NTNU

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Experimental testing of induction based control strategies for wind farm optimization

PhD cand. Jan Bartl

Prof. Lars Sætran

Fluid Mechanics Group
Department of Energy and Process Engineering (EPT)
Norwegian University of Science and Technology (NTNU)

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NOWITECH
CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Outline

1. Motivation
2. Methods
3. Theory: *wake control*
4. Results
5. Discussion & future work

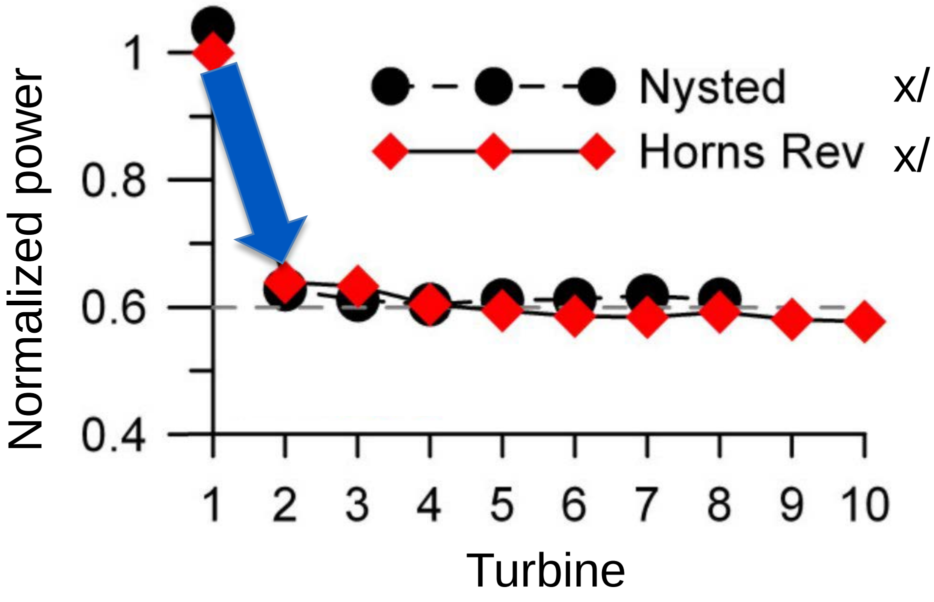
Motivation

Wake effects in a wind farm

Picture source: Hasager et al., ”Wind Farm Wake: The Horns Rev Photo Case”, Energies 2013,
Picture courtesy: Vattenfall

Motivation

Normalized power at Horns Rev and Nysted
for wind directions of full wake interaction



x/D = 10.3 (278 ± 2.5°)
x/D = 7.0 (270 ± 2.5°)

Graph reproduced from:
Barthelmie et al. "Modelling the impact of wakes on power output at Nysted and Horns Rev." EWEC, 2009.

⇨ Biggest power drop (~35%) between first and second row

Methods: wind tunnel experiments

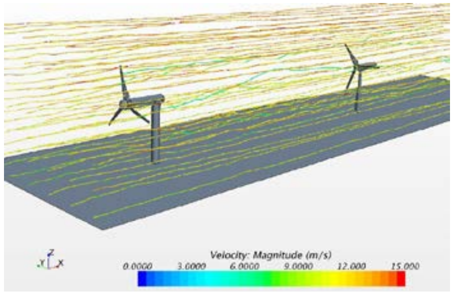
Full-scale measurements

Alpha ventus, Picture: Martina Nolte,
Licence: Creative Commons by-sa-3.0 de

PREDICTION

SCALING??
BLOCKAGE??

Simulations



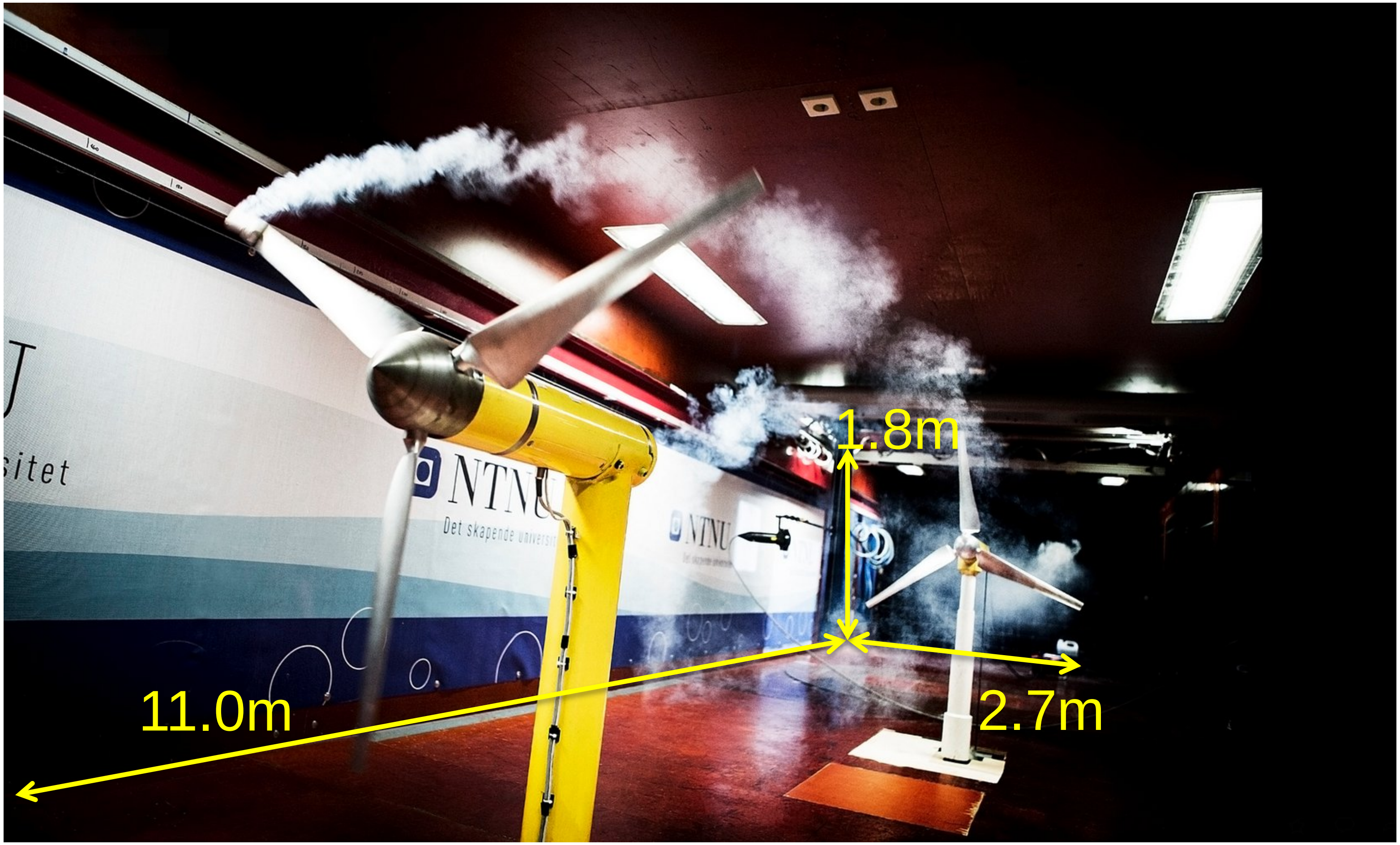
Picture: Jim Ryan, StarCCM+

VALIDATION
&
CALIBRATION

Wind tunnel experiments

Picture: Geir Mogen, NTNU

Low speed wind tunnel at NTNU



Picture credit: Geir Mogen/NTNU

Grid generated inlet turbulence

Simulation of background turblence
TI ≈ 10% at upstream turbine, TI ≈ 5% at downstream turbine

