The Hybrid-Lambda rotor design and control methodology

Enabling low-specific-rating offshore wind energy

Daniel Ribnitzky, Johannes Paulsen, Lars Neuhaus, Vlaho Petrović, Martin Kühn
ForWind - Center for Wind Energy Research, Institute of Physics, University of Oldenburg
Contact: daniel.ribnitzky@uol.de

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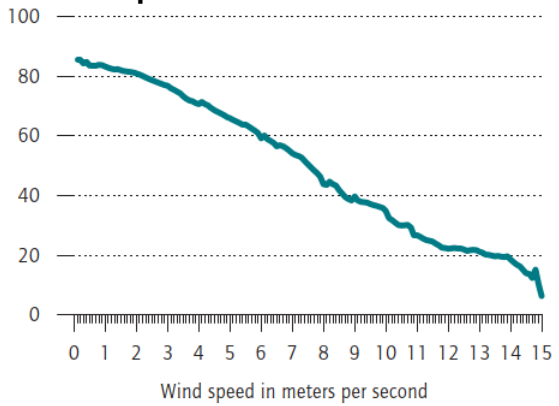
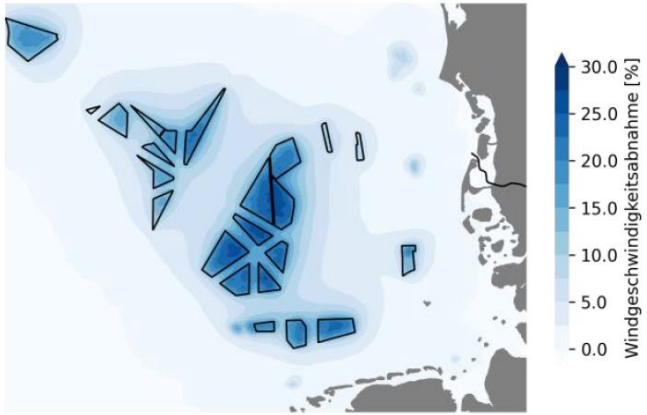
Motivation

Market value of wind power in relation to the wind speed in 2030 in Euro per MWh [1]



Wind speed reduction due to increased clustering of offshore wind farms [2]



Demand:

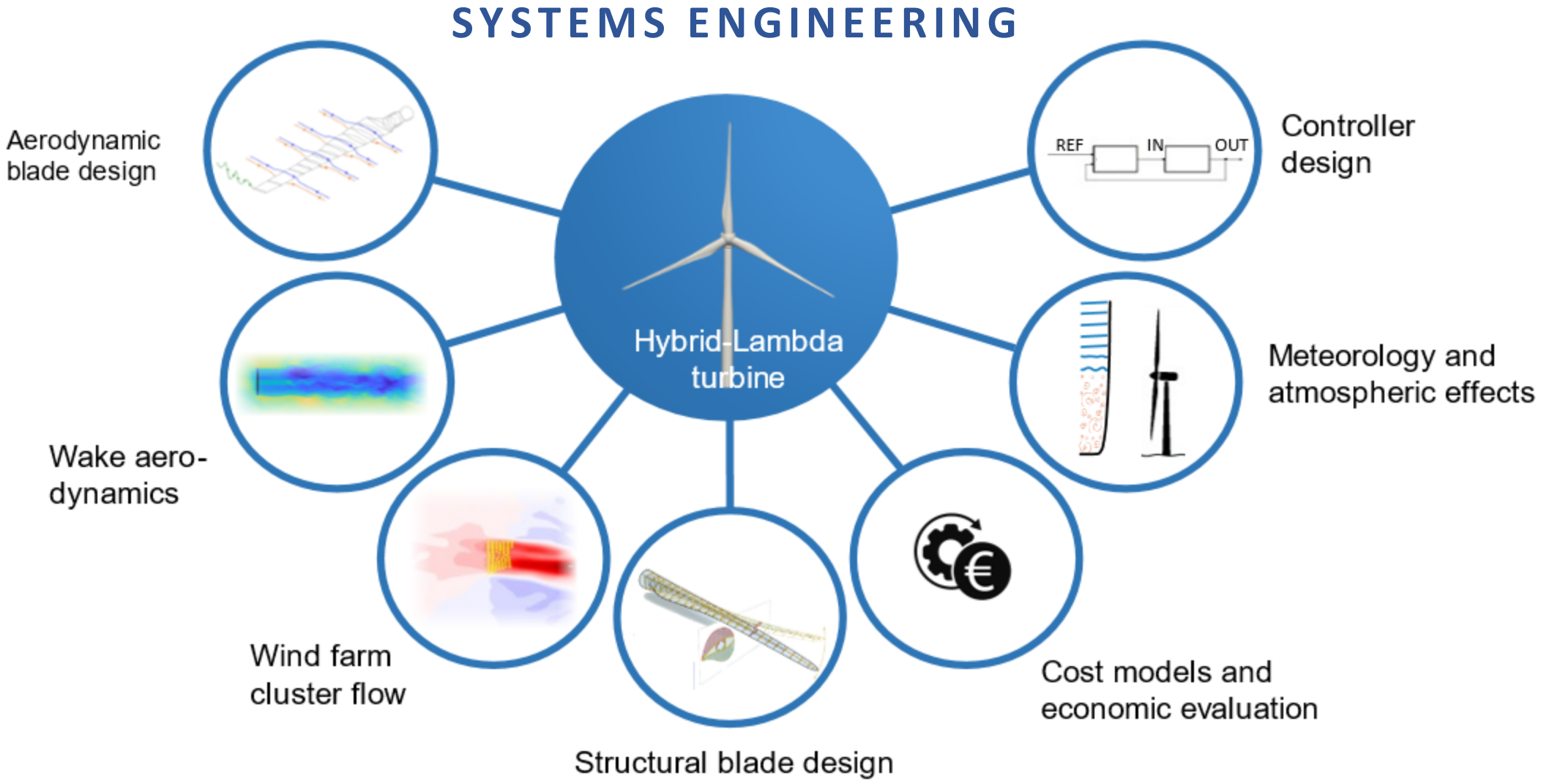
- Increased power at light winds

Need:

- Larger rotors
- Lower specific rating offshore
- Load limiting strategies
- Reduced cluster wake effects

[1] May N, Heuhoff K, Borggrefe F 2015 - *Market incentives for system-friendly designs of wind turbines,* DIW Economic Bulletin 24.2015
[2] Dörenkämper M, et al, *Weiterentwicklung der Rahmenbedingungen zur Planung von Windenergieanlagen auf See und Netzanbindungs-systemen* (Endbericht Fraunhofer IWES), 2023

