Technische Universität Braunschweig

IFAS Institut für Flugantriebe und Strömungsmaschinen

Bergen Energy Lab Talk

Layout and Yaw Optimisation of an Offshore Wind Farm

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07.03.2023

Motivation
Performance Optimisation of Offshore Wind Farms

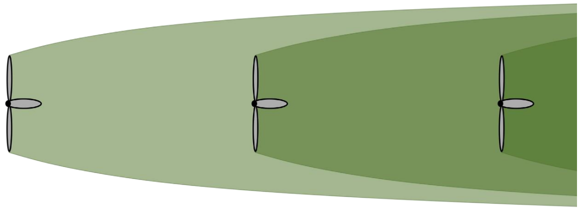
- Planned expansion of offshore wind power by 61% by 2030 in Germany
- Power losses due to wake effects within wind farms
- Wake effects can be modelled analytically
- Wind farms can be optimised with respect to turbine wakes
  - Optimised turbine positioning
  - Innovative control concepts such as yaw angle control

How can wind farm performance be increased through optimised turbine positions and yaw angles?

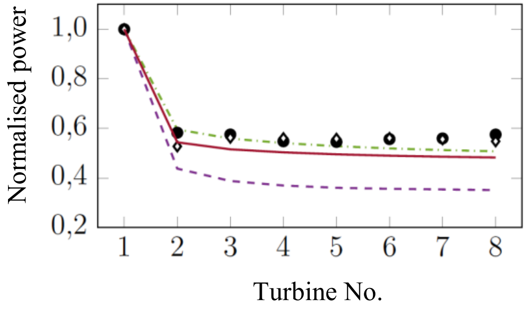
Wind farm Horns Rev 1. [Vattenfall]

Agenda
Performance Pptimisation of Offshore Wind Farms

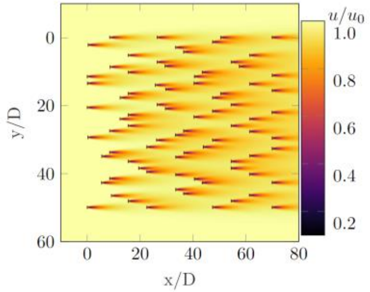
- Wake effects within wind farms
- Analytical modelling of wake effects

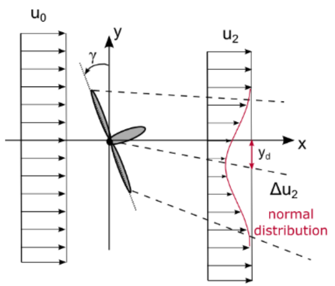


- Validation of proposed tool
- Insight into parameter study

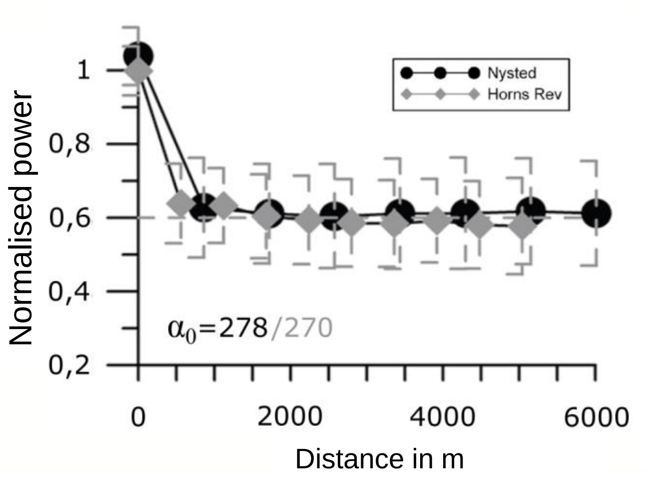


- Optimised wind farm
  - Layout
  - Yaw angles

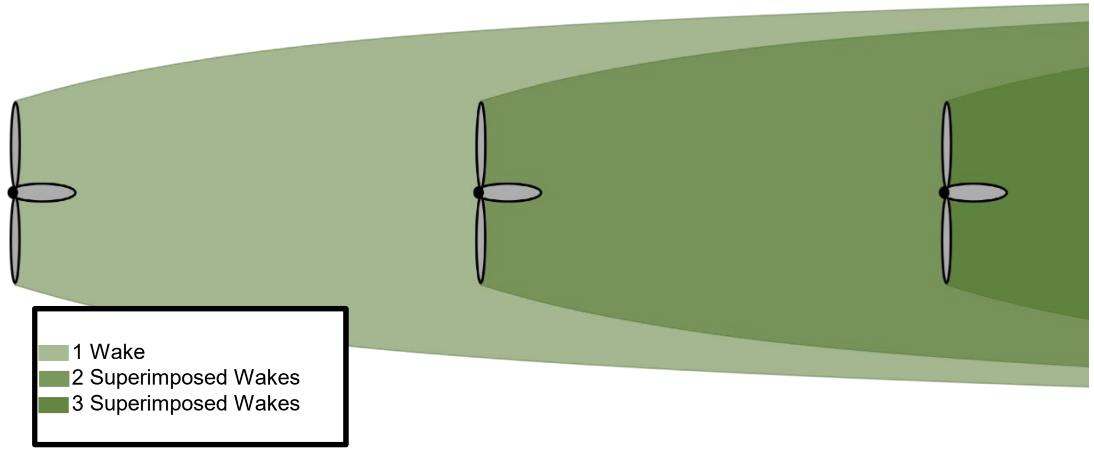




Wake Effects
Power Losses Within a Wind Farm



Power loss within one turbine row [1, Barthelmie et al.]



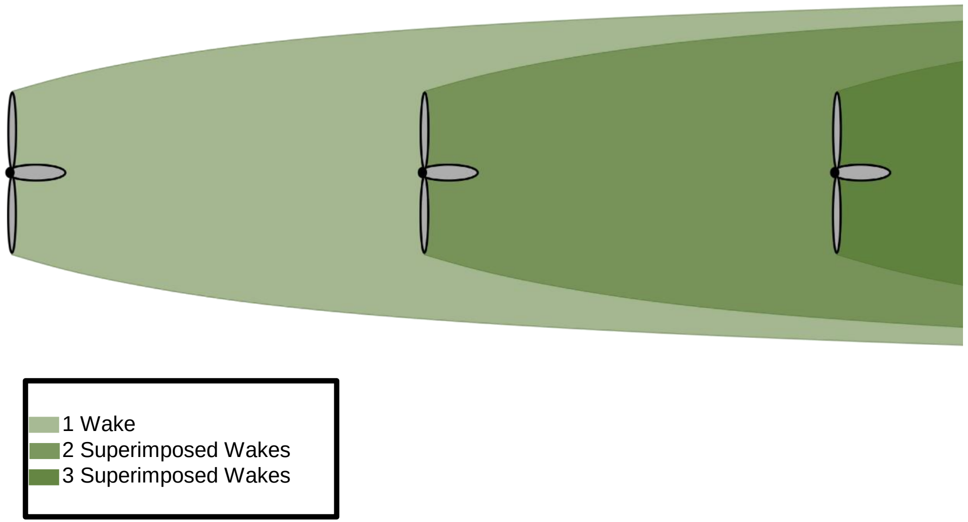
Superimposing wake areas

- Measured performance drop greatest from first to second row
- Subsequently asymptotic course
- Overlapping of several wakes hardly leads to further losses