Background

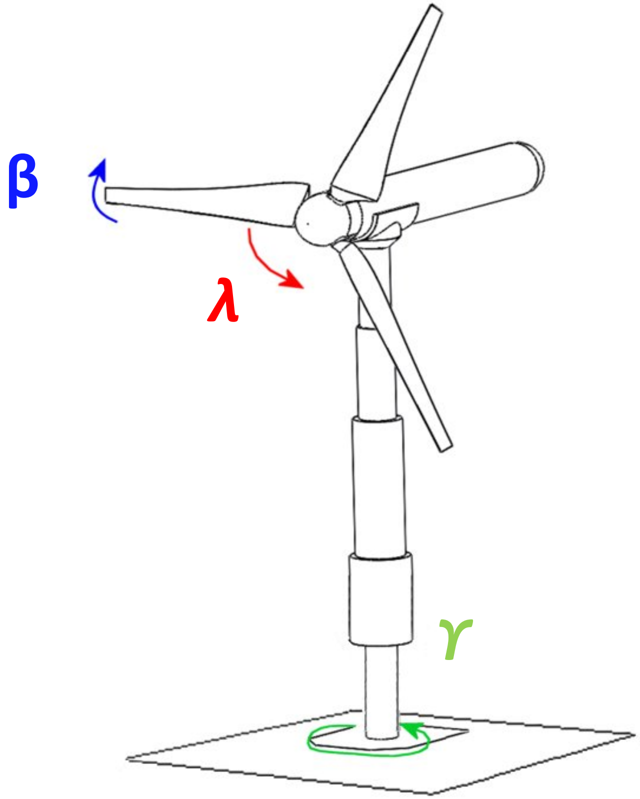
Basic strategies for wake control

Axial induction based control

- **λ: torque (TSR) control**
- **β: blade pitch angle control**

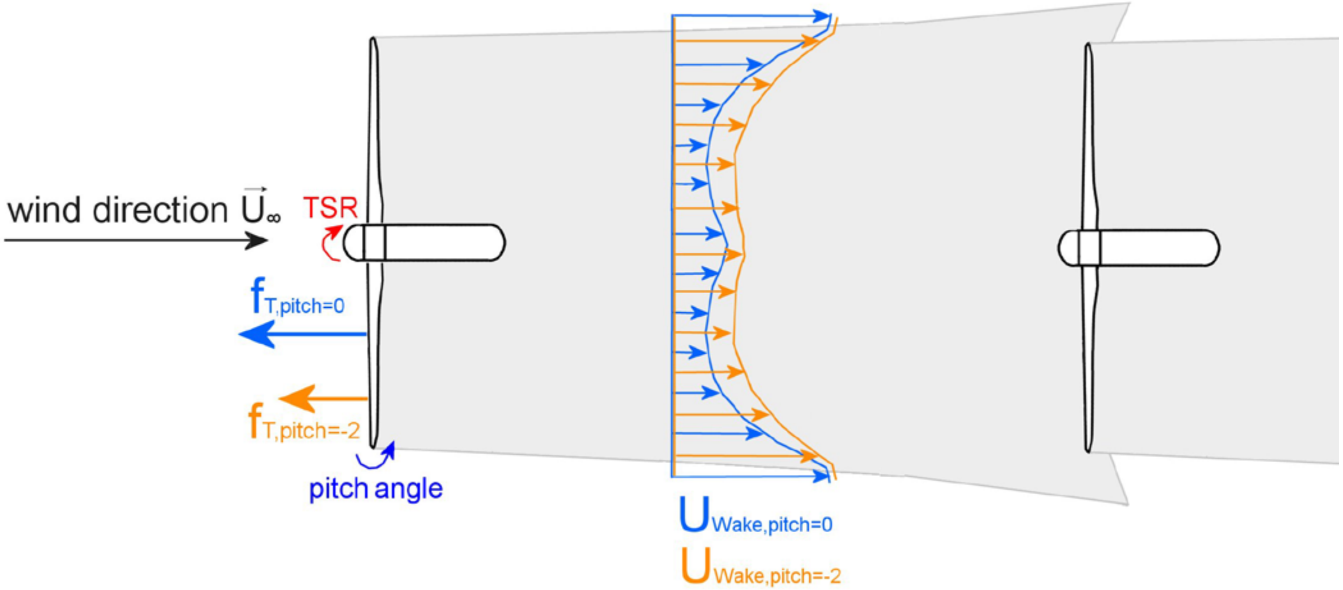
Wake deflection control

- **ϒ: turbine yaw angle control**



⇨ *Reduce energy capture of upstream turbine to the benefit of the downstream turbines*

Axial induction based wake control

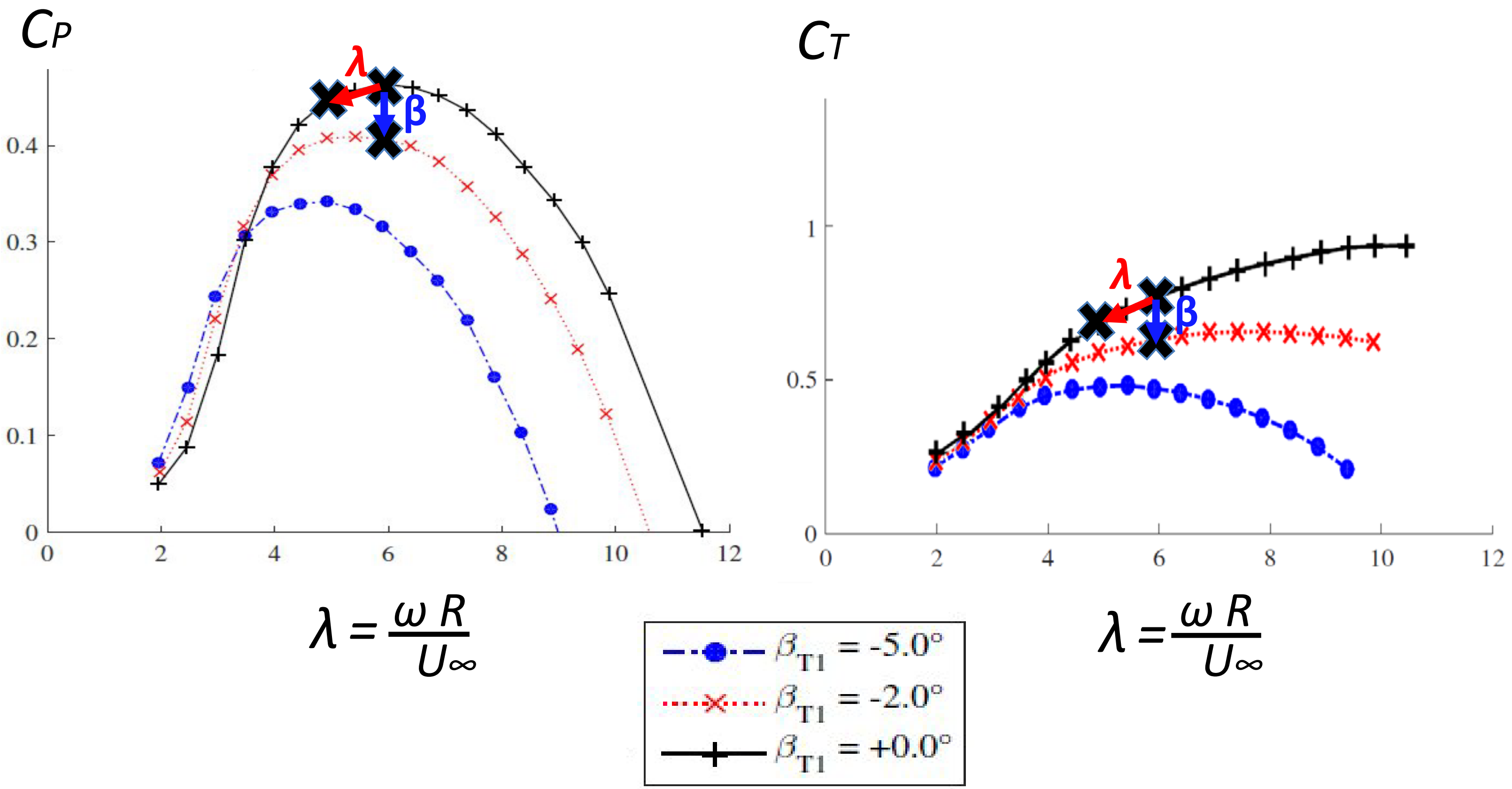


Variation of upstream turbine tip speed ratio λ or pitch angle β

⇨ assessment of mean and turbulent wake flow

⇨ assessment of downstream turbine performance (C_P, C_T)

Axial induction based wake control



$$\lambda = \frac{\omega R}{U_\infty}$$

Results

λ-variations:

Selected results of Master thesis by
C. Ceccotti, *A. Spiga*, *P. Wiklak* and *S. Luczynski*