Content



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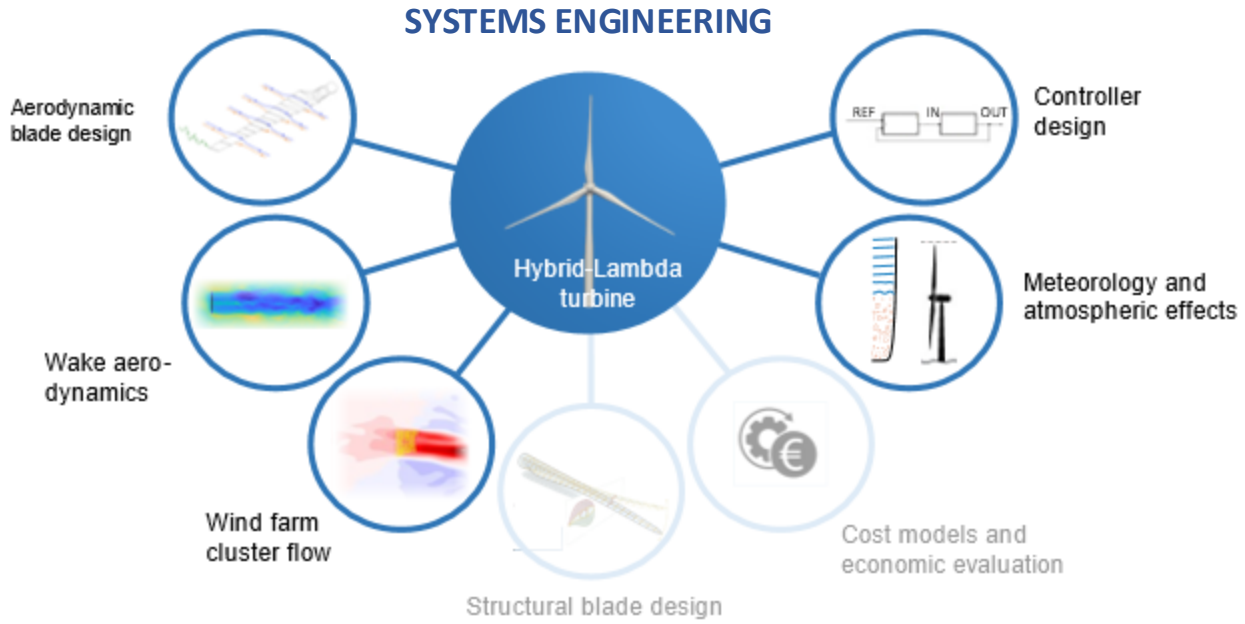


1. Aerodynamic concept and control
2. Wake effects: Single turbine, wind farm & cluster scale
3. Turbulent-non-turbulent interface in the atmosphere
4. Conclusions

Aerodynamic concept

Objective:

- Design large rotors that capture more energy in light winds, when wind energy is more valuable
- Design a rotor for a 15 MW offshore wind turbine with a specific rating of $180\frac{W}{m^2}$, $D = 326\,m$
- Limit flapwise root bending moments (RBM) to maximum value of IEA 15 MW turbine

IEA reference turbine: 15 MW, Ø 240m, $332\frac{W}{m^2}$

Up-Scaling: 15 MW, Ø 326m, $180\frac{W}{m^2}$

„Hybrid-Lambda“ Concept: 15 MW, Ø 326m, $180\frac{W}{m^2}$

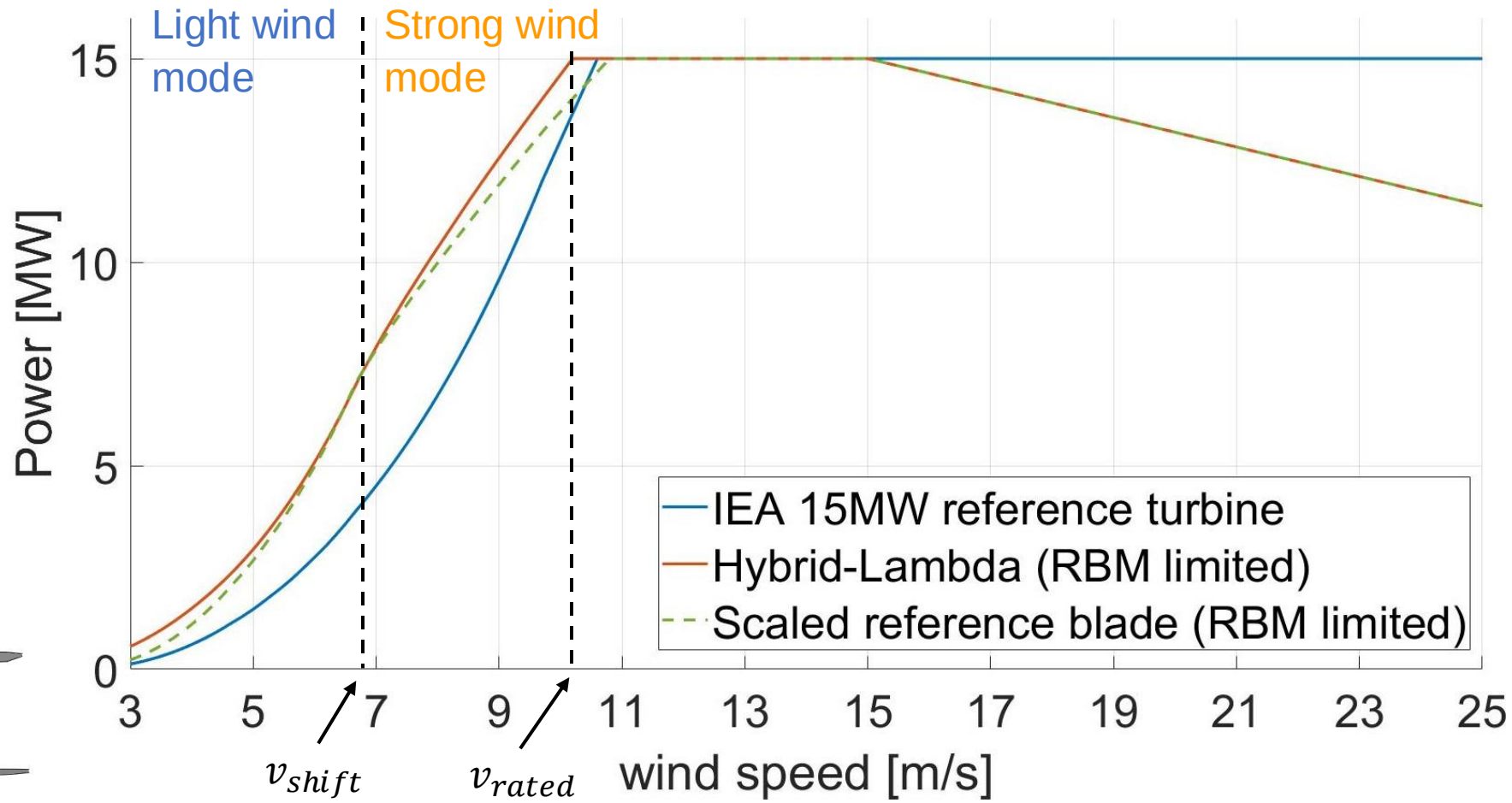
Further info:
Ribnitzky, Berger, Petrović, Kühn: *Hybrid-Lambda: A low specific rating rotor concept for offshore wind turbines*, WES, 2024

Aerodynamic concept – Power curve

IEA reference turbine

Up-Scaling

„Hybrid-Lambda“ Concept



Aerodynamic concept – Control schedule

Concept idea:

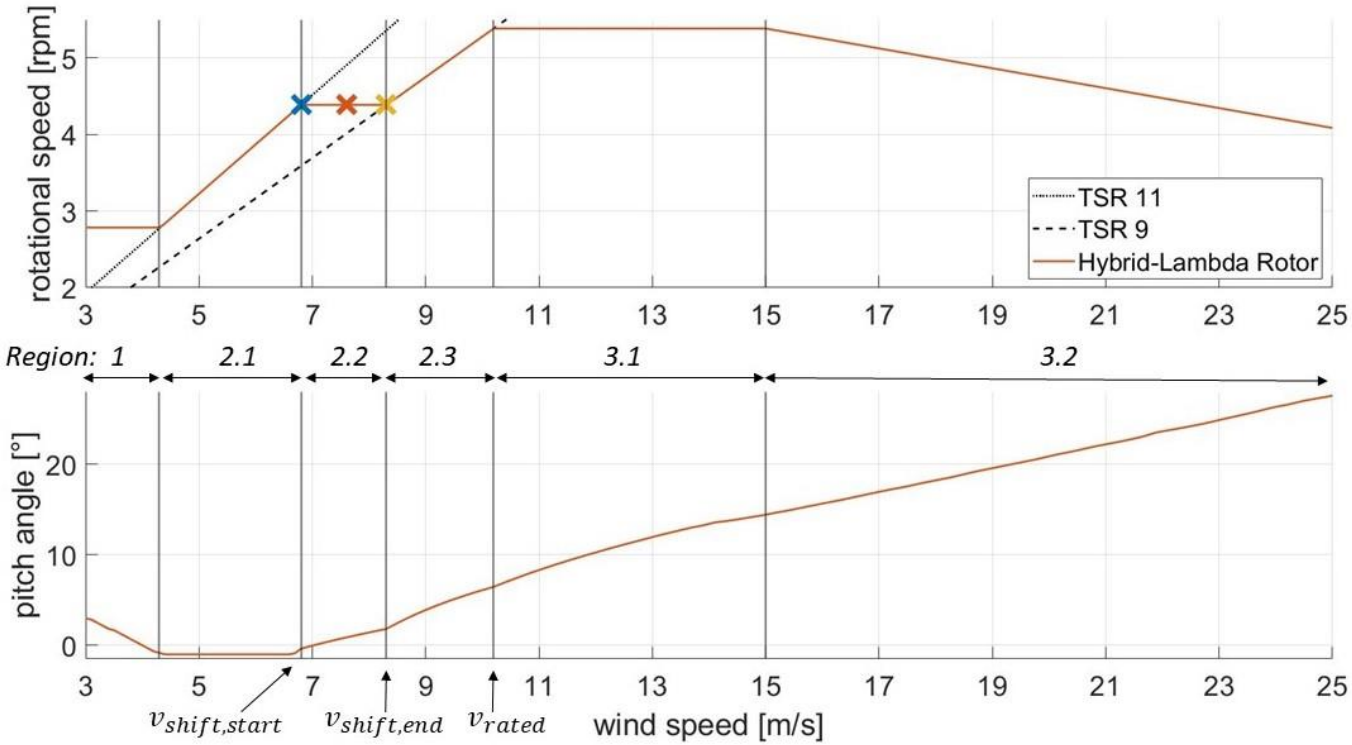
Operating mode 1: Light winds (TSR 11)

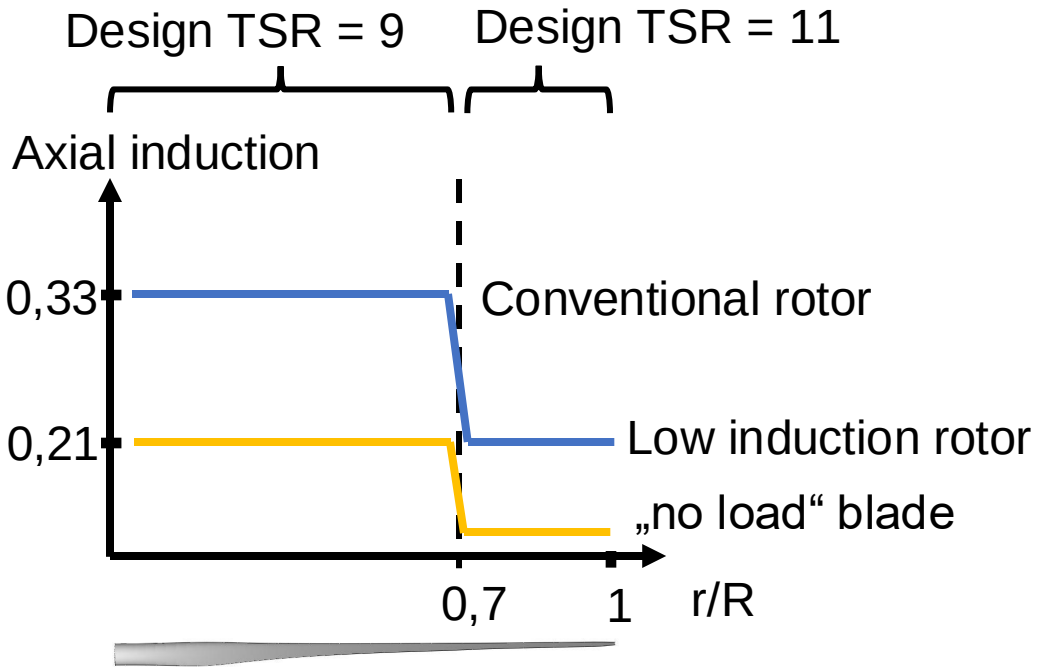
⬇ for $v > v_{shift,start}$ *(limiting loads)*

Operating mode 2: Strong winds (TSR 9)