→ First drop in performance must be reduced

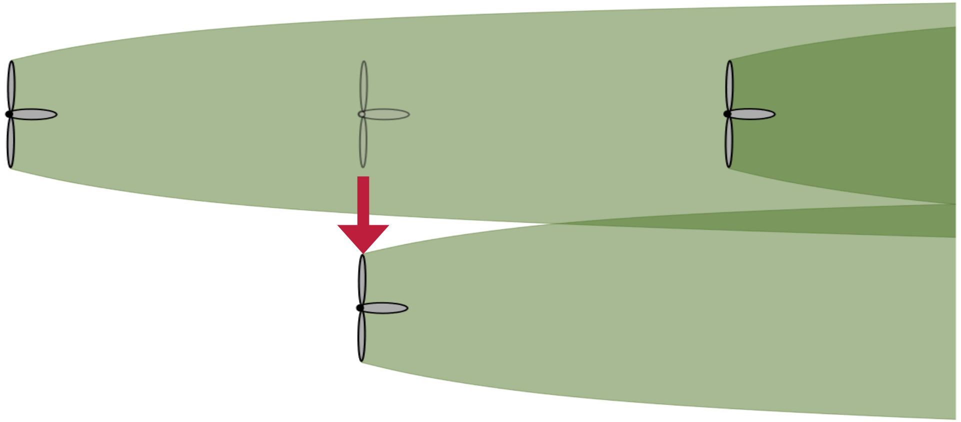
Wake Effects

Proposals

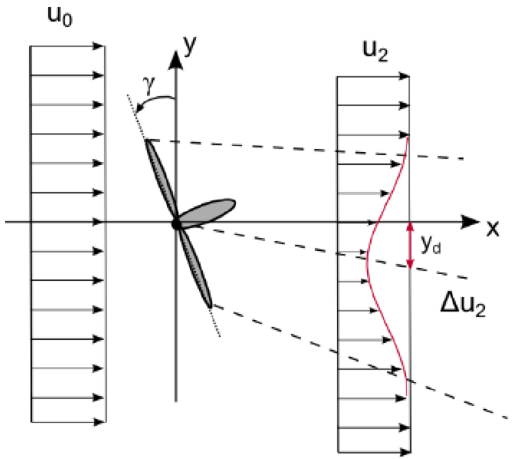


Superimposing wake areas

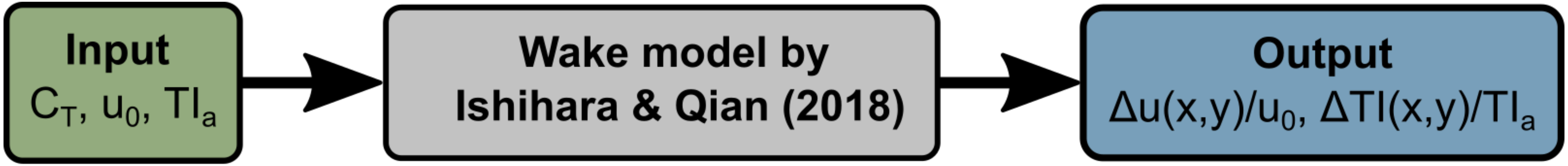
Layout



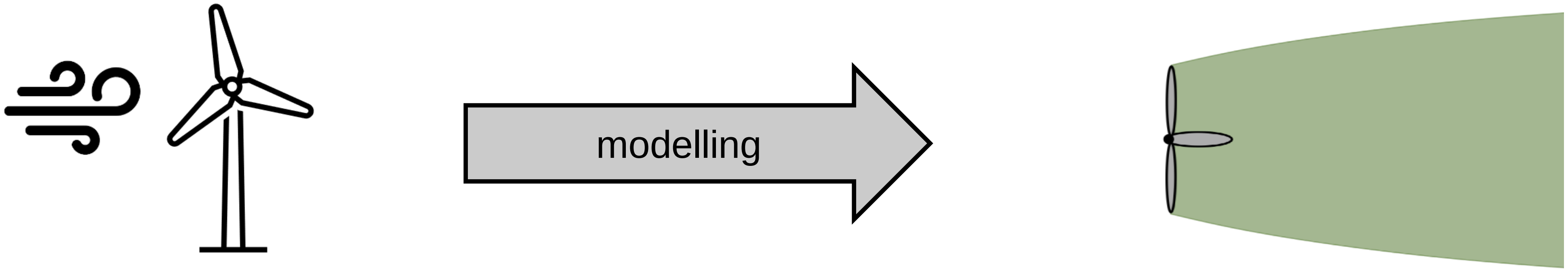
Yaw steering



Analytical Modelling

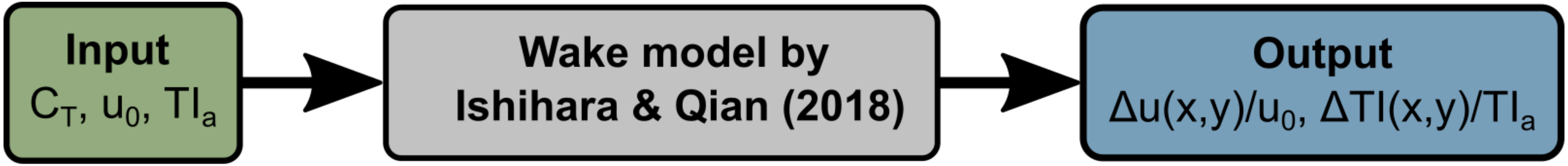


In- and output parameters of the wake model [3, Ishihara et al.]



ambient & turbine data

wind speed & turbulence in wake region



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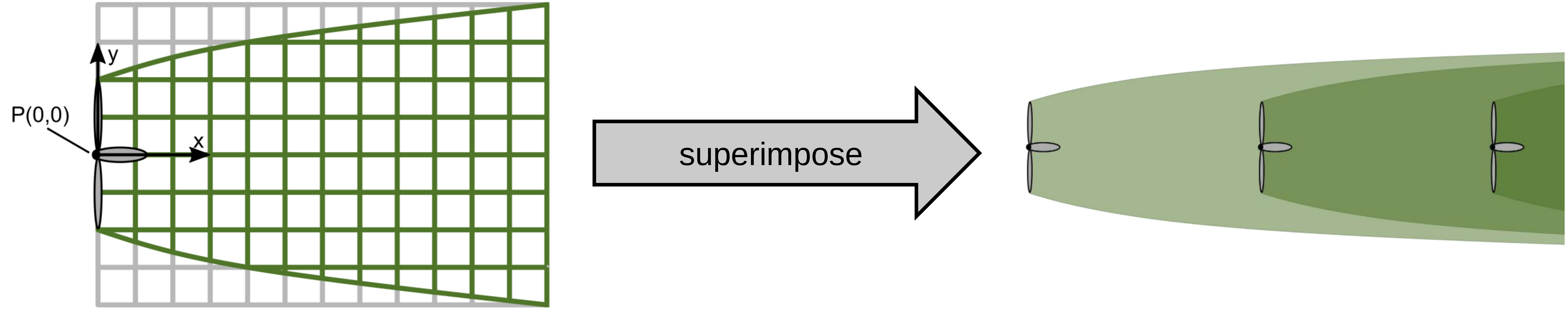
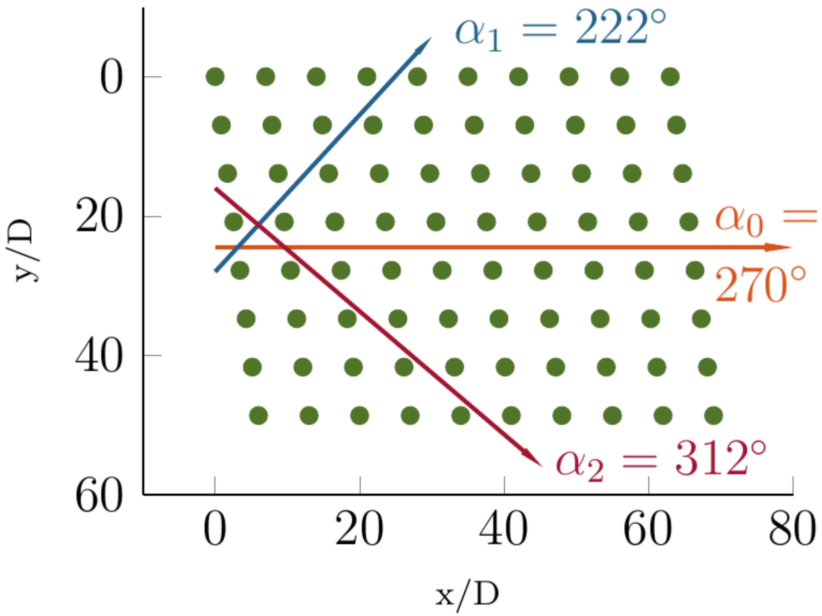


Computation points of the wake model

Superimposed wake areas

Reference Plant

Top view on the Wind Farm: Horns Rev 1 [4, Carsten Ingemann /IND]

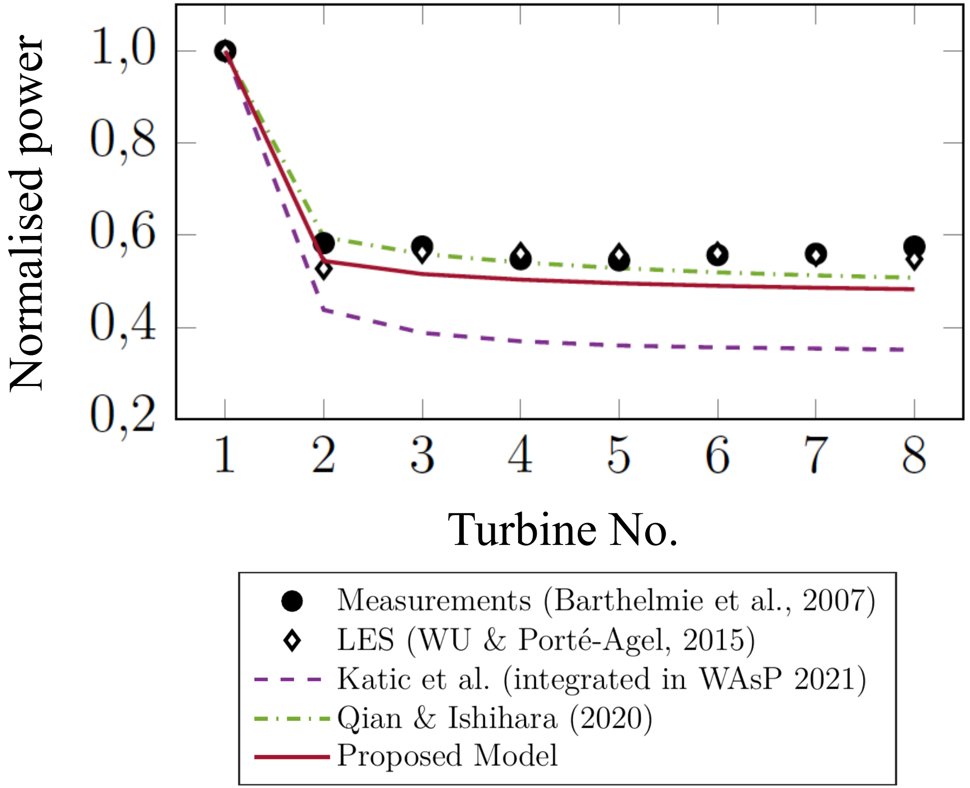


Layout Horns Rev 1 based on [5, Qian et al.]

Wind farm with extensive performance data and comparative studies

Validation
First Main Wind Direction at $\alpha = 270°$

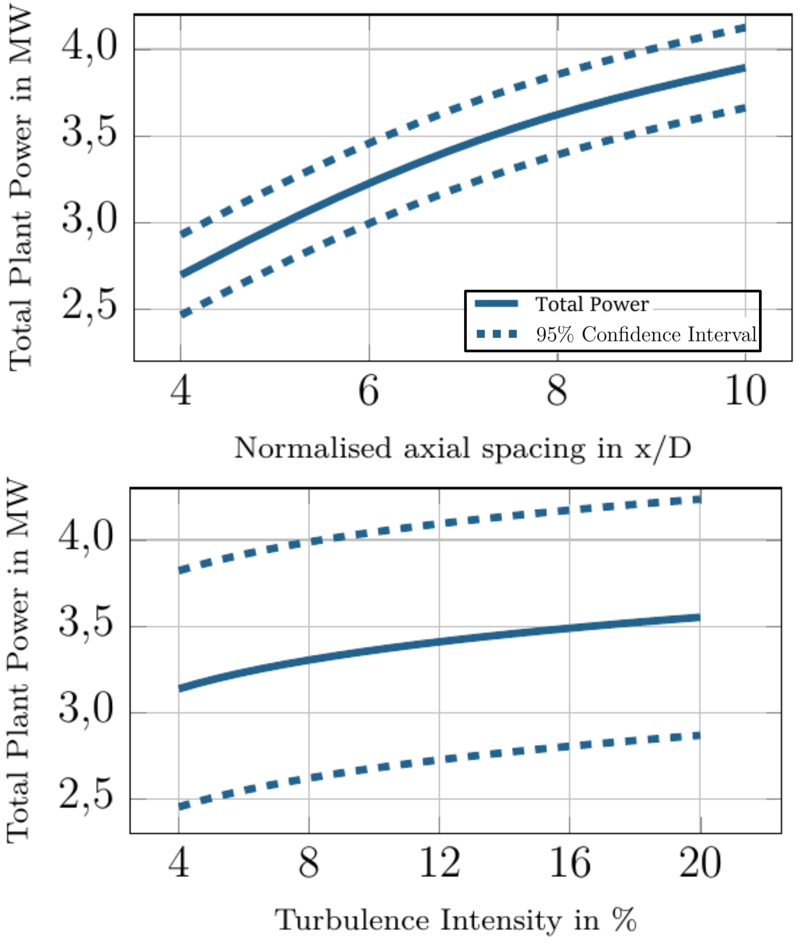
- Power normalised to the yield of the first turbine row
- WAsP planning software as industrial standard
- Deviations in comparison to original data of Qian & Ishihara