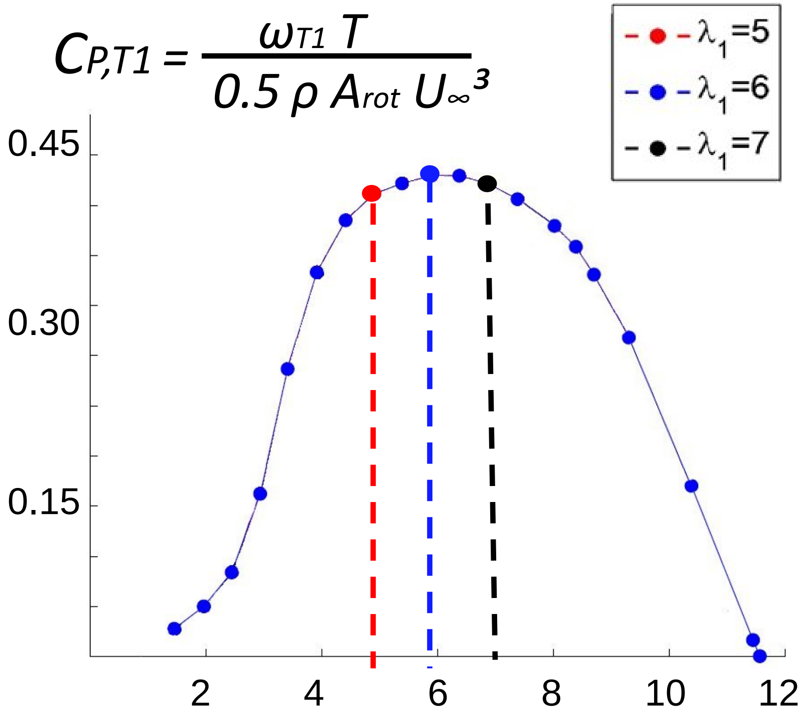
β-variations

Selected results of Master thesis by *M. Löther*

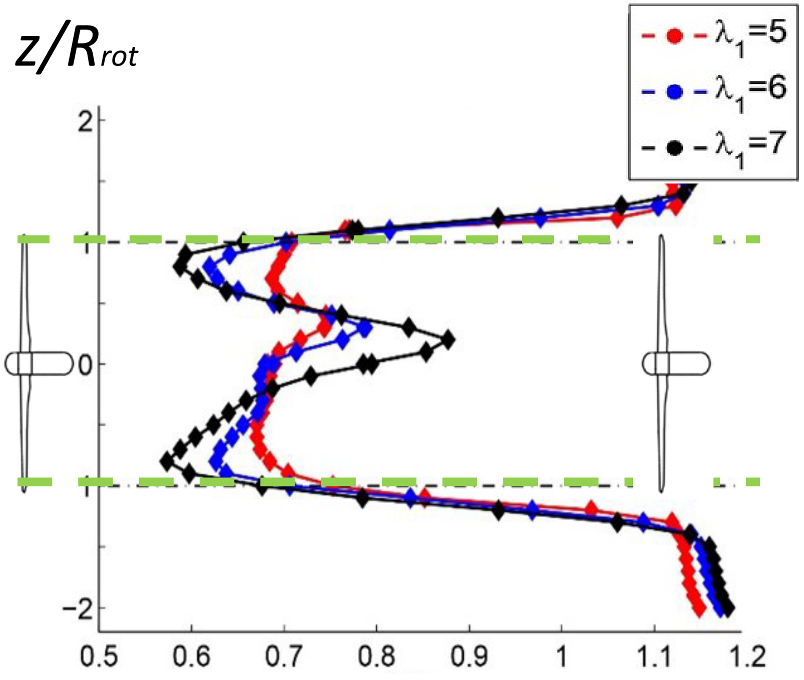
Results: λ-control of upstream turbine

Turbine 1 → **Wake flow at x/D=3** →

$$C_{P,T1} = \frac{\omega_{T1}\, T}{0.5\, \rho\, A_{rot}\, U_\infty^3}$$



$$\lambda_{T1} = \frac{\omega_{T1}\, R}{U_\infty}$$

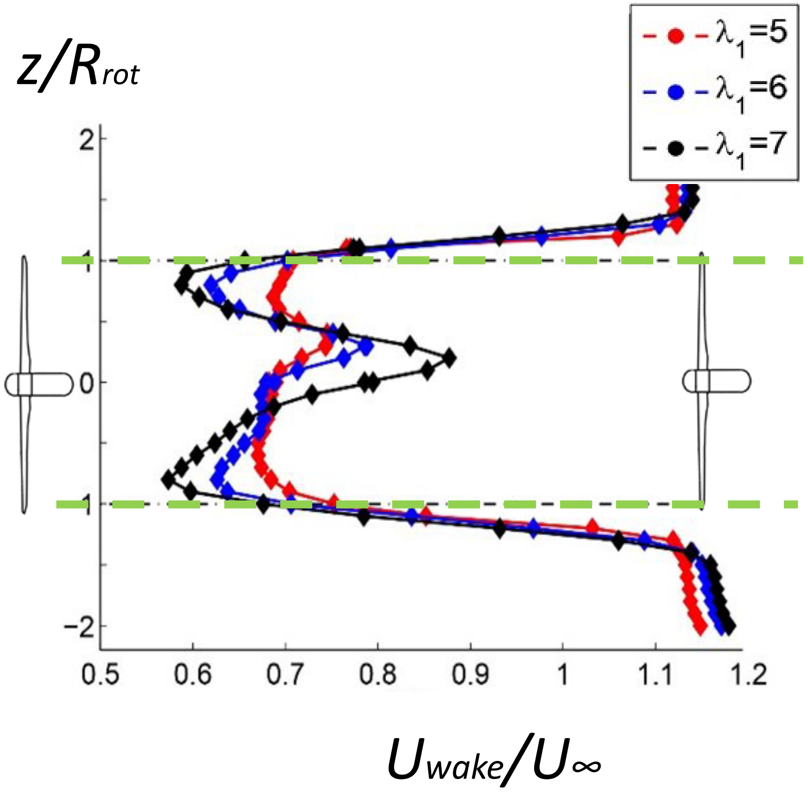


U_{wake}/U_∞

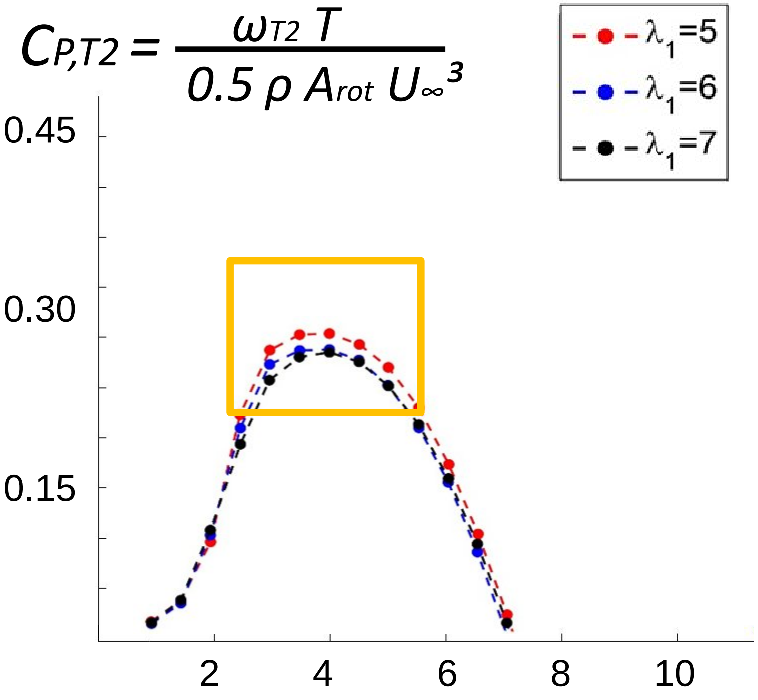
Results: λ-control of upstream turbine

Wake flow at x/D=3

Turbine 2 at x/D=3

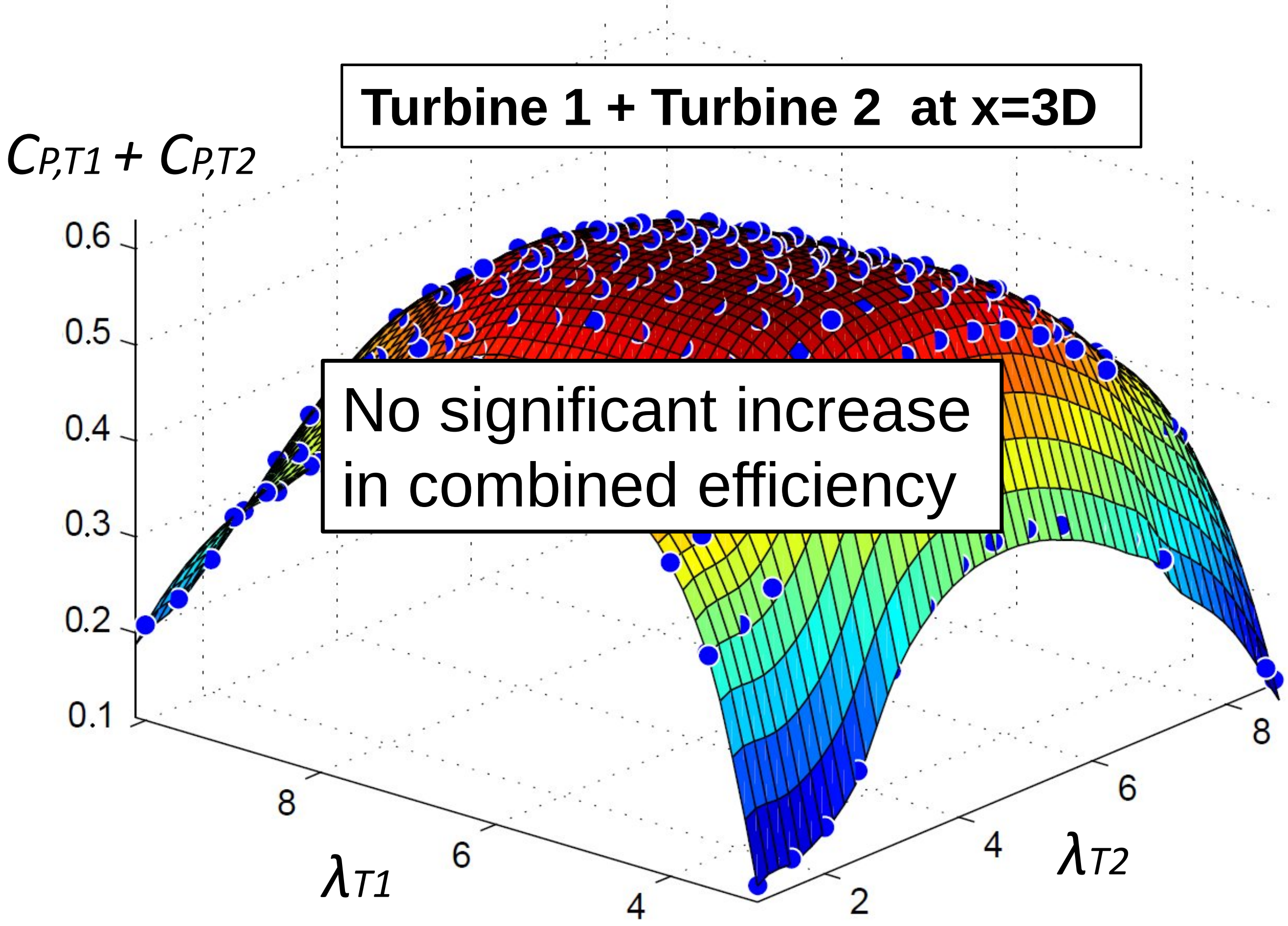


$$C_{P,T2} = \frac{\omega_{T2}\, T}{0.5\, \rho\, A_{rot}\, U_\infty^3}$$



$$\lambda_{T2} = \frac{\omega_{T2}\, R}{U_\infty}$$

Results: λ-control of upstream turbine

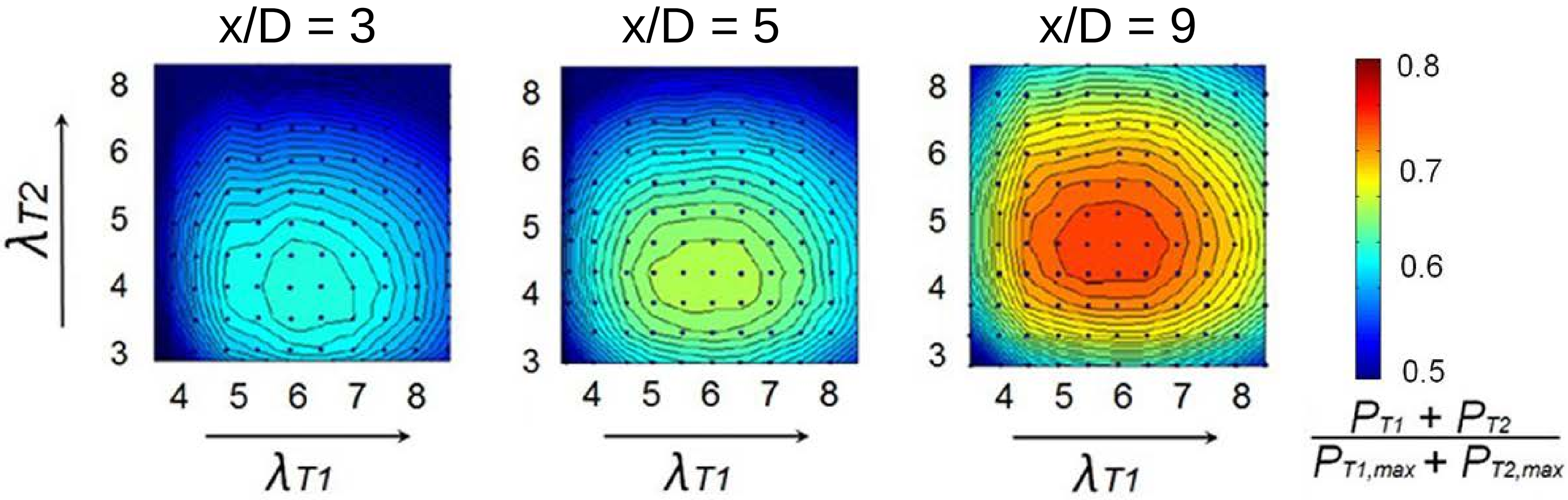


Turbine 1 + Turbine 2 at x=3D

No significant increase in combined efficiency

Results: λ-control of upstream turbine