⬇

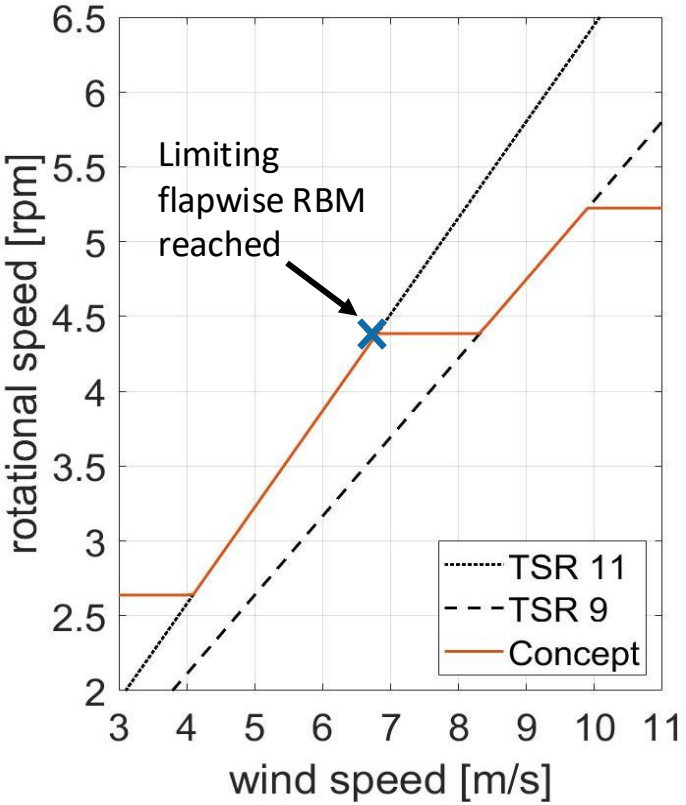
Rated wind speed

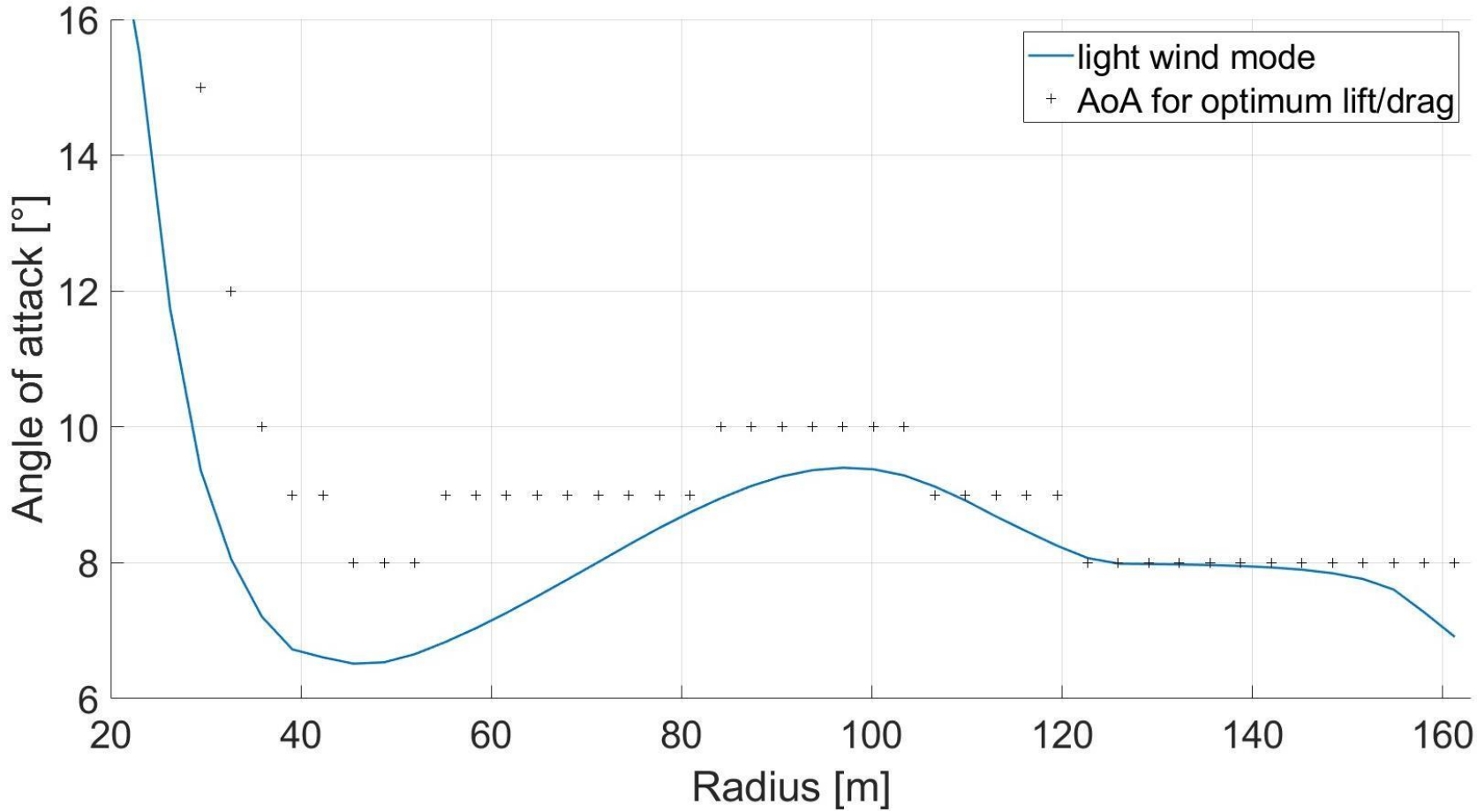




TSR : tip speed ratio (λ) = tip speed / wind speed

Aerodynamic concept – Angle of attack control