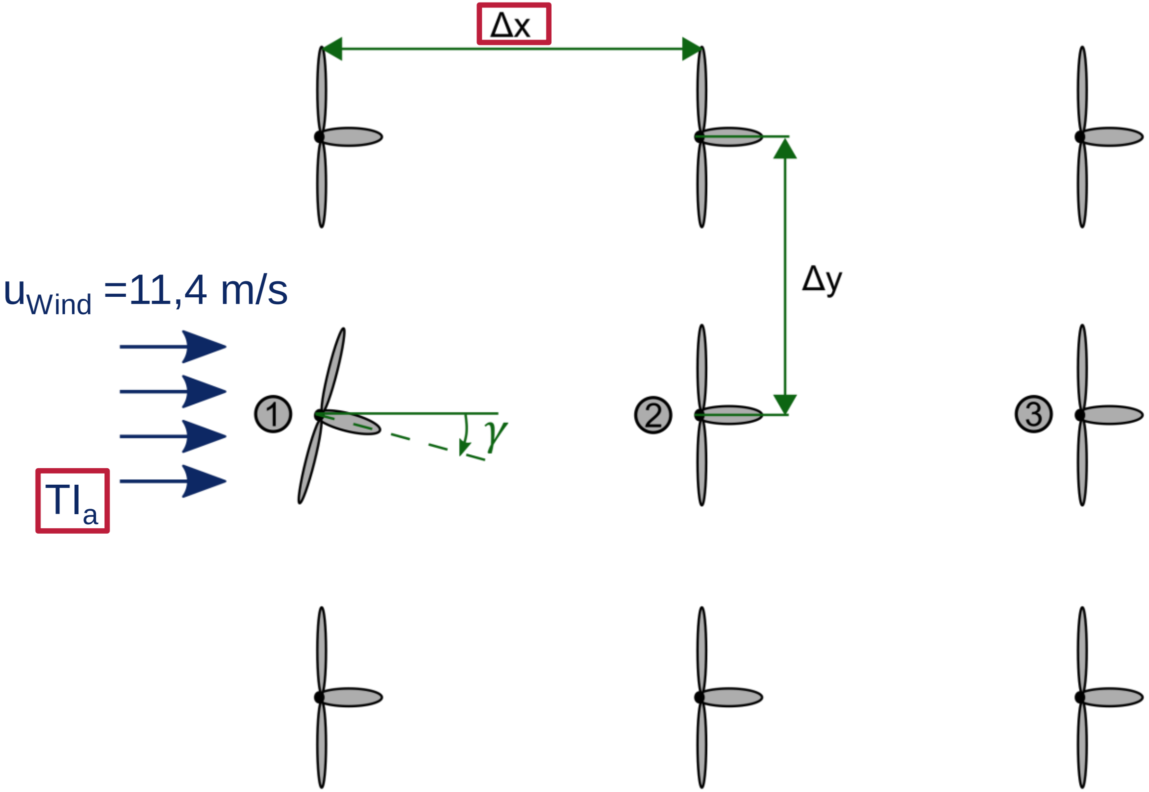
Modelled and measured power of on turbine row
[2, Sukhman et al., submitted to: J. Phys.: Conf. Ser. (2023)]

Study on Wind Farm Performance Parameters

Axial Spacing Δx & Turbulence Intensity TI_a



Impact of Δx and TI_a on the total power [2, Sukhman et al.]

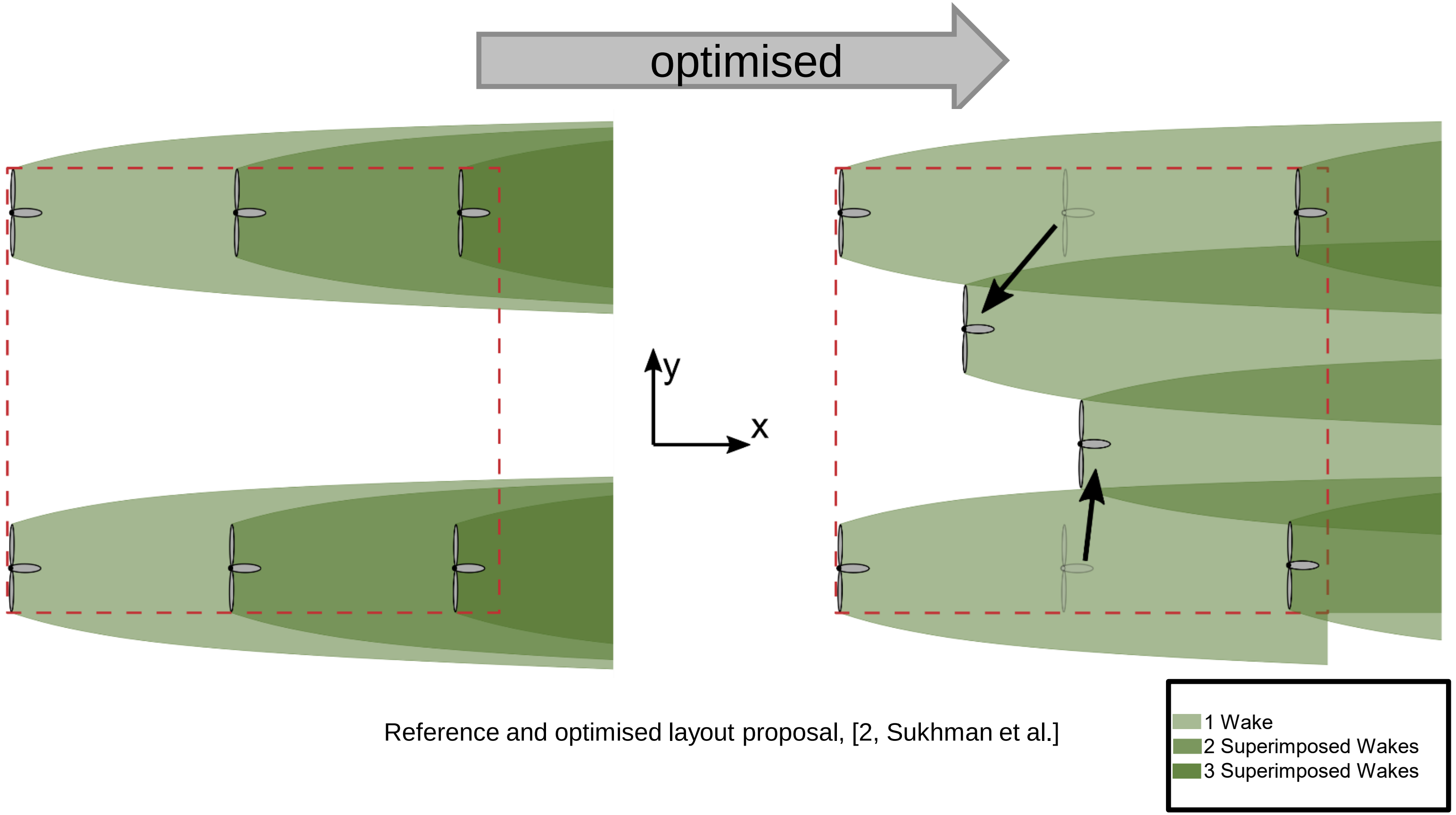


Schematic illustration of the 3x3 wind farm

Conclusion and Optimisation Outlook

- Avoid first shadowing
- If unavoidable:
  Increase axial distance

Diagonal alignment of the turbines to wind direction



Reference and optimised layout proposal, [2, Sukhman et al.]

Study on Wind Farm Performance Parameters
Conclusion and Optimisation Outlook

- Avoid first shadowing
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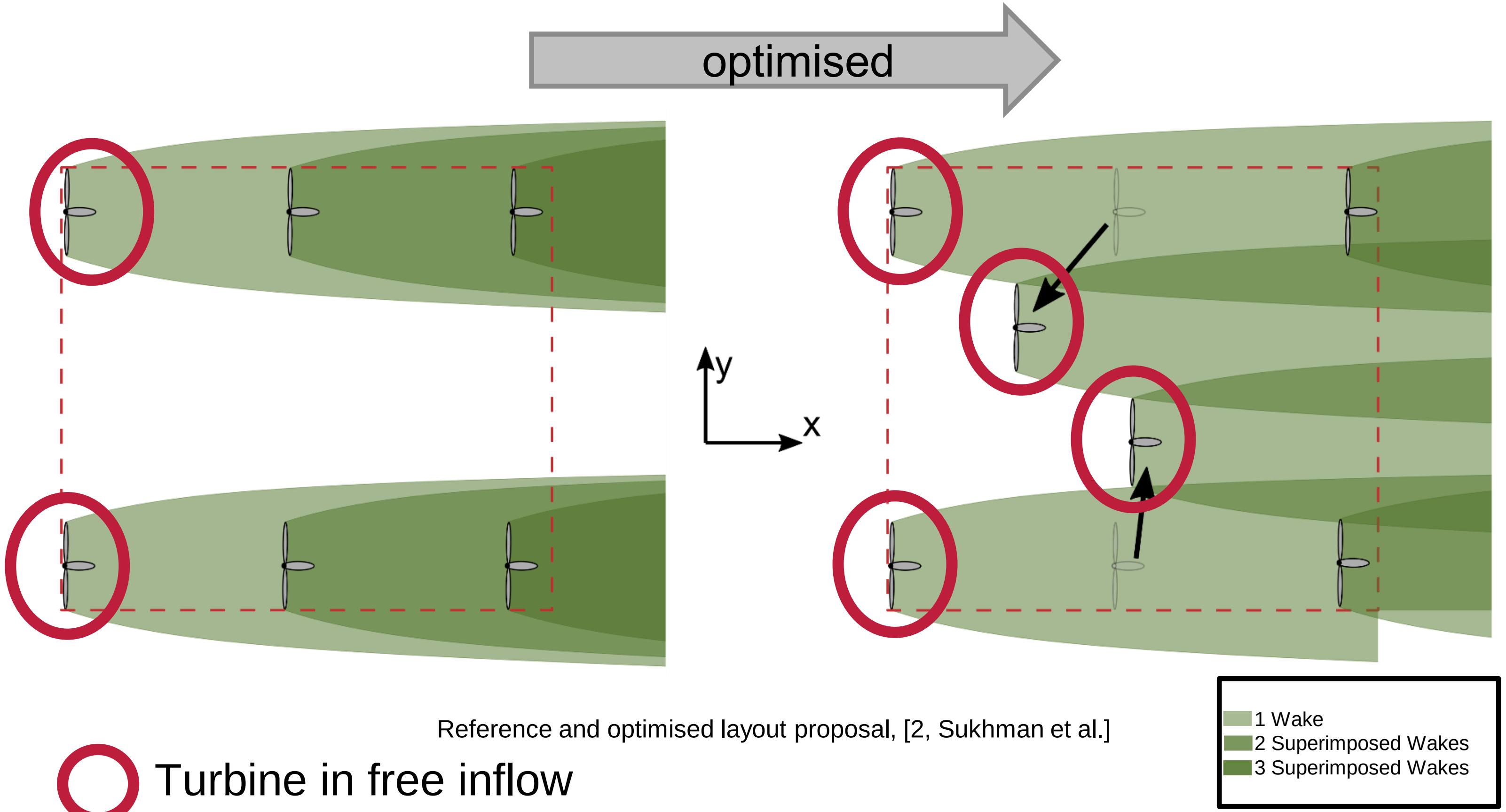
Diagonal alignment of the turbines to wind direction