Effect of turbine separation distance x/D



For increasing downstream distance x/D

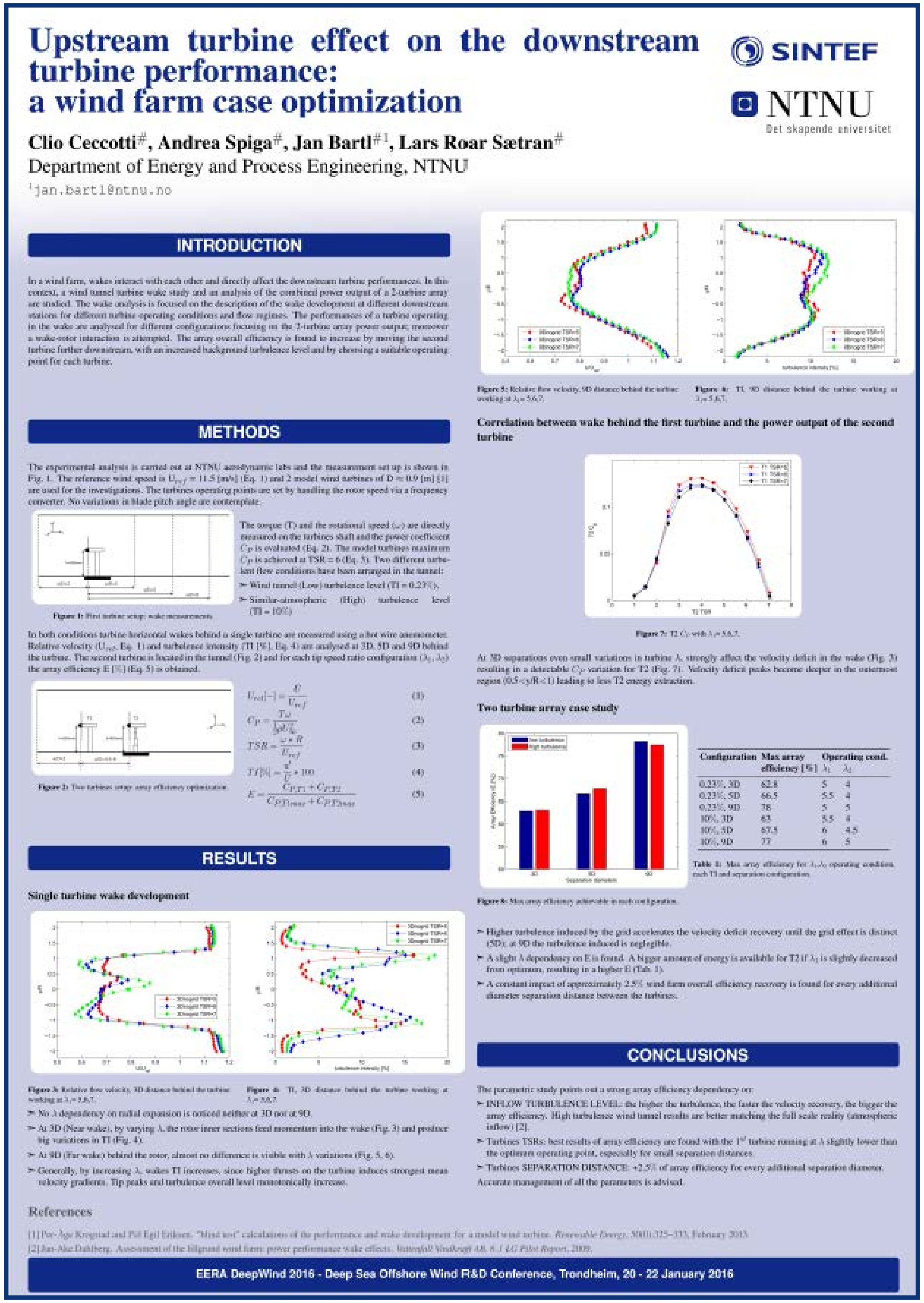
⇨ more energy is recovered from T2

⇨ λ-control has less influence on wake recovery

More information:

Poster by
Clio Ceccotti and
Andrea Spiga

Upstream turbine effect on downstream turbine performance



Upstream turbine effect on the downstream turbine performance: a wind farm case optimization

Clio Ceccotti#, Andrea Spiga#, Jan Bartl#1, Lars Roar Sætran#
Department of Energy and Process Engineering, NTNU
[1] `jan.bartl@ntnu.no`

INTRODUCTION

METHODS

RESULTS

Single turbine wake development

Correlation between wake behind the first turbine and the power output of the second turbine

Two turbine array case study

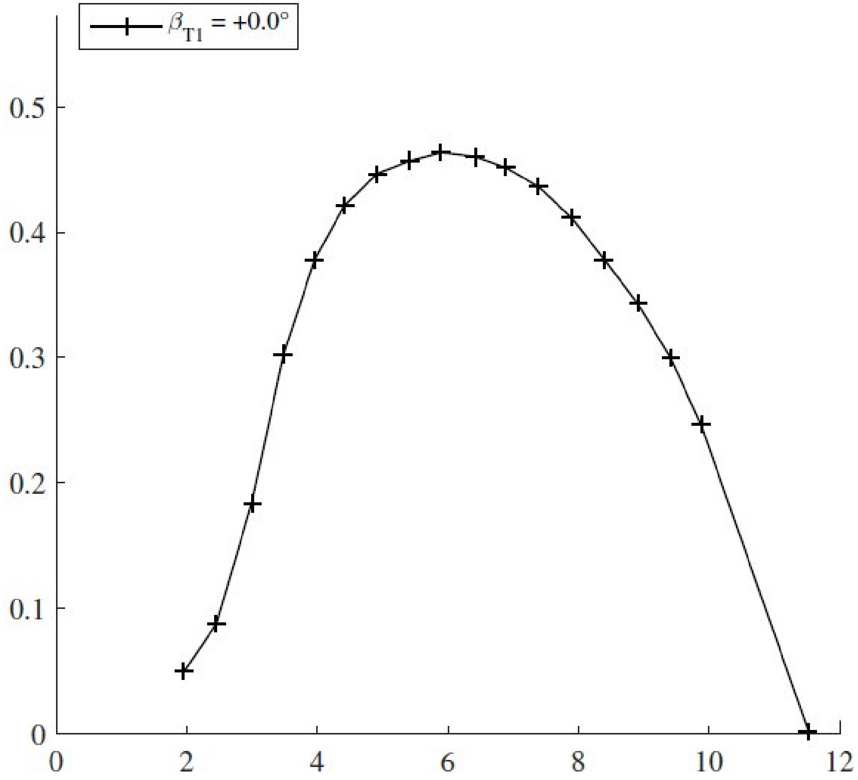
CONCLUSIONS

References

EERA DeepWind 2016 - Deep Sea Offshore Wind R&D Conference, Trondheim, 20 - 22 January 2016