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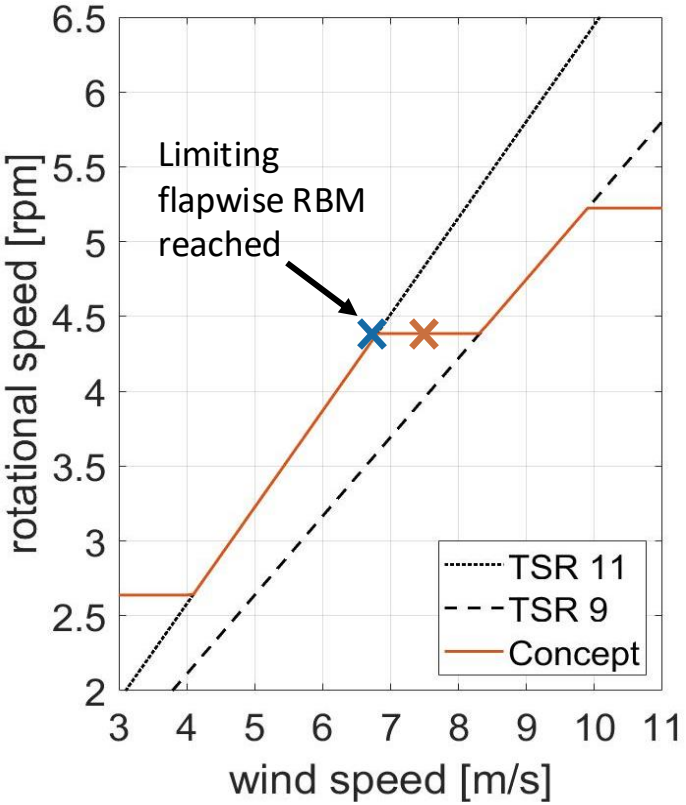
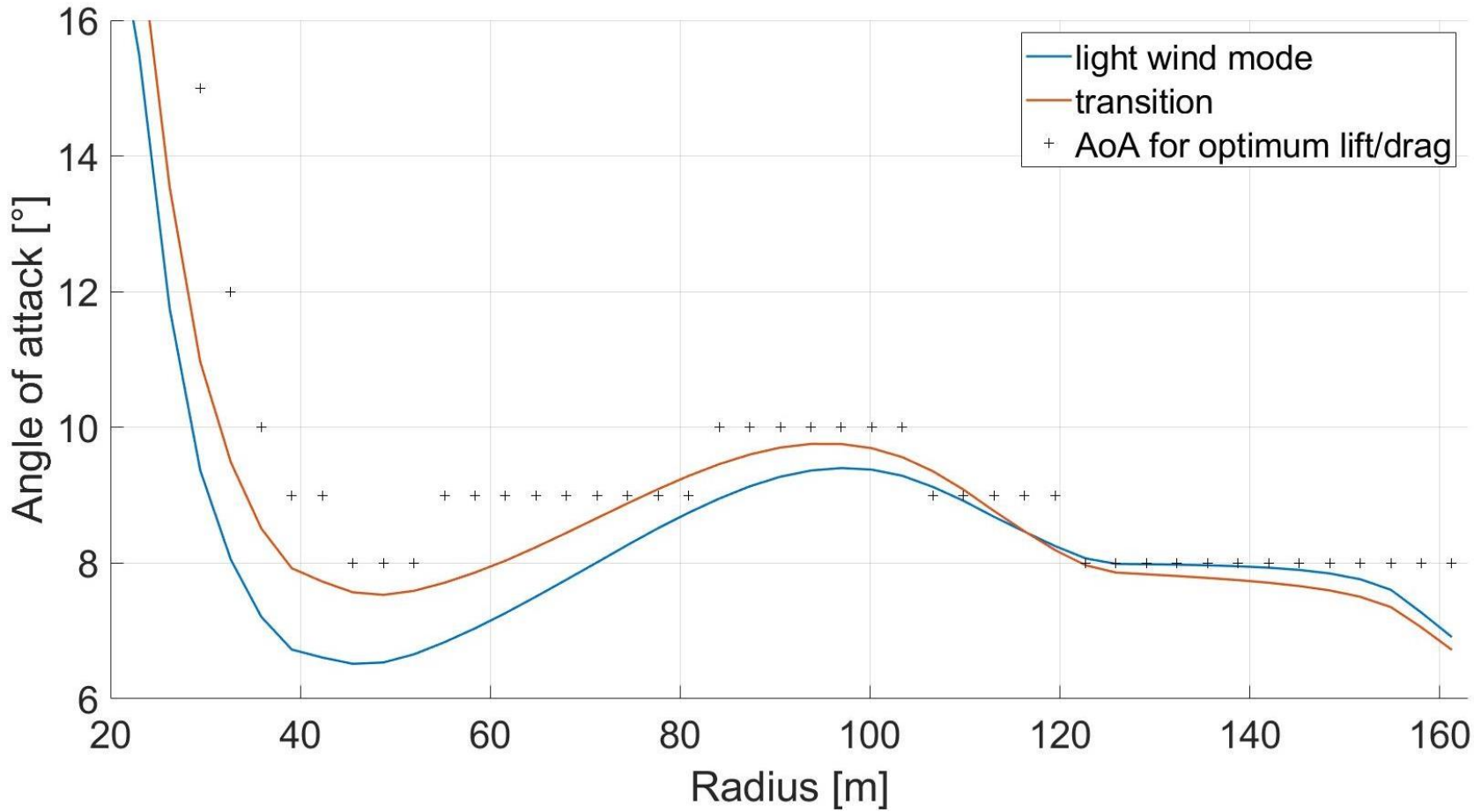
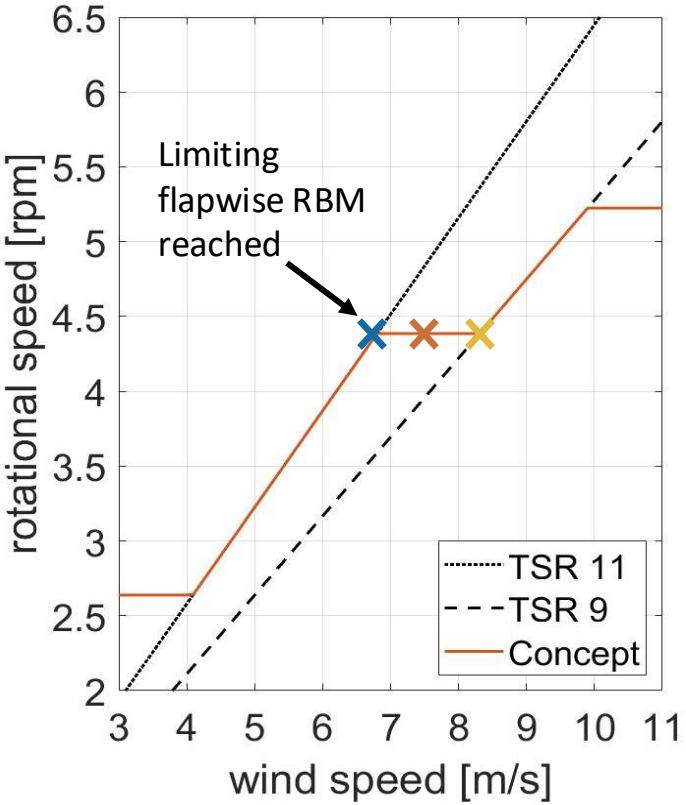
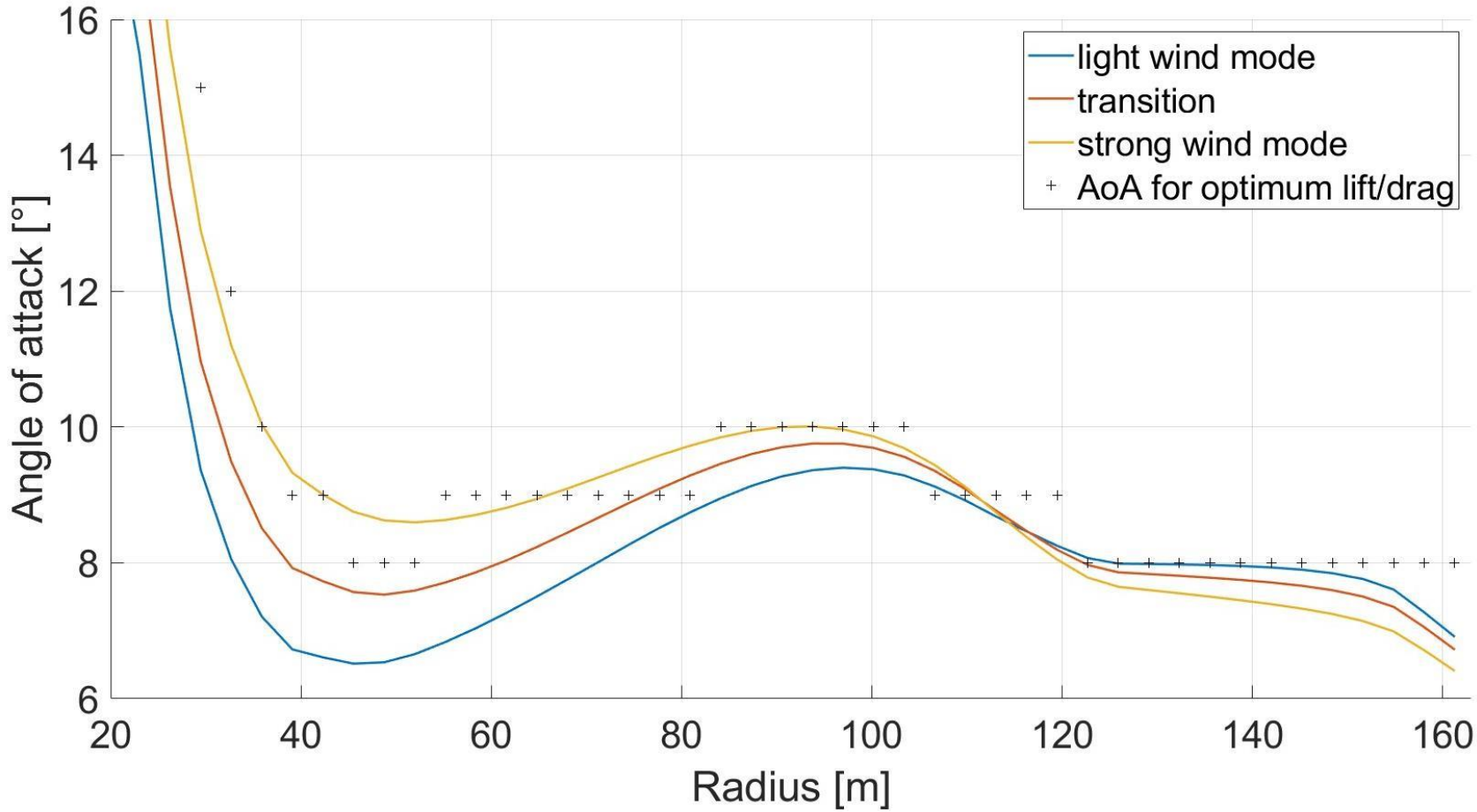