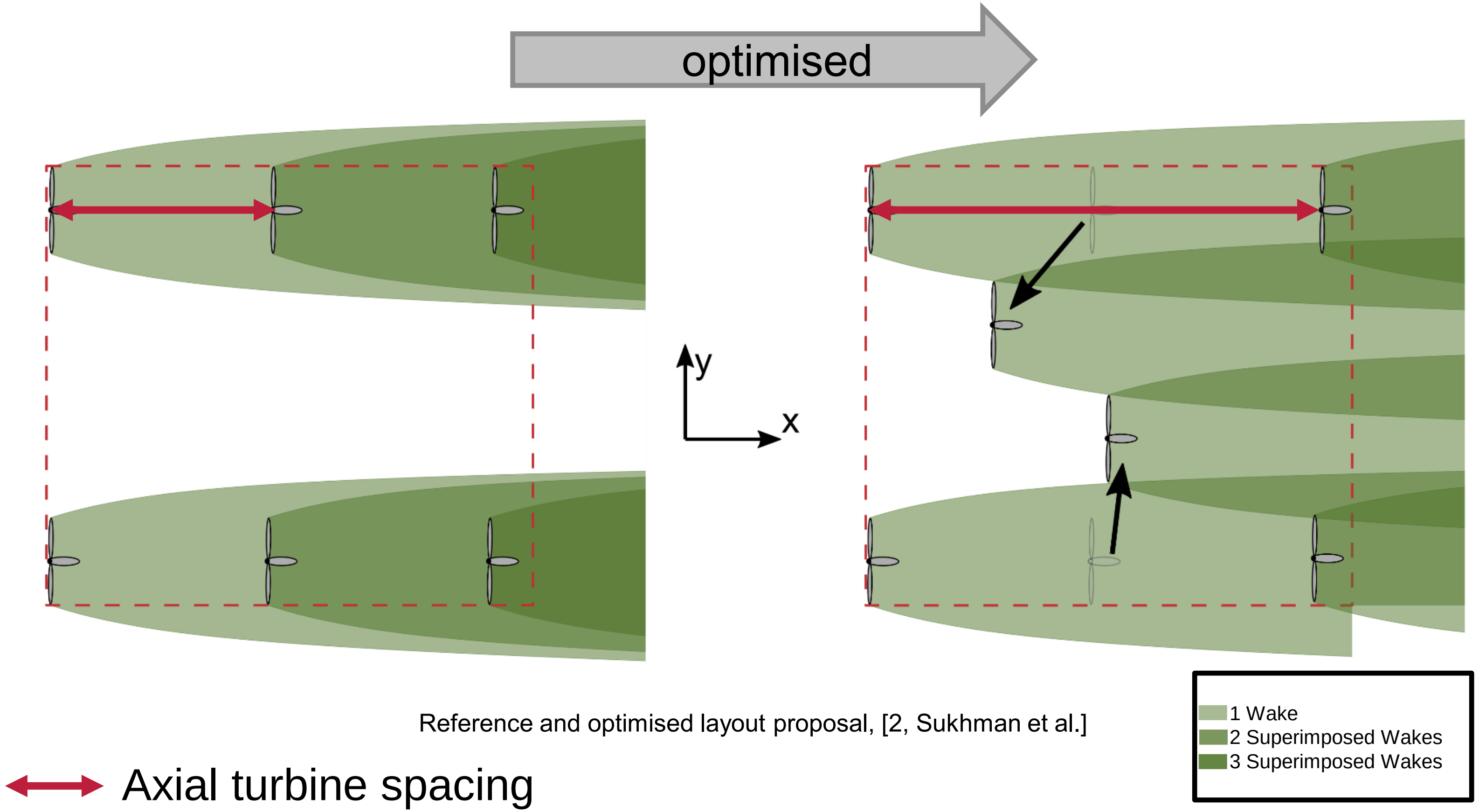


Reference and optimised layout proposal, [2, Sukhman et al.]

Turbine in free inflow

- Avoid first shadowing
- If unavoidable:
  Increase axial distance

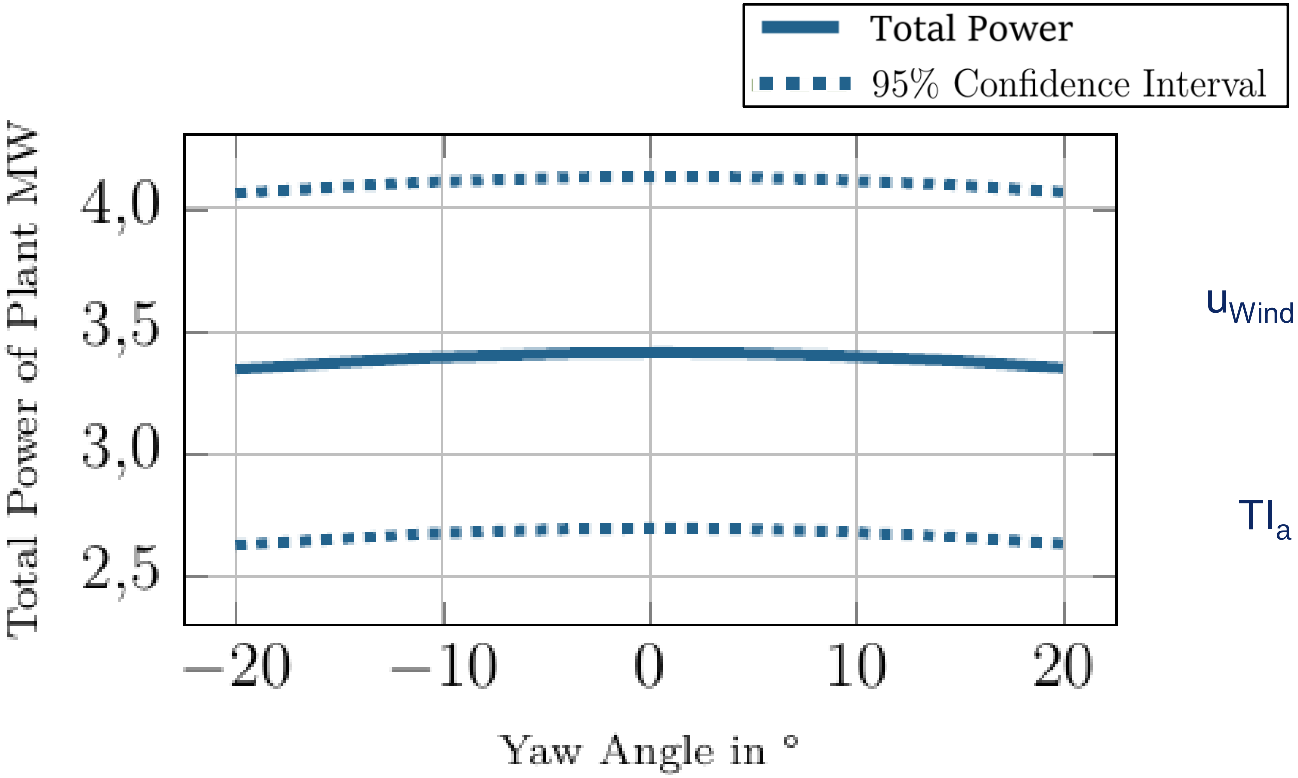
Diagonal alignment of the turbines to wind direction



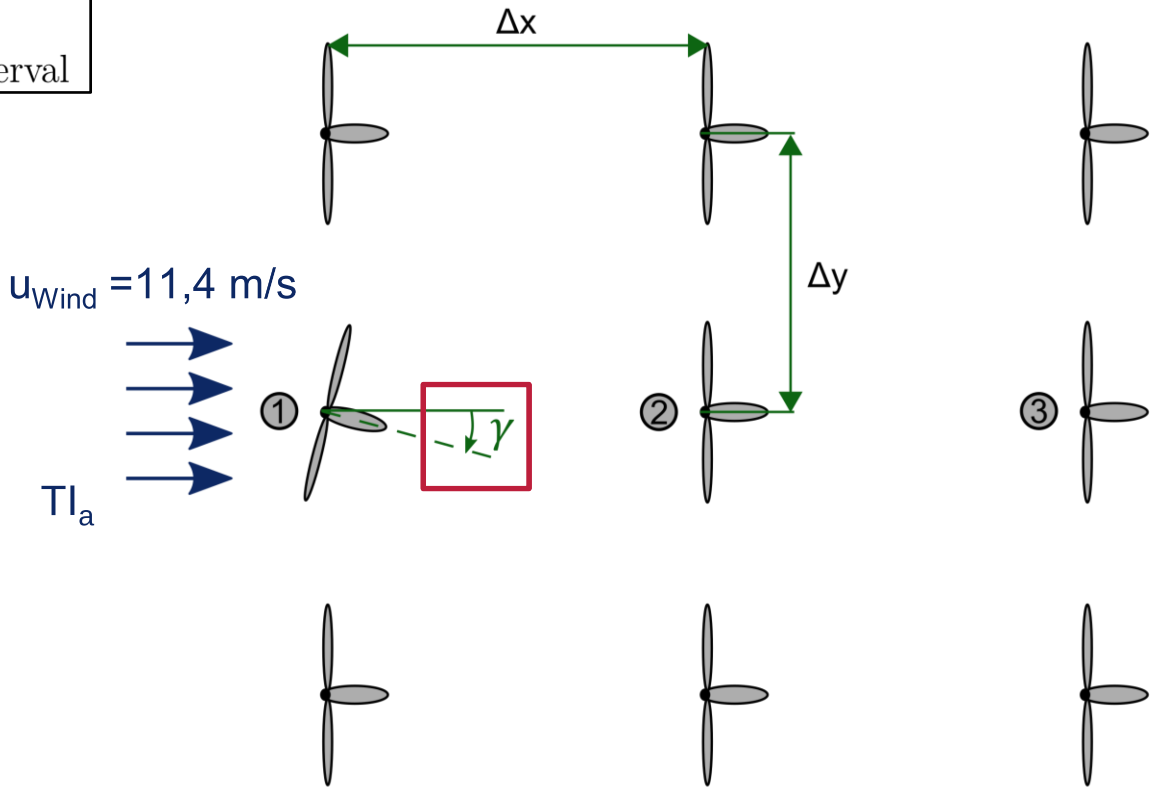
Reference and optimised layout proposal, [2, Sukhman et al.]