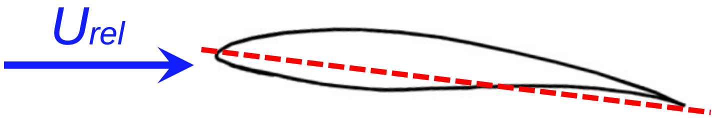
Results: β-control of upstream turbine

$C_{P,T1}$



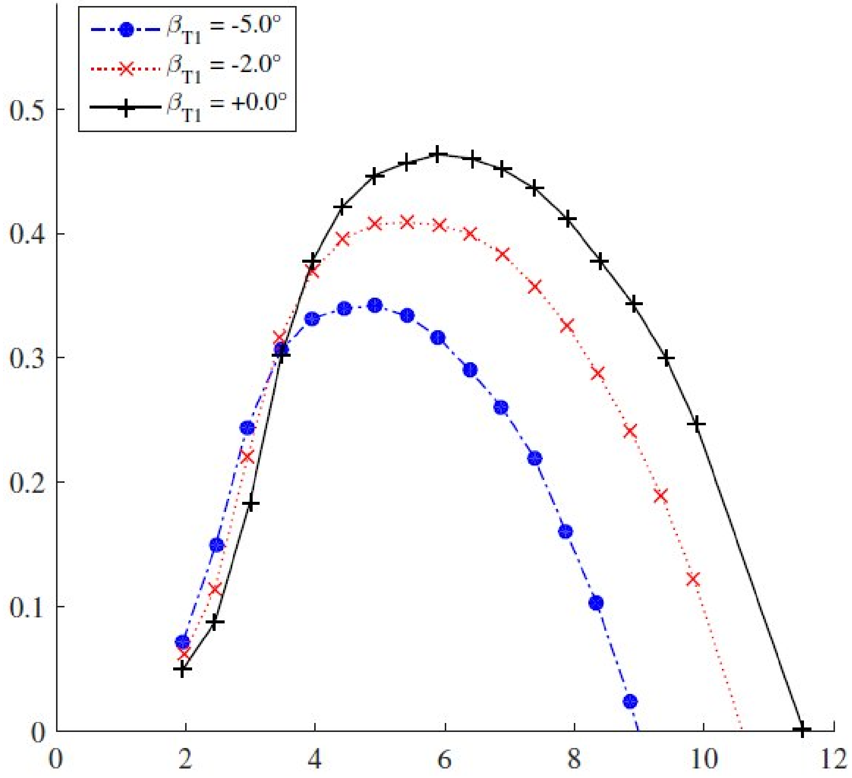
$$\lambda_{T1} = \frac{\omega_{T1} R}{U_\infty}$$

