03-20.

Rathmann O. S., Hansen B. O., Hansen K. S., Mortensen N. G., Murcia Leon J. P. The Park2 Wake Model - Documentation and Validation. DTU Wind Energy E Vol. 160 (2018). Link: https://orbit.dtu.dk/en/publications/d527ae78-d931-450c-a1eb-1fc6c1989133