Study on Wind Farm Performance Parameters

Yaw Angle γ_1 of Turbine No. 1



Impact of γ_1 on the total power

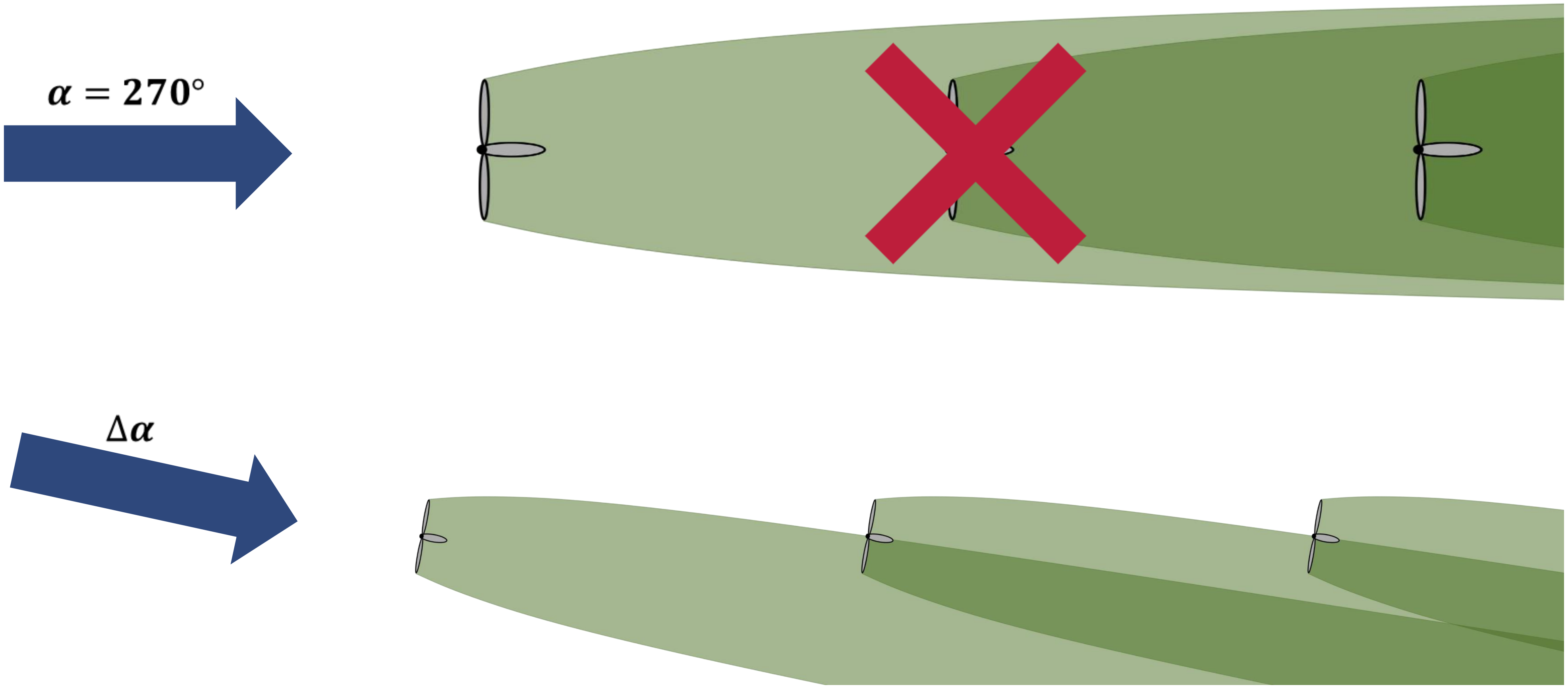


No positive effect on power by yawing the turbine

Schematic illustration of the 3x3 wind farm

Study on Wind Farm Performance Parameters

Conclusion and Optimisation Outlook



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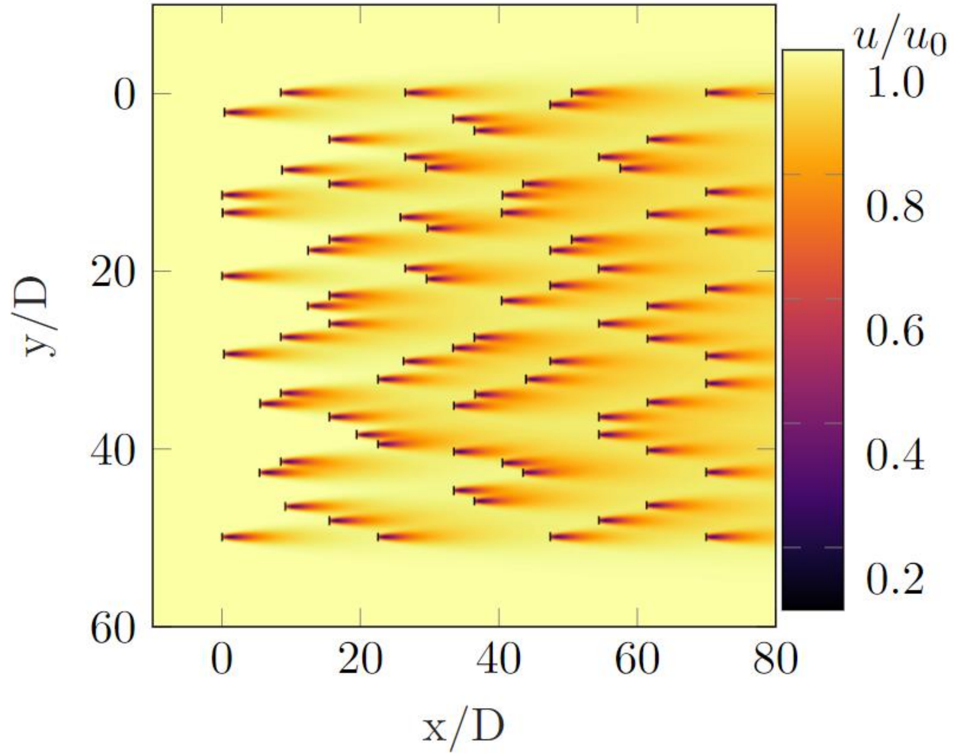
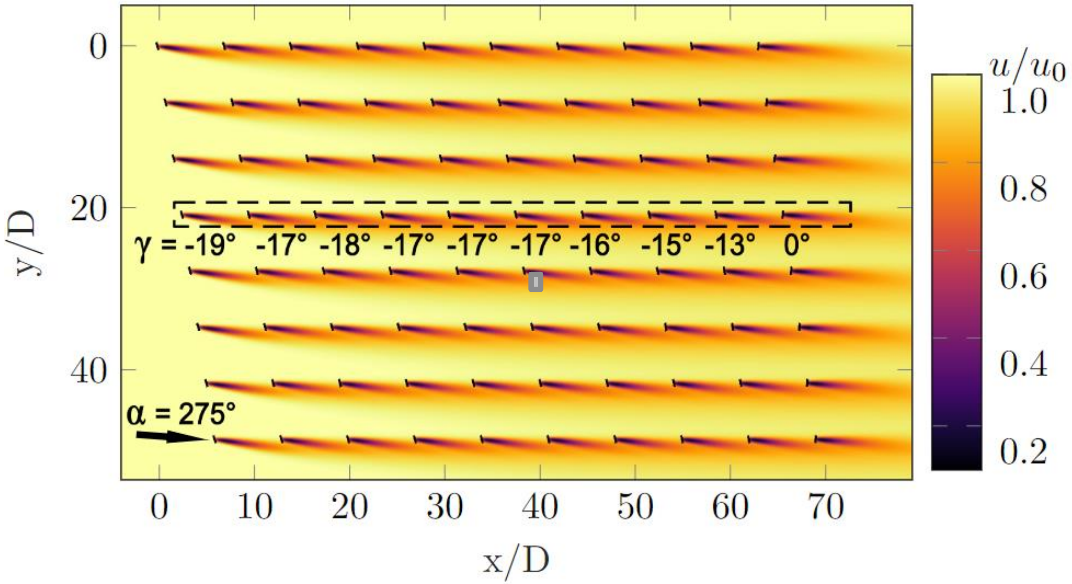
1. Layout Optimisation