Zero pitch:
all blade elements at
design angle of attack α=7°



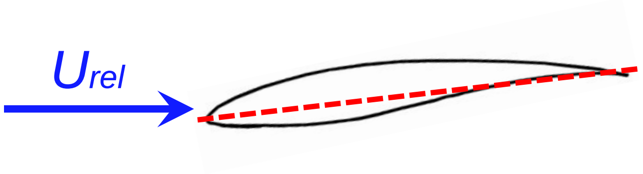
Results: β-control of upstream turbine

$C_{P,T1}$

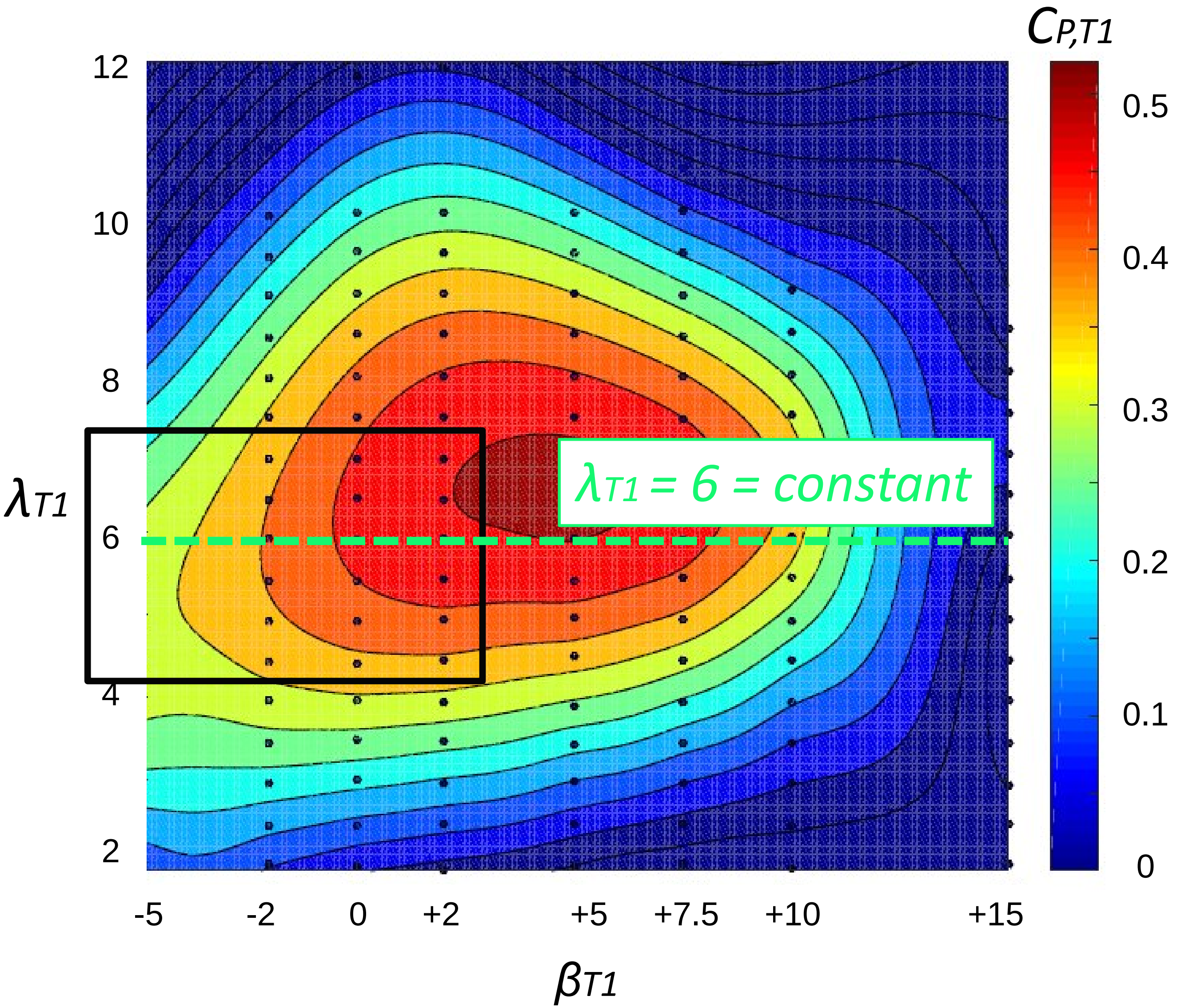


$$\lambda_{T1} = \frac{\omega_{T1} R}{U_\infty}$$

<u>Negative pitch:</u>
- towards lower α
- towards feather position



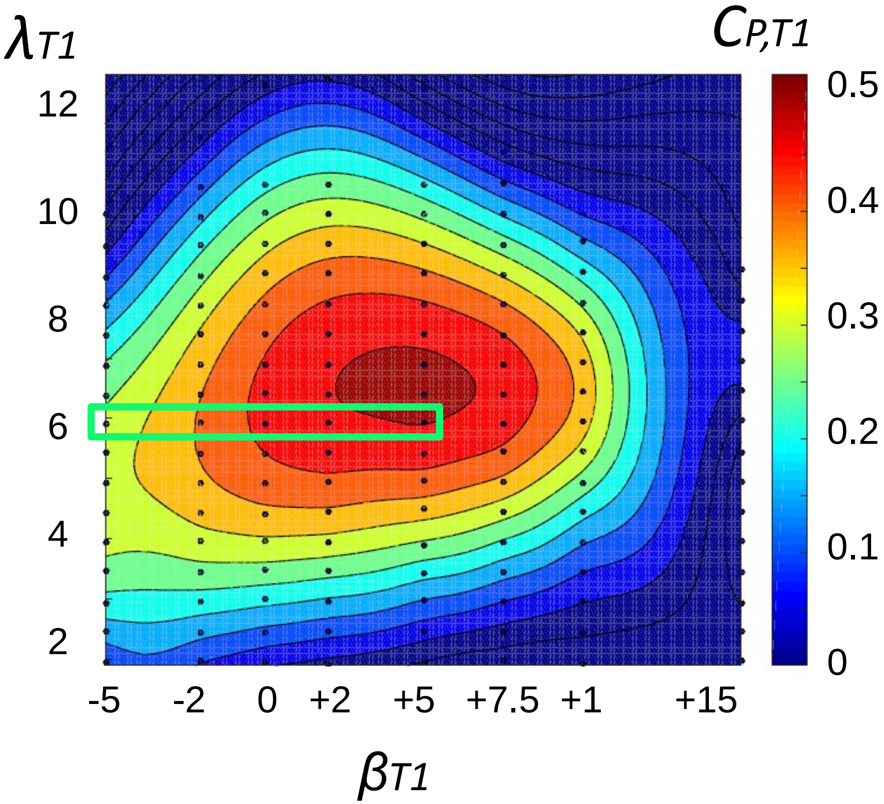
Results: β-control of upstream turbine

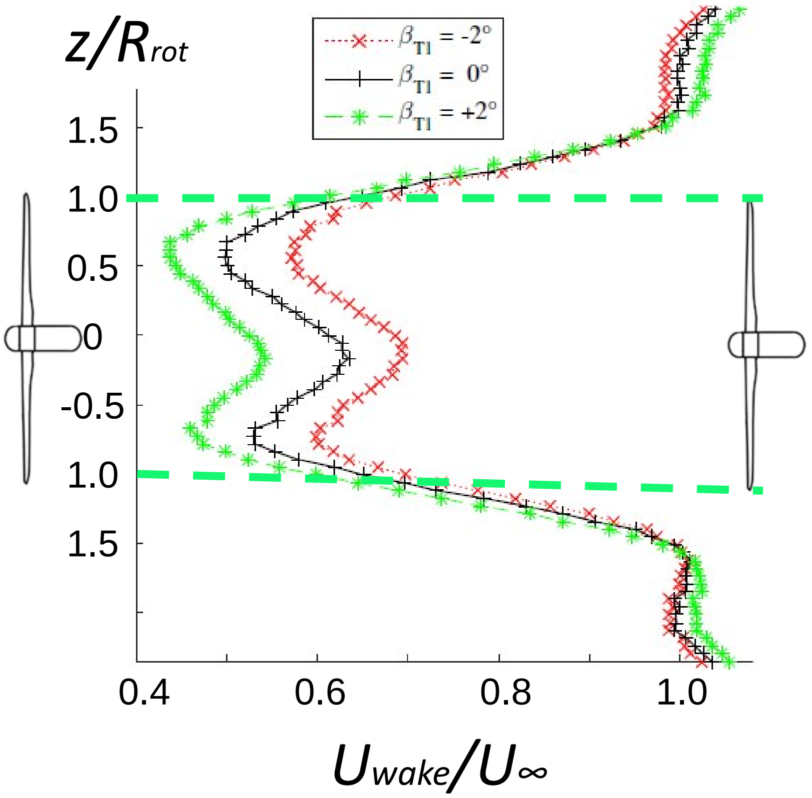


Results: β-control of upstream turbine

Turbine 1

Wake flow at x/D=3

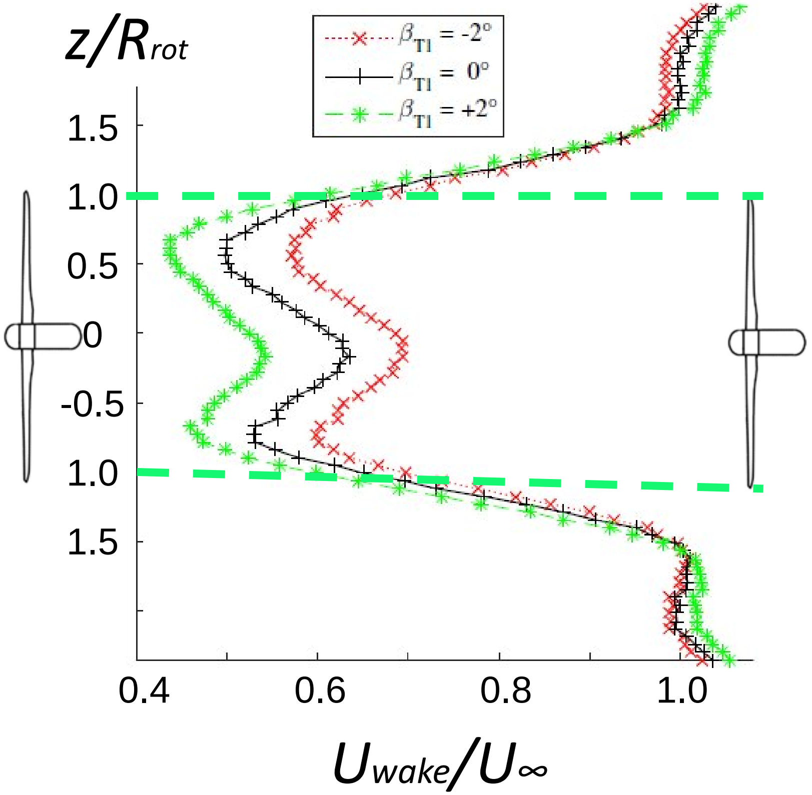


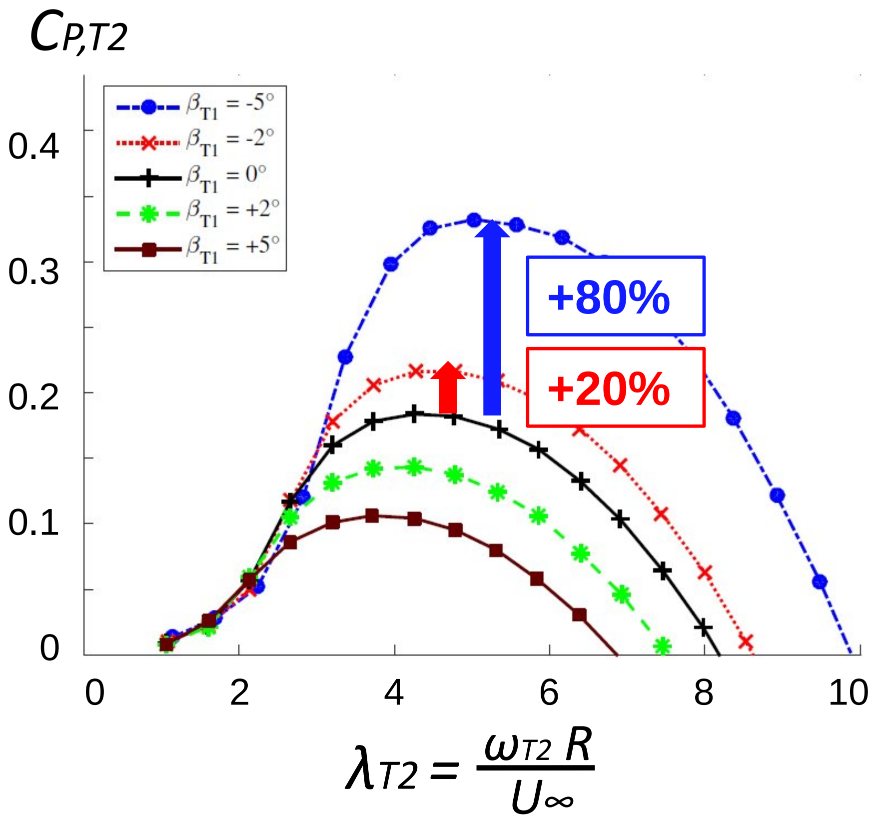


Results: β-control of upstream turbine

Wake flow at x/D=3

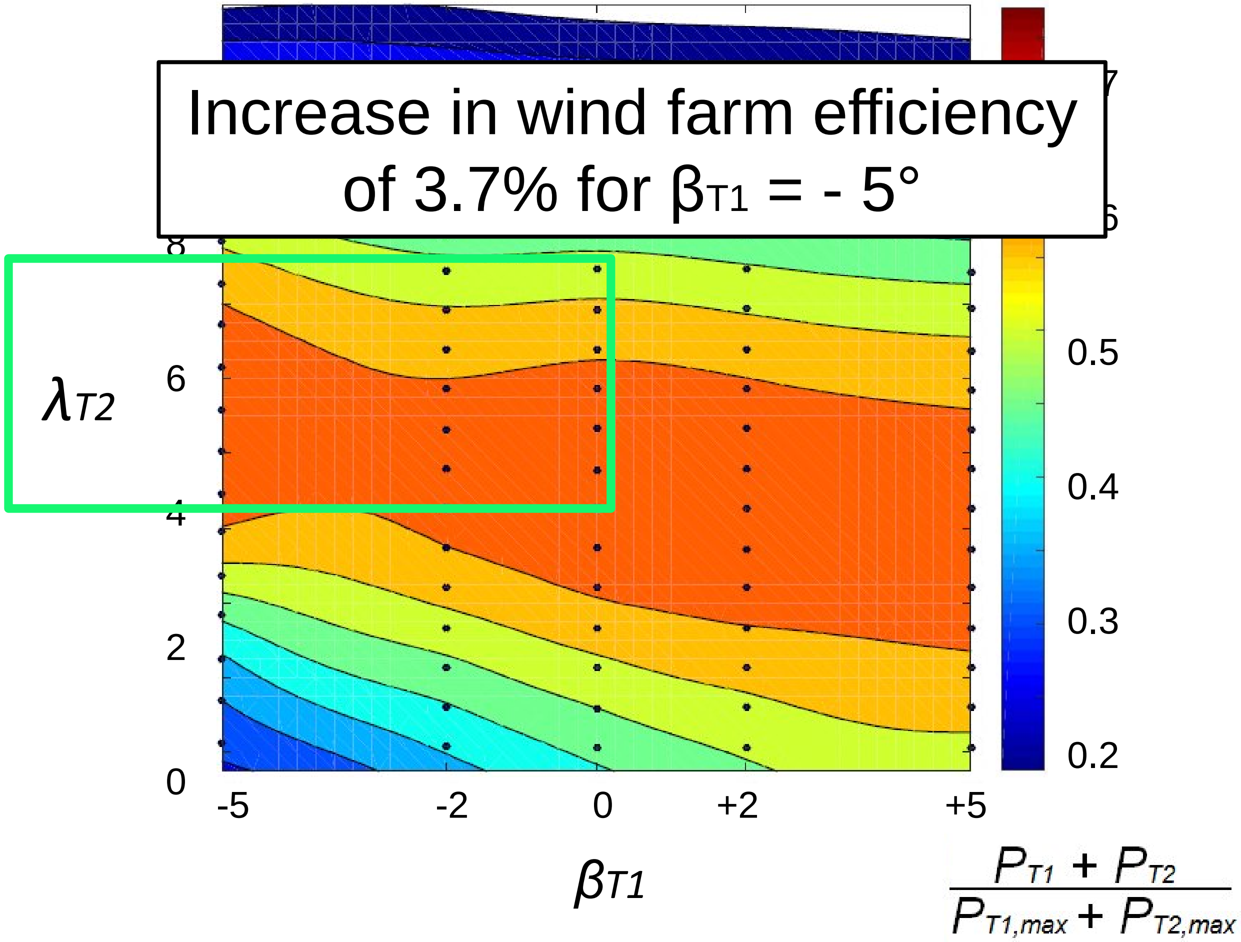
Turbine 2 at x/D=3





Results: β-control of upstream turbine

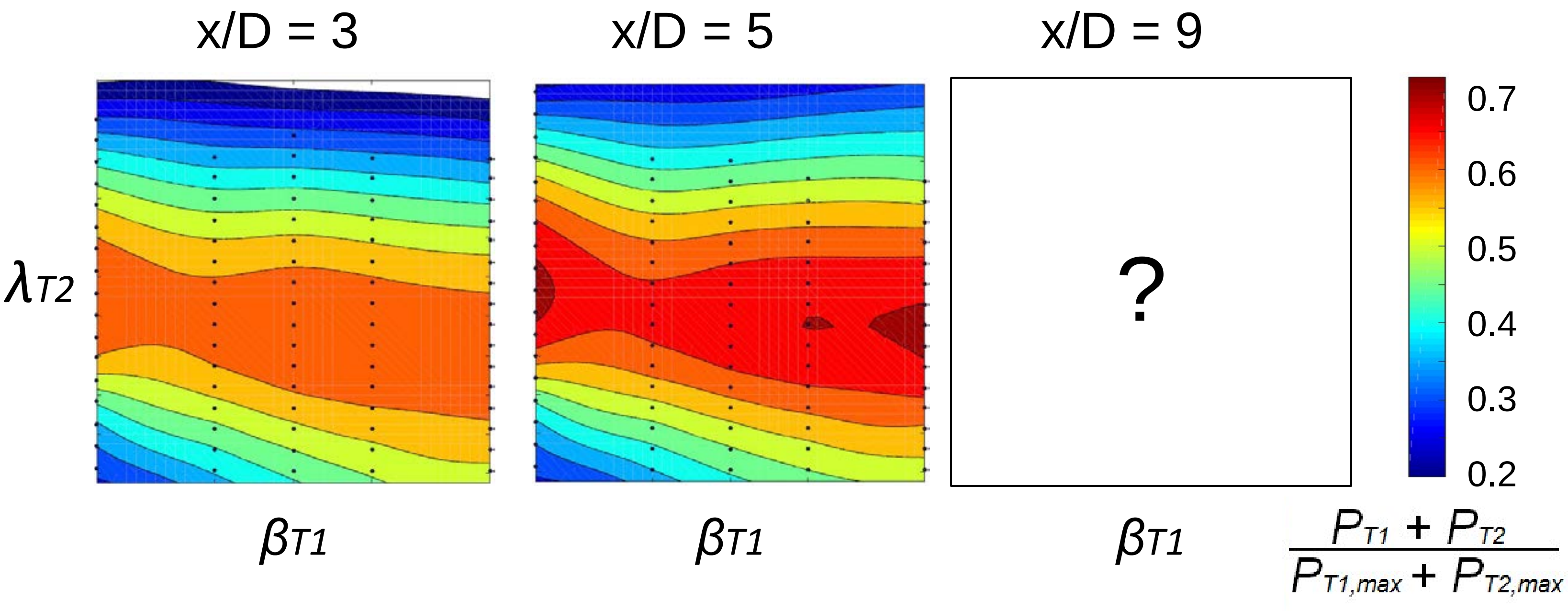
Combined wind farm efficiency $P_{T1} + P_{T2}$, x/D=3



Increase in wind farm efficiency of 3.7% for β_{T1} = - 5°

Results: β-control of upstream turbine

Effect of turbine separation distance x/D



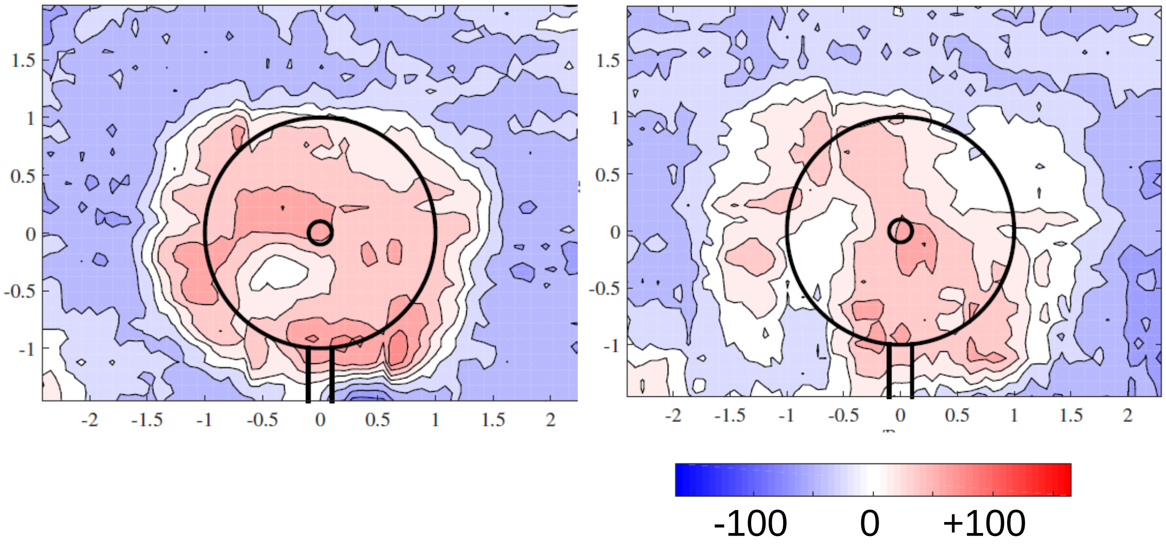