Aerodynamic concept – Angle of attack control

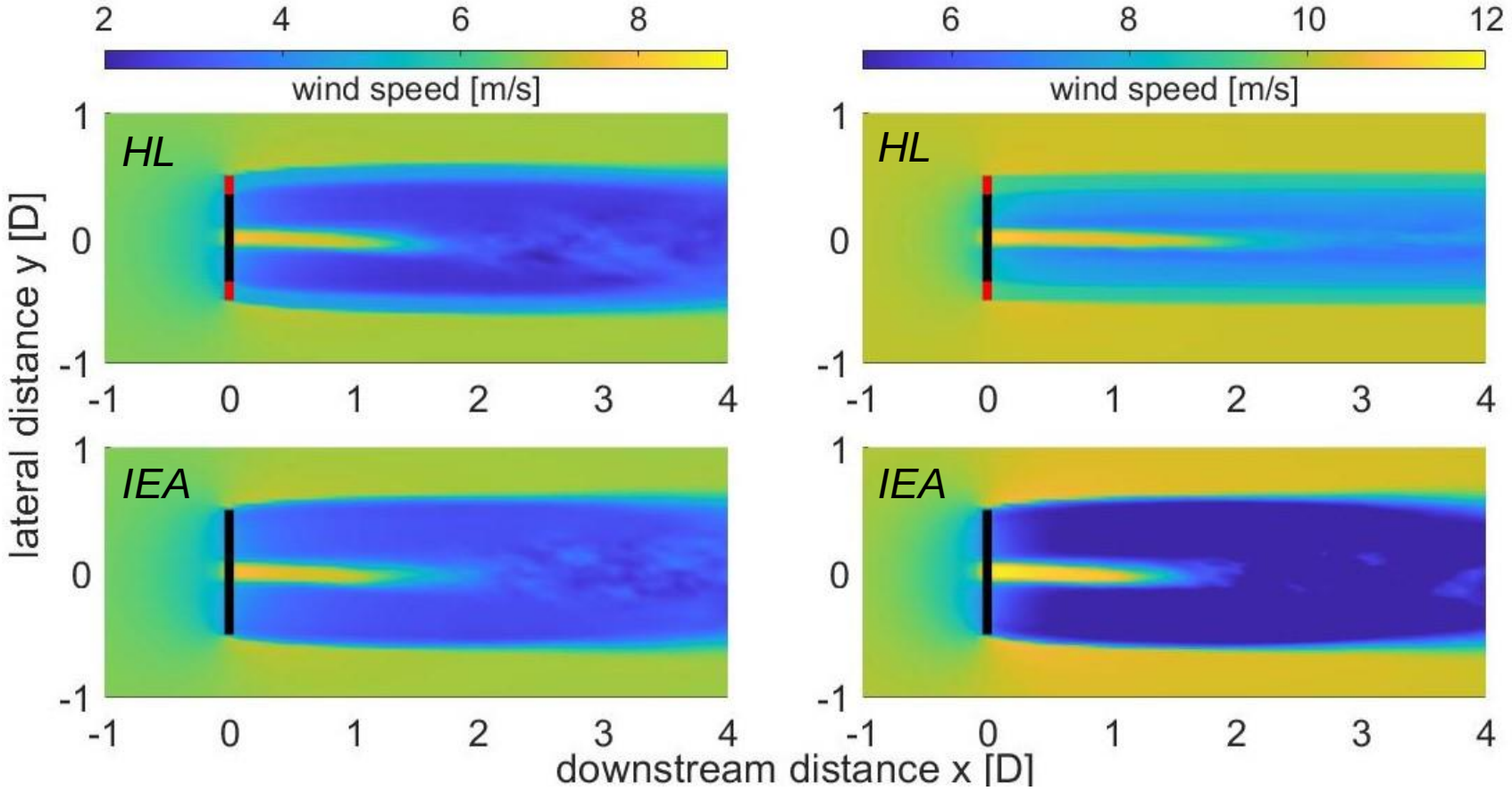




Wake deployment

Free-vortex-wake

- Steady, uniform inflow
- Low-induction tip displayed in **red**
- Additional gradients in the wake profiles
- Low wake deficits in strong wind mode

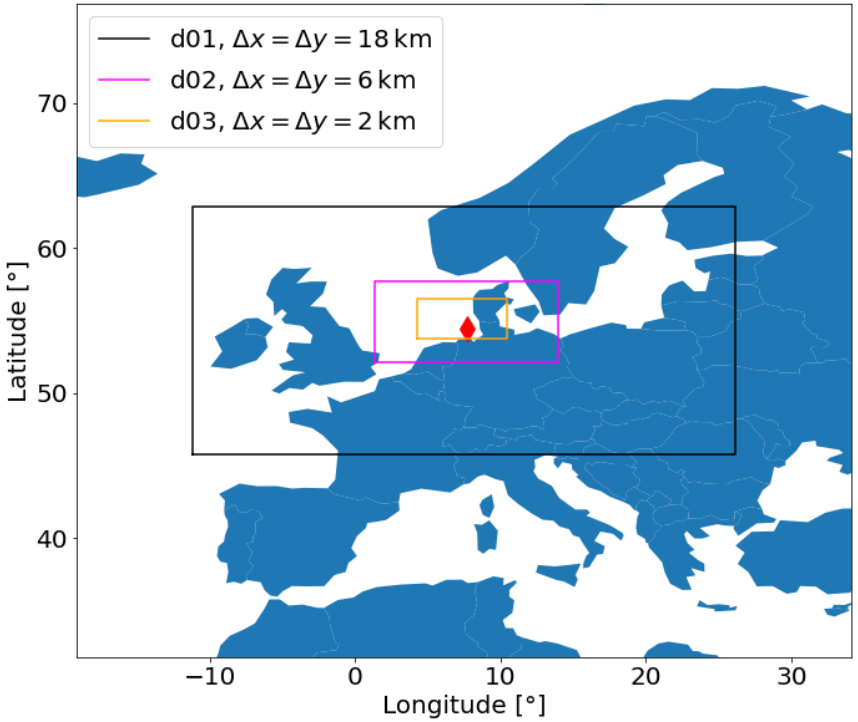


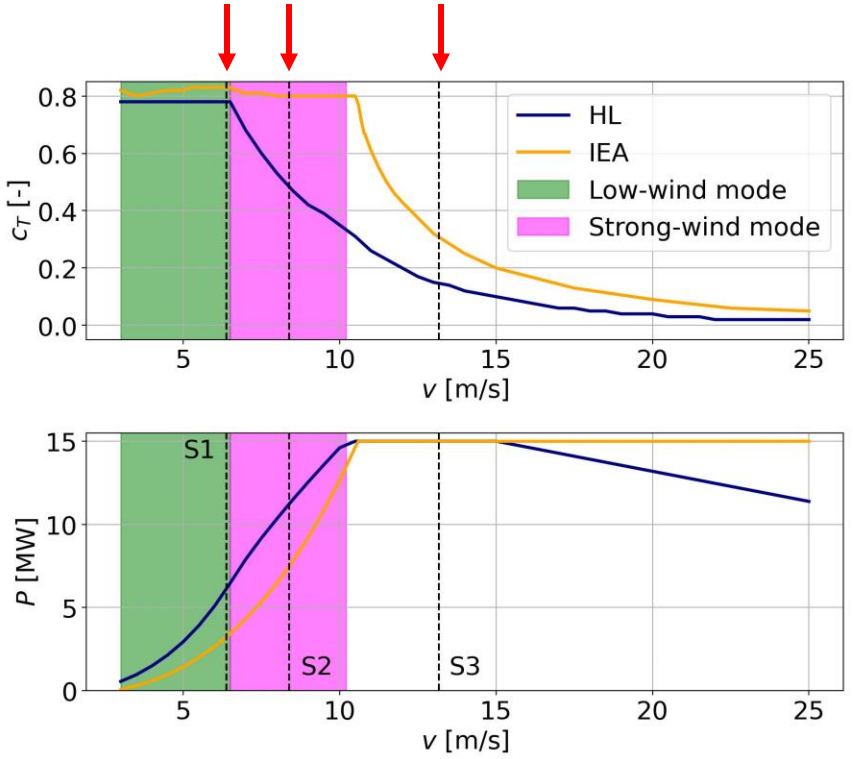
Light wind mode $\left(6.8\ \frac{m}{s}\right)$ Strong wind mode $\left(10.2\ \frac{m}{s}\right)$

Large-scale wake effects on a wind farm level

Mesoscale simulations:

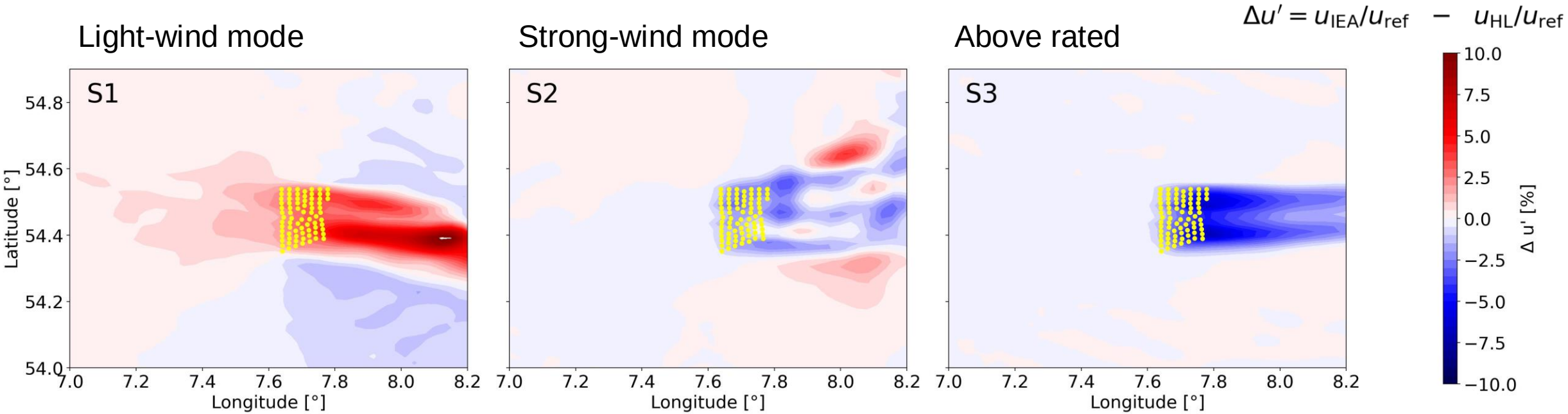
- **W**eather **R**esearch and **F**orecasting model (**WRF**)
- Simulating one entire year
- Comparing IEA 15 MW with Hybrid-Lambda 15 MW
- Same absolute spacing (same power density)





Further info:
Paulsen, Dörenkämper, Steinfeld: *Power production and large-scale wake effects of offshore wind turbines with low specific rating*. JoP: Conf. Series, 2767(9):092060, 2024.

Large-scale wake effects on a wind farm level



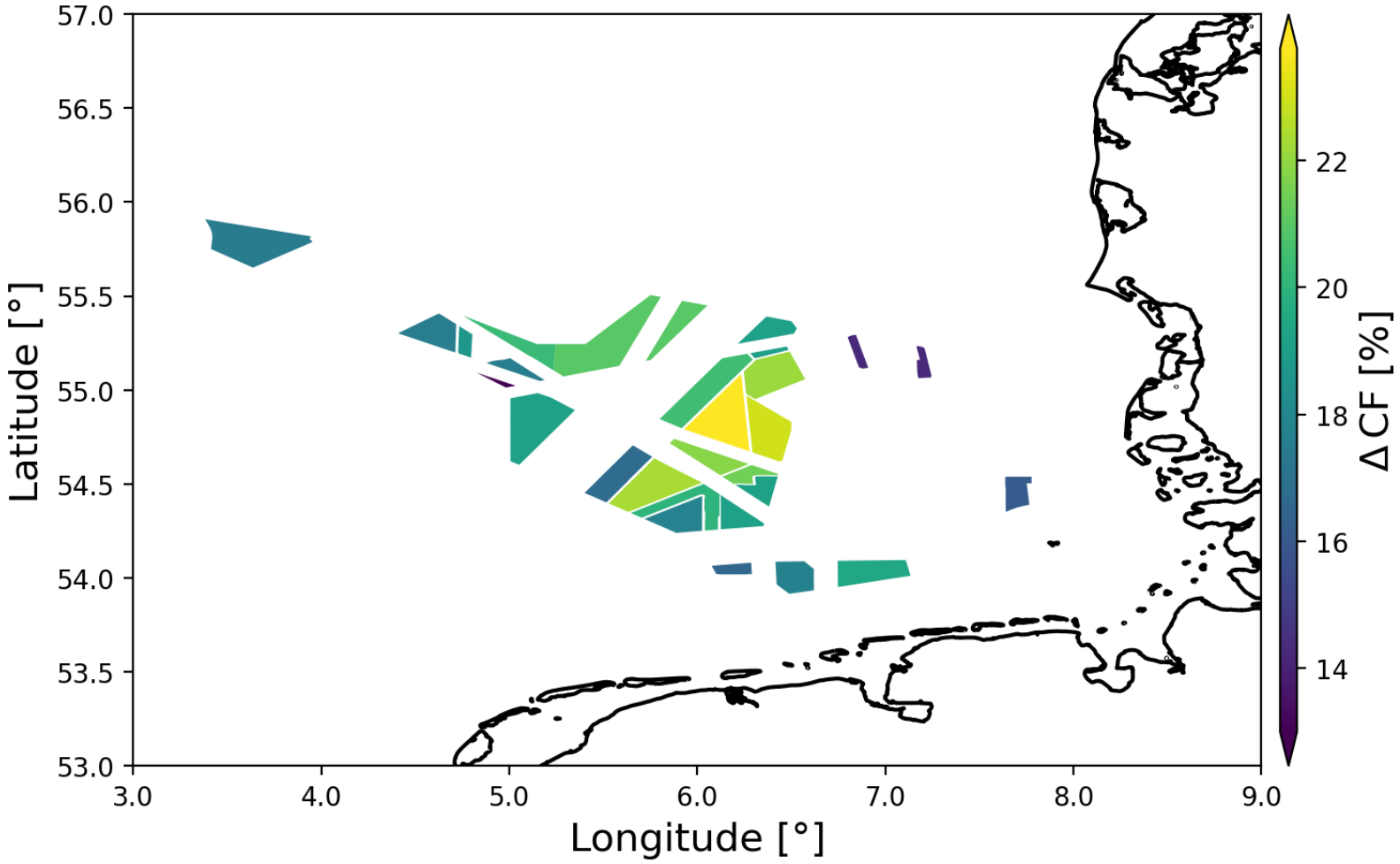
- u = 6.36 ms^{-1}
- Θ = 269.9 °
- P_{HL} / P_{IEA} = 1.86
- Stronger wake deficit for HL farm

- u = 8.78 ms^{-1}
- Θ = 262.1 °
- **P_{HL} / P_{IEA} = 2.00**
- Slightly lower wake deficit for HL farms

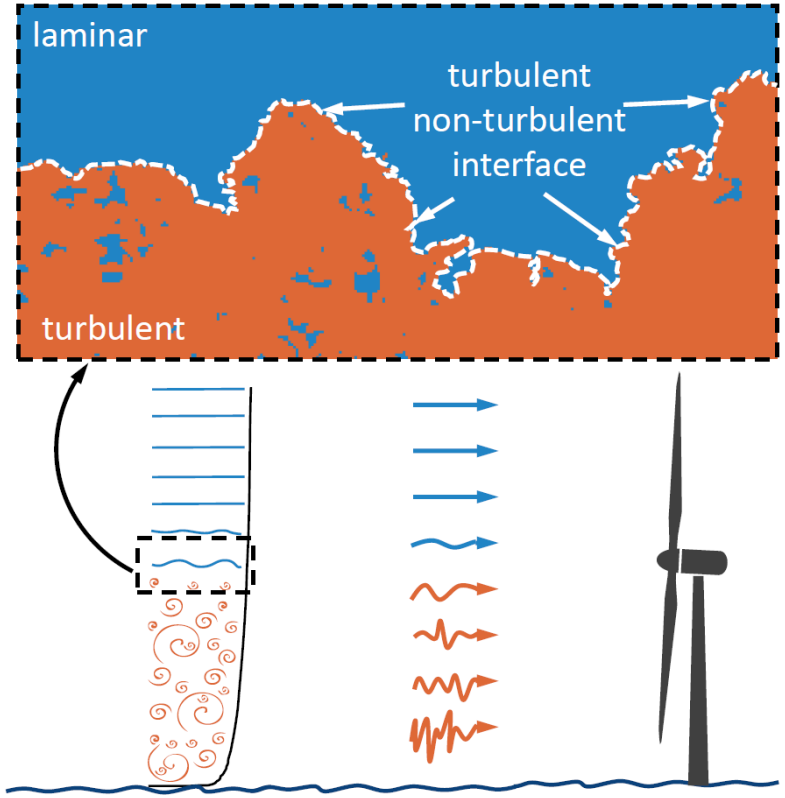
- u = 13.17 ms^{-1}
- Θ = 274.1 °
- P_{HL} / P_{IEA} = 1.00
- Lower wake deficit for HL farm