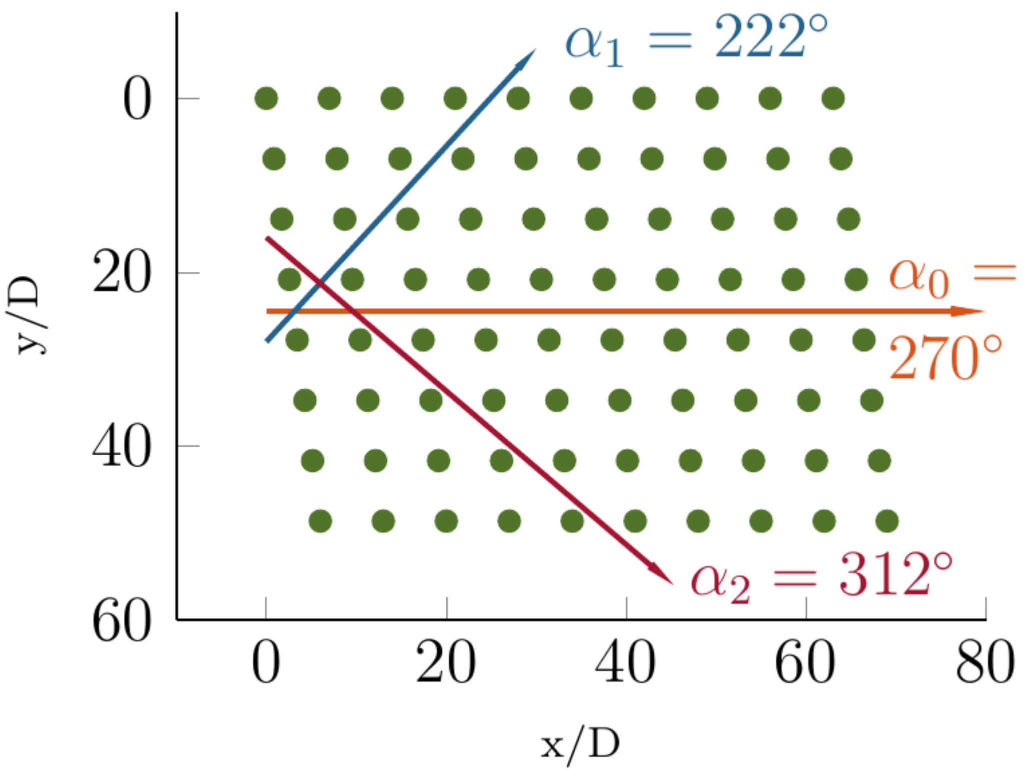


2. Yaw Optimisation



Wind Farm Layout Optimisation
Overview

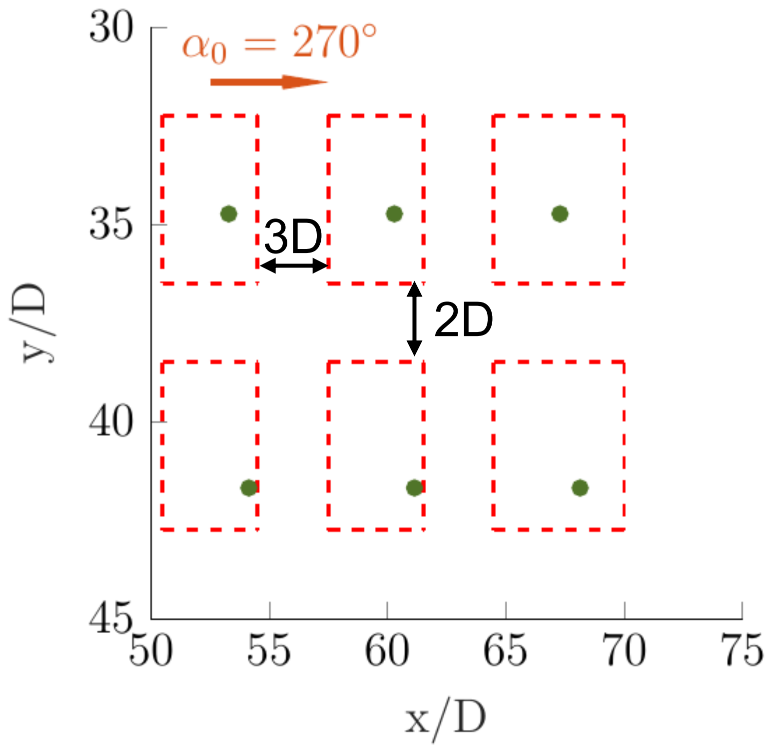
- Gradient-based extreme value search function *fmincon*
- Reference Layout: Horns Rev 1
- Ambient Data
  - $u_0 = 10\,\frac{m}{s}$
  - $TI_a = 6{,}4\%$
- Optimisation carried out for all three main wind directions



Layout Horns Rev 1 based on [5, Qian et al.]

Wind Farm Layout Optimisation
Structure

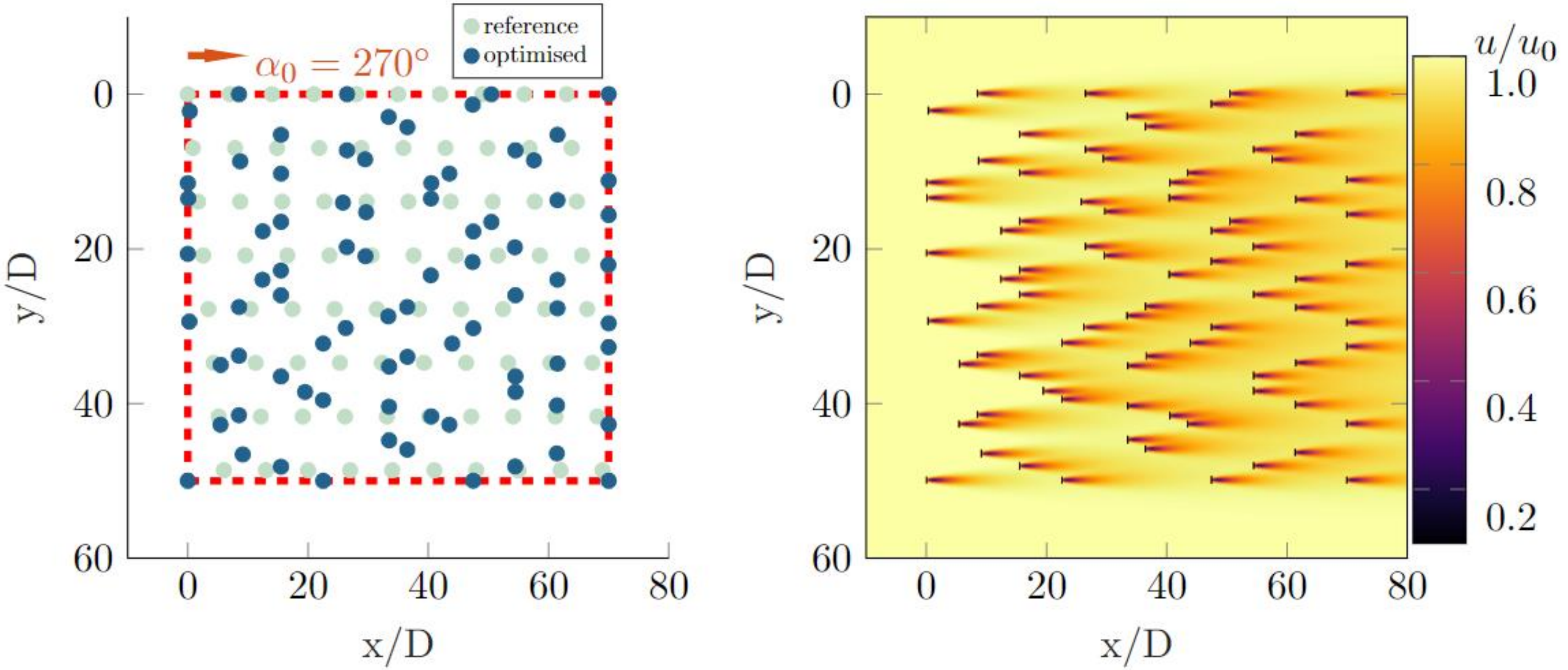
- Gradient-based extreme value search function *fmincon*
- Reference Layout: Horns Rev 1
- Ambient Data
  - $u_0 = 10\,\frac{m}{s}$
  - $TI_a = 6{,}4\%$
- Optimisation carried out for all three main wind directions
- Definition of position boundaries



Boundaries of turbine positions [2, Sukhman et al.]

Wind Farm Layout Optimisation
First Main Wind Diraction $\alpha = 270°$

Clearly visible, diagonal alignment of the turbines in relation to the inflow

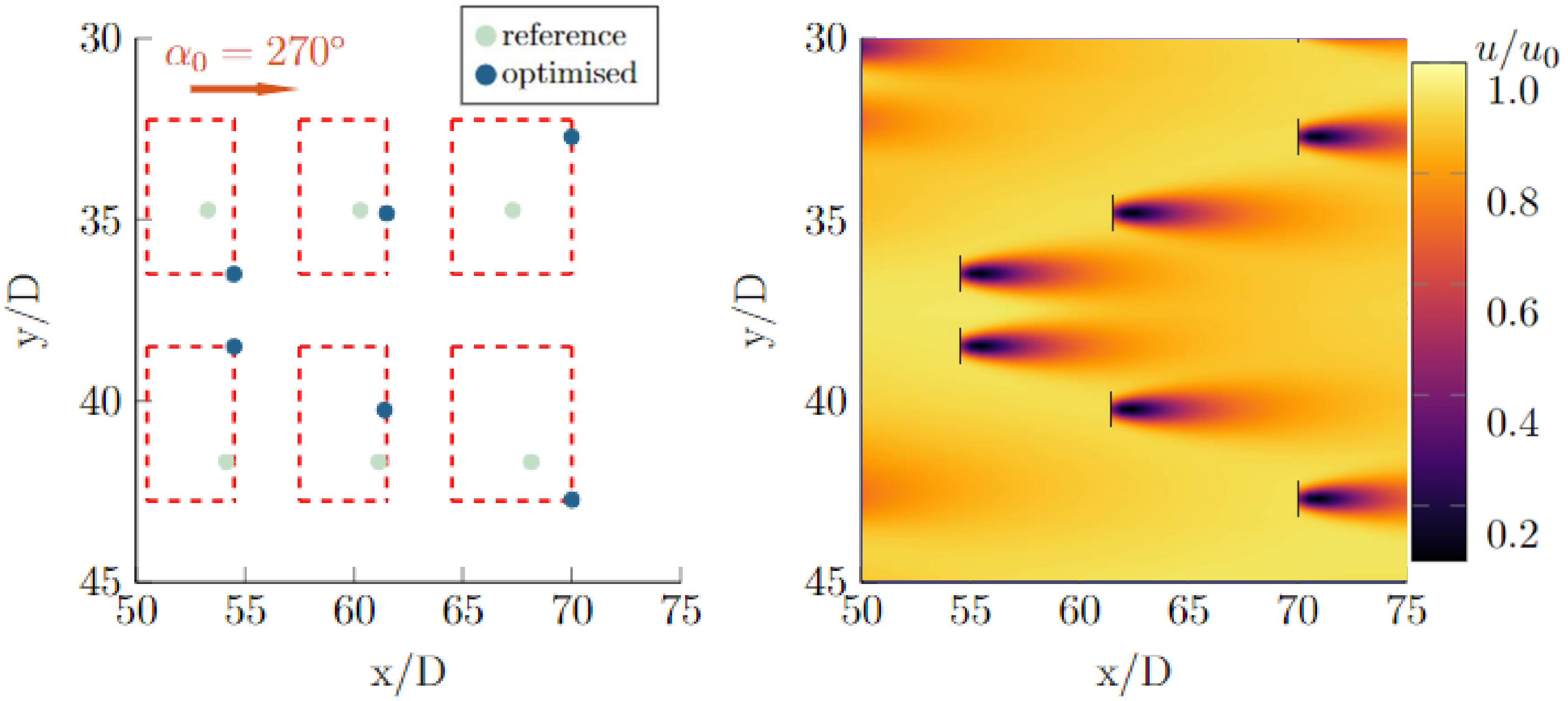


Optimal layout for main wind direction. Left schematic layout, right velocity distribution. [2, Sukhman et al.]