$$\frac{P_{T1} + P_{T2}}{P_{T1,max} + P_{T2,max}}$$

⇨ More energy can be recovered by downstream turbine

Results: β-control of upstream turbine

Where is the added kinetic energy located in the wake?

x/D = 3 x/D = 5 x/D = 9



?

$$\frac{P}{A} = \frac{1}{2} \cdot \rho \cdot U_M^3 \left[\frac{W}{m^2}\right]$$

⇨ Added kinetic energy is diffusing outside the downstream rotor area

Some concluding remarks

***λ*-control:**

- Insignificant effect on total power output from slight variations around the design tip speed ratio
- power lost on the upstream turbine is recovered by the downstream turbine

⇨ total power production is stable around design TSR

***β*-control:**

- Higher potential for wind farm efficiency increase
- Pitch angle of β=-5° gives highest combined efficiency

⇨ more pitch angles to be analysed

⇨ more thorough wake analysis needed

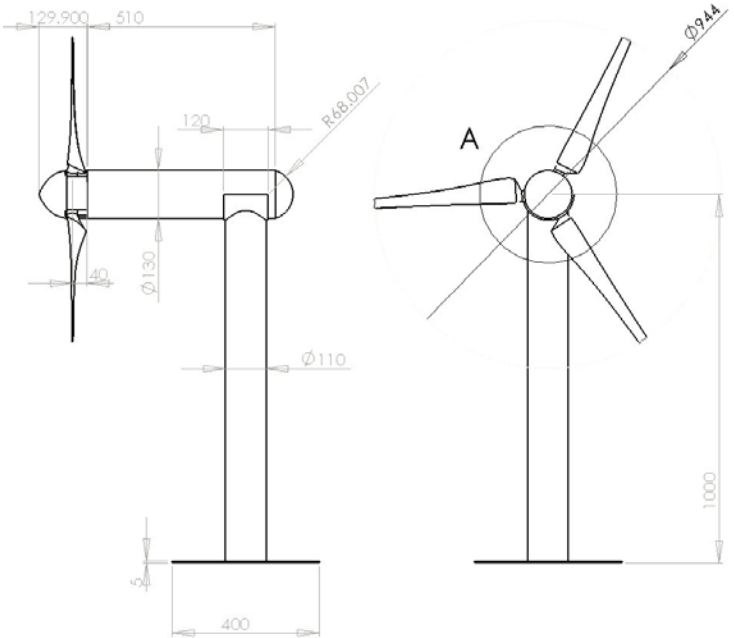
Further work

- Wake analysis for pitch angles β_{T1}
- 3rd turbine?
- Υ-control

Thank you for your attention!