Large-scale wake effects on a wind farm cluster level

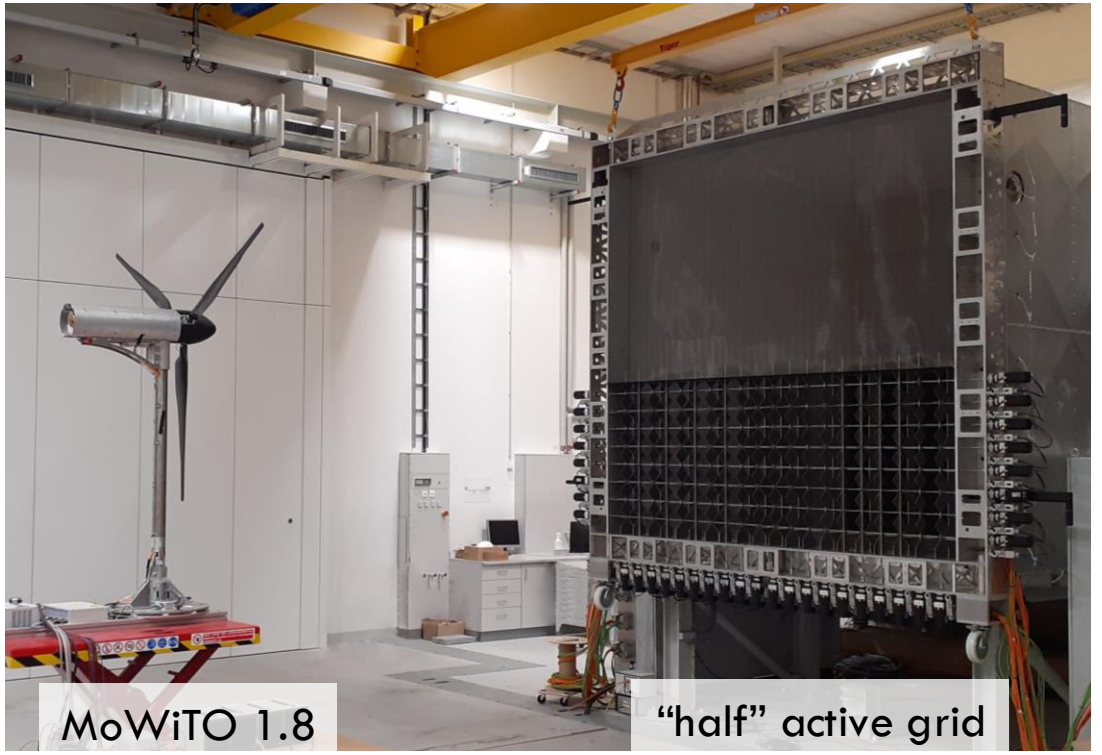
- Difference in capacity factor between IEA and HL wind farm

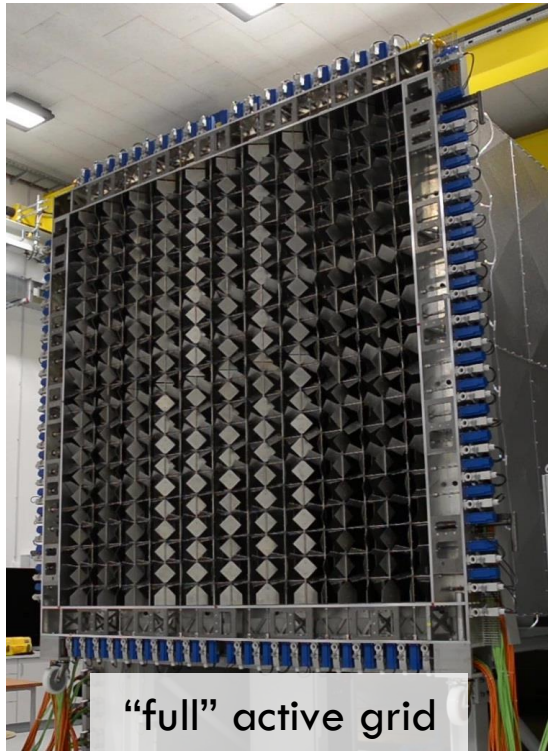


Turbulent-non-turbulent interface in the atmosphere



Neuhaus et al., Wind Energ. Sci., 9, 2024





Further info:
Neuhaus et al.: *Model wind turbine performance in turbulent–non-turbulent boundary layer flow.* JoP: Conf. Series, 2767(9):092060, 2024.

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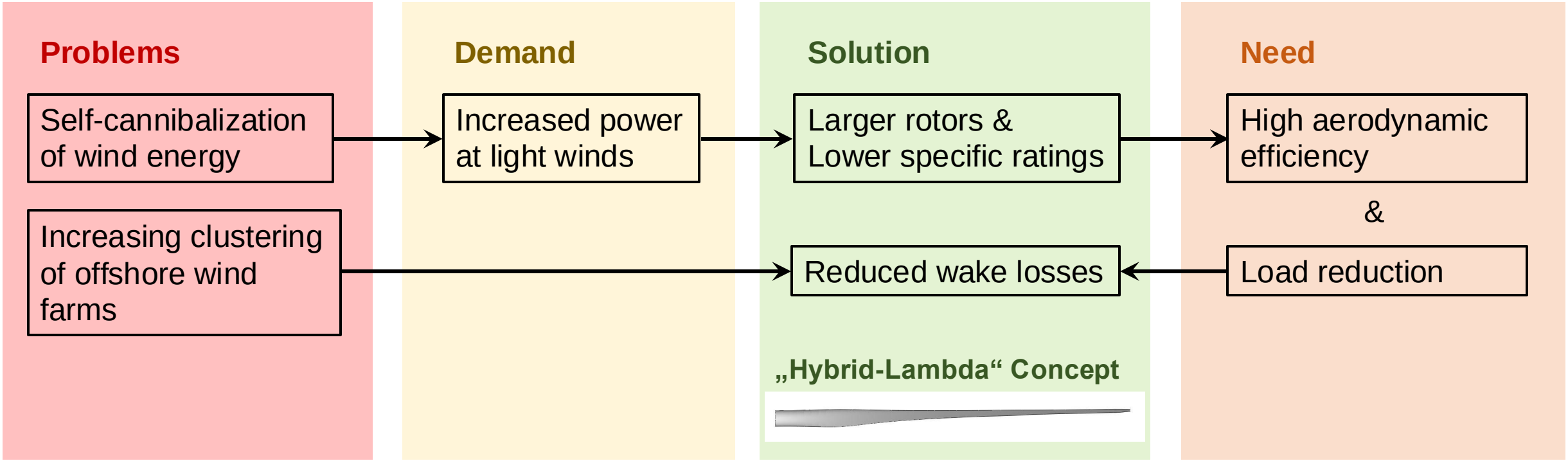
ForWind Center for Wind Energy Research
Bremen Hannover Oldenburg

Conclusions



Thanks for your attention!

contact:
daniel.ribnitzky@uol.de

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Hybrid-Lambda **open-source** simulation model (openFAST, windIO, operational data, etc.)