Wind Farm Layout Optimisation

First Main Wind Diraction $\alpha = 270°$, Enlarged View

Clearly visible, diagonal alignment of the turbines in relation to the inflow

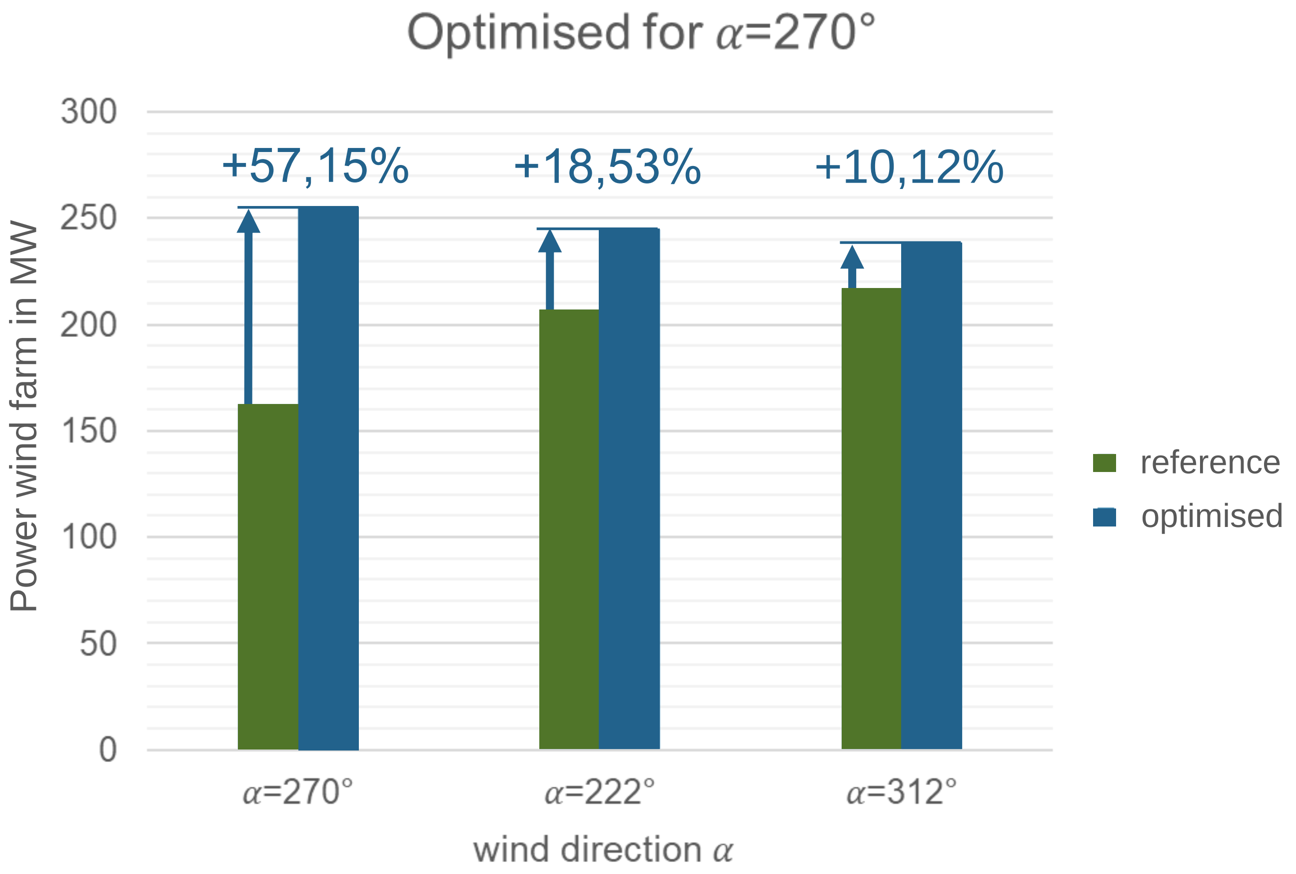


Section of the optimal layout. Left schematic layout, right velocity distribution.

Wind Farm Layout Optimisation

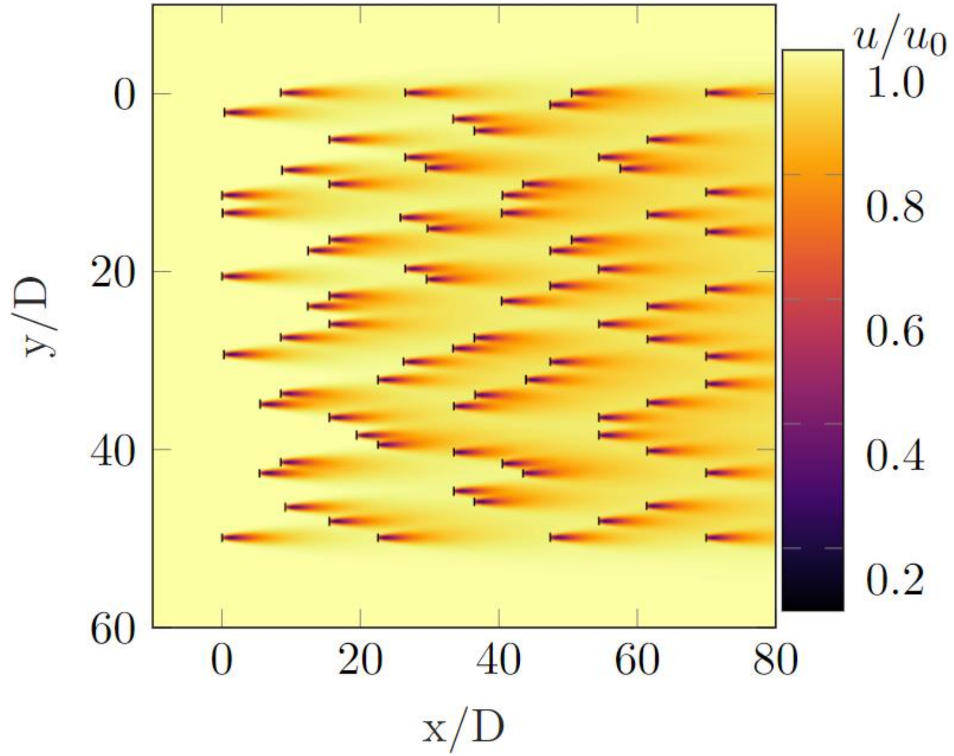
Results Layout Optimisation First Main Wind Direction

- Clear increase in performance from an aerodynamic point of view
- Visible dependence on wind direction α

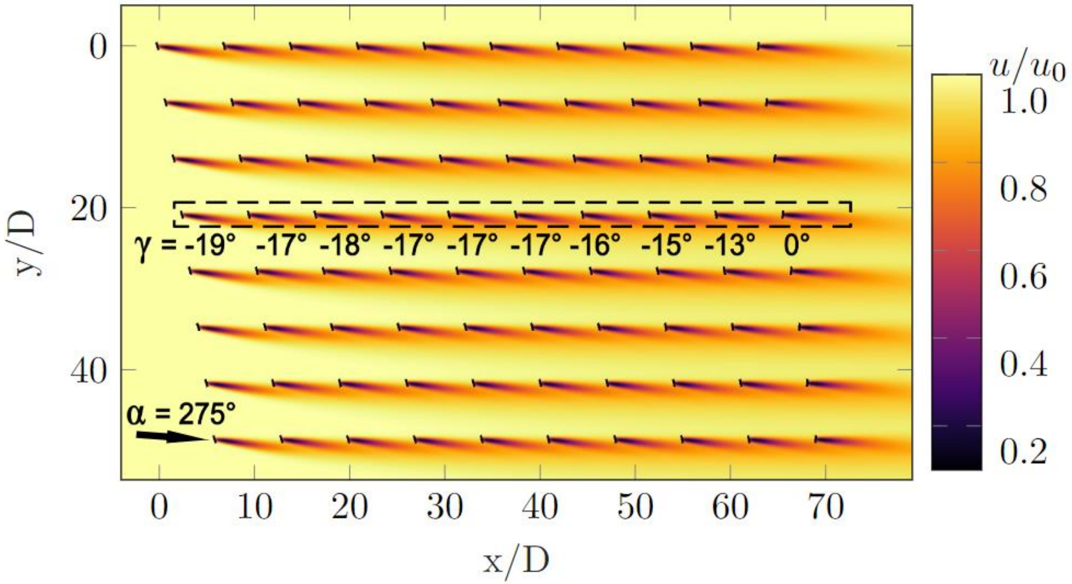


Increased performance due to optimised layout

1. Layout Optimisation



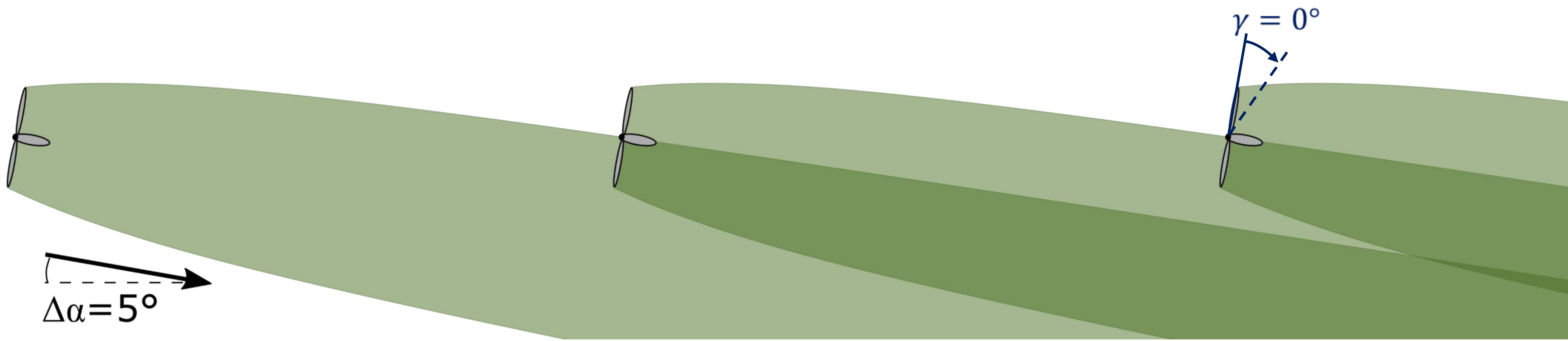
2. Yaw Optimisation



Wind Farm Yaw Angle Optimisation

Retrospect and Structure

- Wake steering potential off main wind directions
- Layout: Horns Rev 1
- Inclined inflow by $\Delta\alpha = 5°$

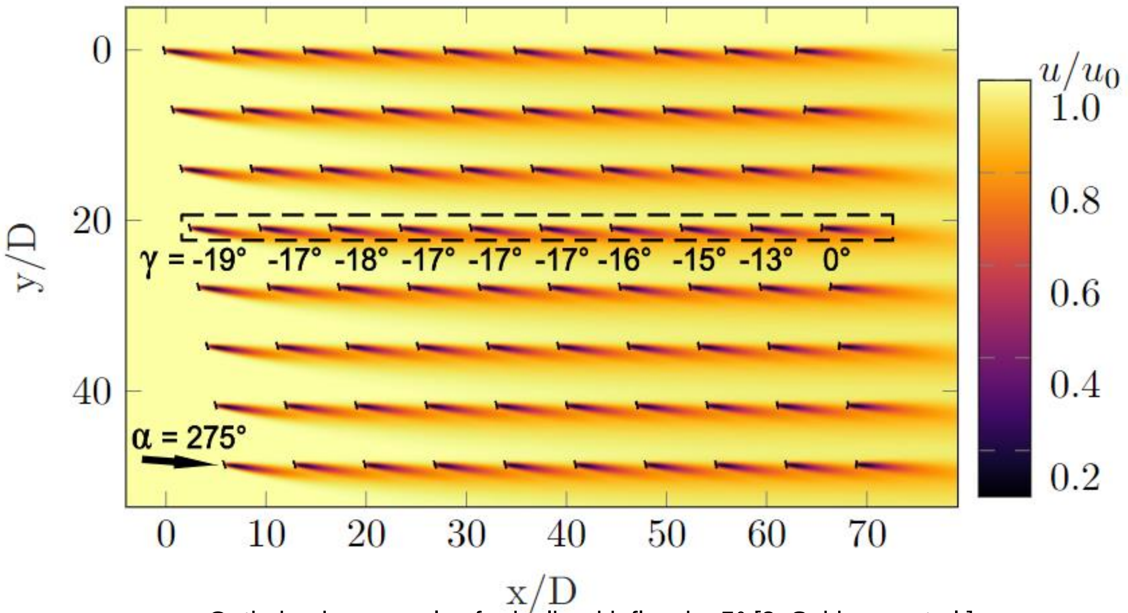


Wake areas with inclined flow of the wind farm [2, Sukhman et al.]

Wind Farm Yaw Angle Optimisation

Results for Inclinded Inflow $\alpha = 275°$

- Power increase possible with yaw angle control for inclined inflow
- Consideration of the wind direction absolutely necessary
- Structural mechanics not considered



Optimised yaw angles for inclined inflow by 5° [2, Sukhman et al.]

Optimised for wind direction $\alpha = 275°$		
$P_{\text{reference}}$	$P_{\text{optimised}}$	ΔP_{total}
196,317 MW	209,500 MW	+6, 29 %

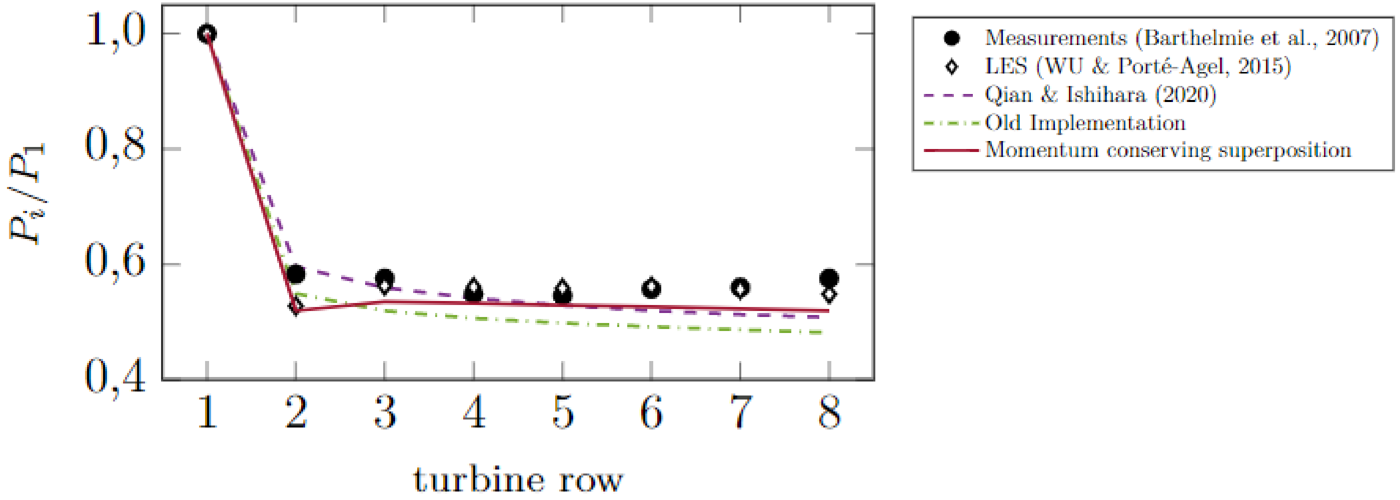
Predicted performance increase through yaw angle optimisation [2, Sukhman et al.]

Conclusion & Ongoing Work

- Development of an analytical computation tool in MATLAB
  - Implementation of the Wake Model of Qian & Ishihara (2020)

- Validation using existing data on the Horns Rev 1 wind farm
  - Good agreement with measured data compared to the benchmark model
  - Potential for expansion of the model

60 x Faster



Momentum conserving superposition [8, Zong, Porté-Agel]

Offshore wind turbines [6, EDF Renewables]

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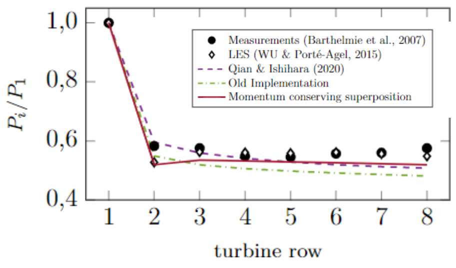

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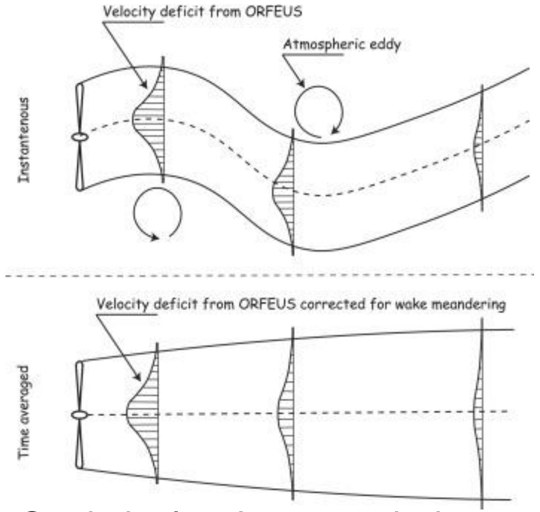
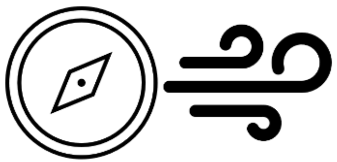


Statistical wake meandering model [9, Braunbehrens, Segalini]

Offshore wind turbines [6, EDF Renewables]

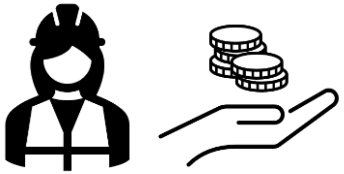
Conclusion & Ongoing Work

- Yield increase through layout optimisation shows high potential
- Yaw angle control interesting when operating off main wind directions
- Factors to include:



wind direction

turbine loads



maintenance
& costs

Offshore wind turbines [6, EDF Renewables]

Thank you!

Horns Rev 1 [Vattenfall]

Image Sources

[1] Barthelmie, R. J., Pryor, S. C., Frandsen, S. T. et al.: „Quantifying the Impact of Wind Turbine Wakes on Power Output at Offshore Wind Farms“. In: Journal of Atmospheric and Oceanic Technology 27(8) (2010), 1302–1317.

[2] Sukhman, D., Lück, S., Göing, J. et al.: „Layout and yaw optimisation of an offshore wind farm through analytical modelling”. Submitted to: Journal of Physics: Conference Series (2023).

[3] Ishihara, T. & Qian, G.-W.: „A new Gaussian-based analytical wake model for wind turbines considering ambient turbulence intensities and thrust coefficient effects“. In: Journal of Wind Engineering and Industrial Aerodynamics 177 (2018), 275–292.

[4] https://energiwatch.dk/Energinyt/Renewables/article13013824.ece, last visited 06.03.2023.

[5] Qian, G.-W. & Ishihara, T.: „Wind farm power maximization through wake steering with a new multiple wake model for prediction of turbulence intensity“. In: Energy 220 (2020), 119680.

[6] https://www.edf-renouvelables.com/en/project-development/offshore-wind/, last visited 17.07.2022

[7] Zong, H. & Porté-Agel F.: „A momentum-conserving wake superposition method for wind farm power prediction“. In: Journal of Fluid Mechanics 889 (2020), A8.

[8] Braunbehrens, R. & Segalini, A.: „A statistical model for wake meandering behind wind turbines“. In: Journal of Wind Engineering & Industrial Aerodynamics 193 (2019), 103954