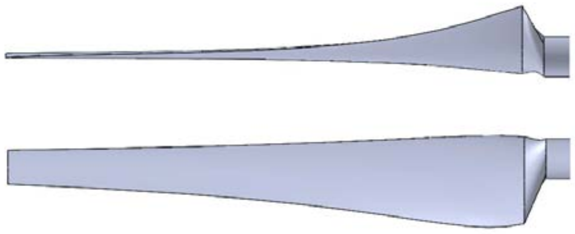
Model wind turbines & blade geometry

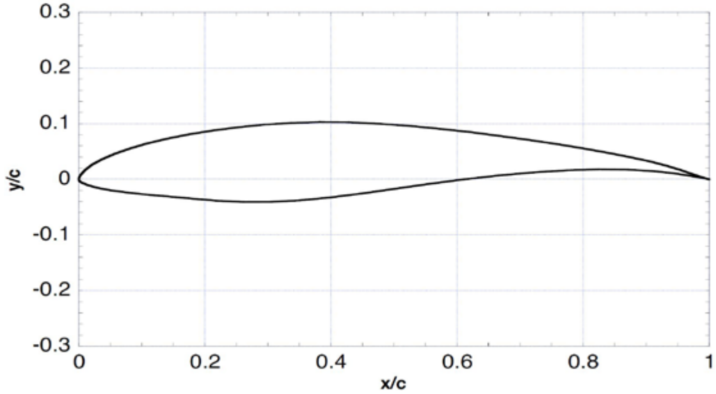
Two model turbines



$D_{Rotor,T1} \approx 0.90$ m

Blade: NREL S826 airfoil

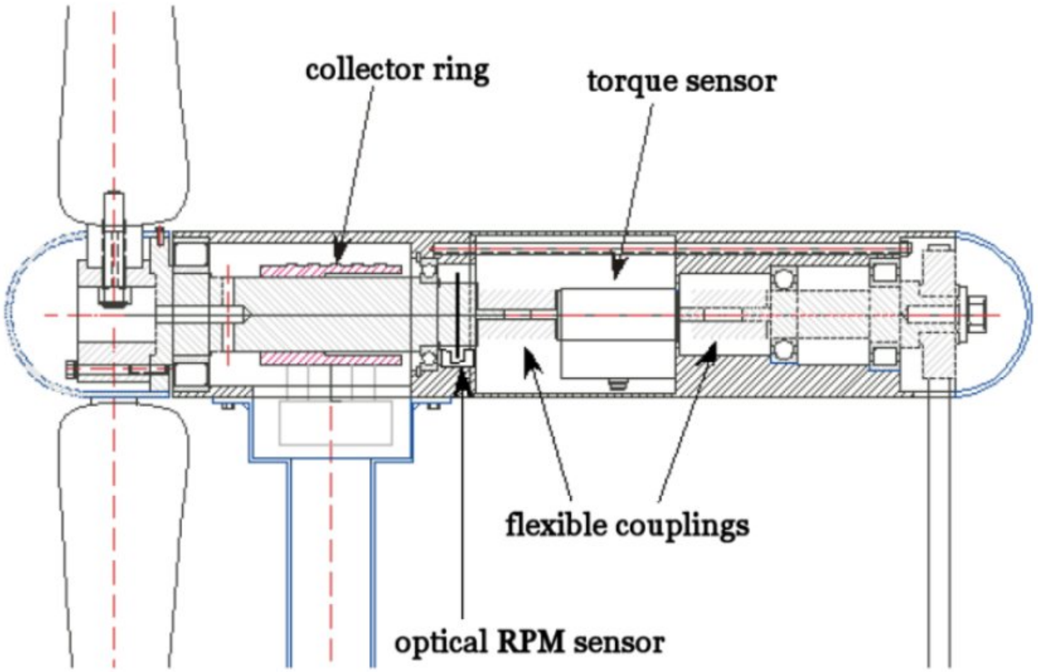




Solid blockage $\sigma = \frac{A_{Rotor}}{A_{Tunnel}} = 12\%$

- designed for Re = 10^6
- operated at Re ≈ 10^5

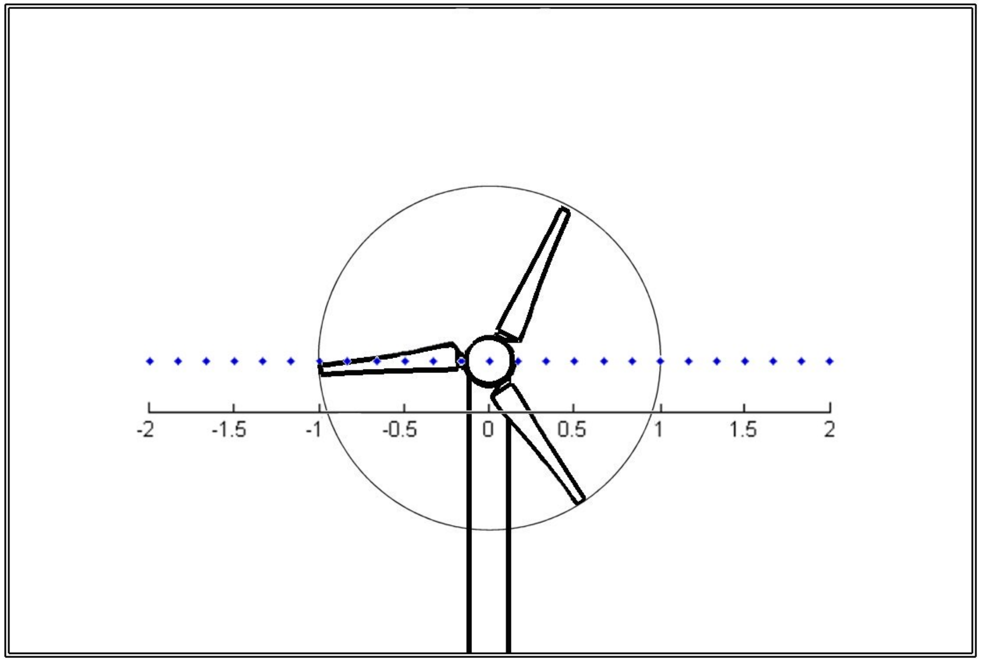
Power measurements



$$\boxed{P = \omega\ * T}$$

Wake flow measurements

Constant Temperature Anemometry (CTA) Hot-wire



41 measurement points in the wake z/R = -2 to z/R = +2

NREL S826 airfoil characteristics

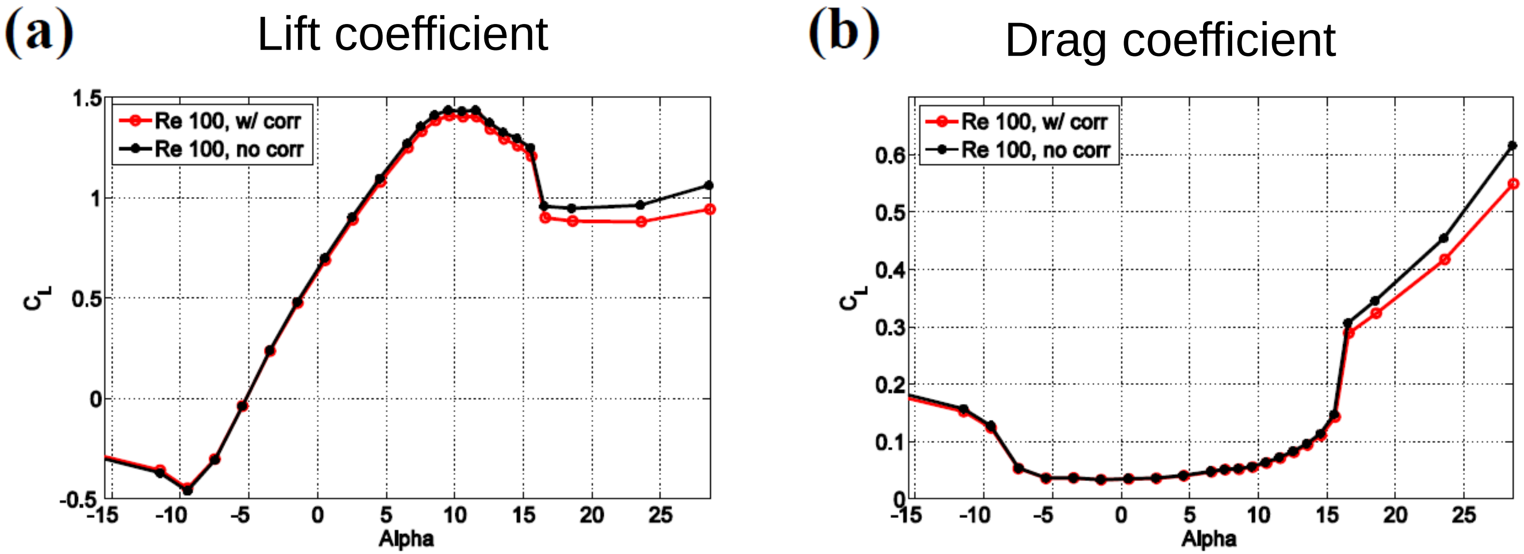
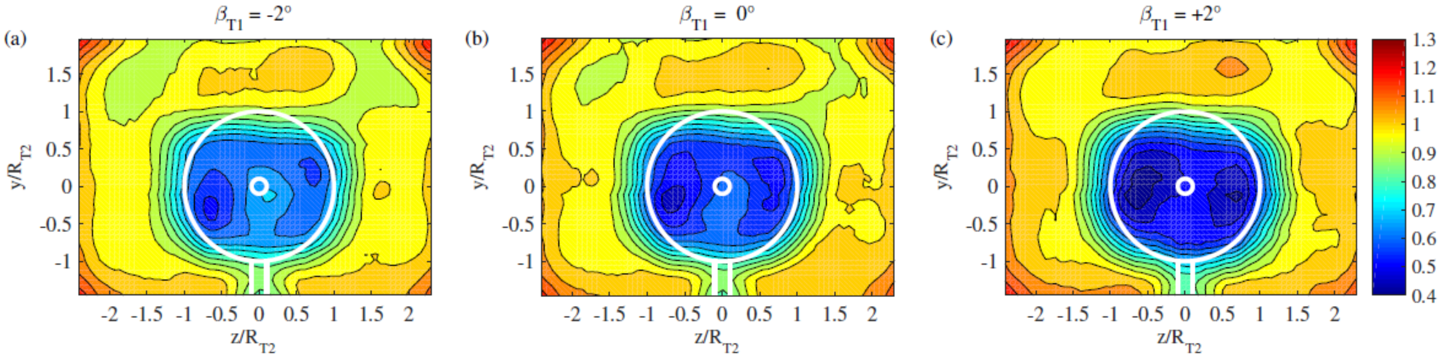


Figure 7 a-b: Lift- and drag measurements corrected for solid blockage, wake blockage and streamline curvatures. $Re = 1.0 \times 10^5$, $TI = 0.71\%$

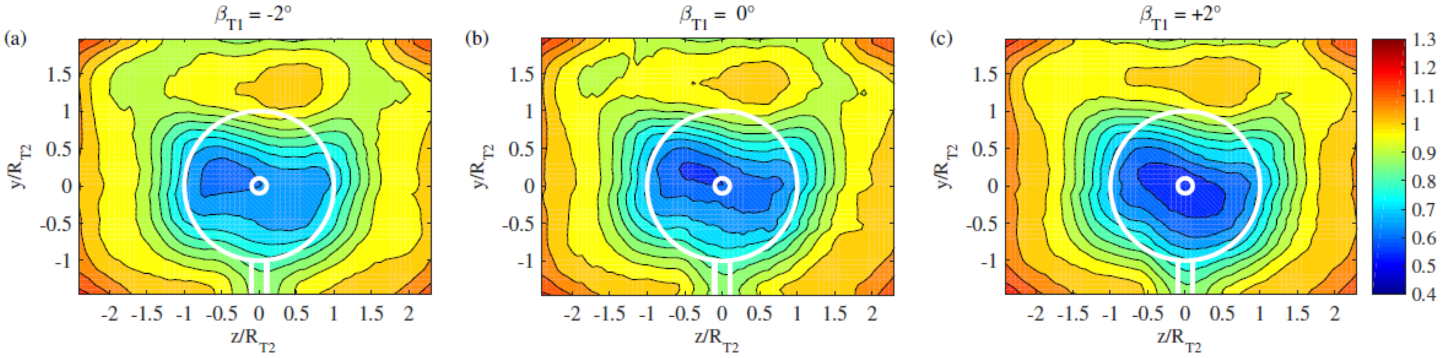
Source: Initial measurements on S826 wing, N.Aksnes & J.Bartl, NTNU

Full-area wake measurements, β= -2, 0, +2

x/D=3

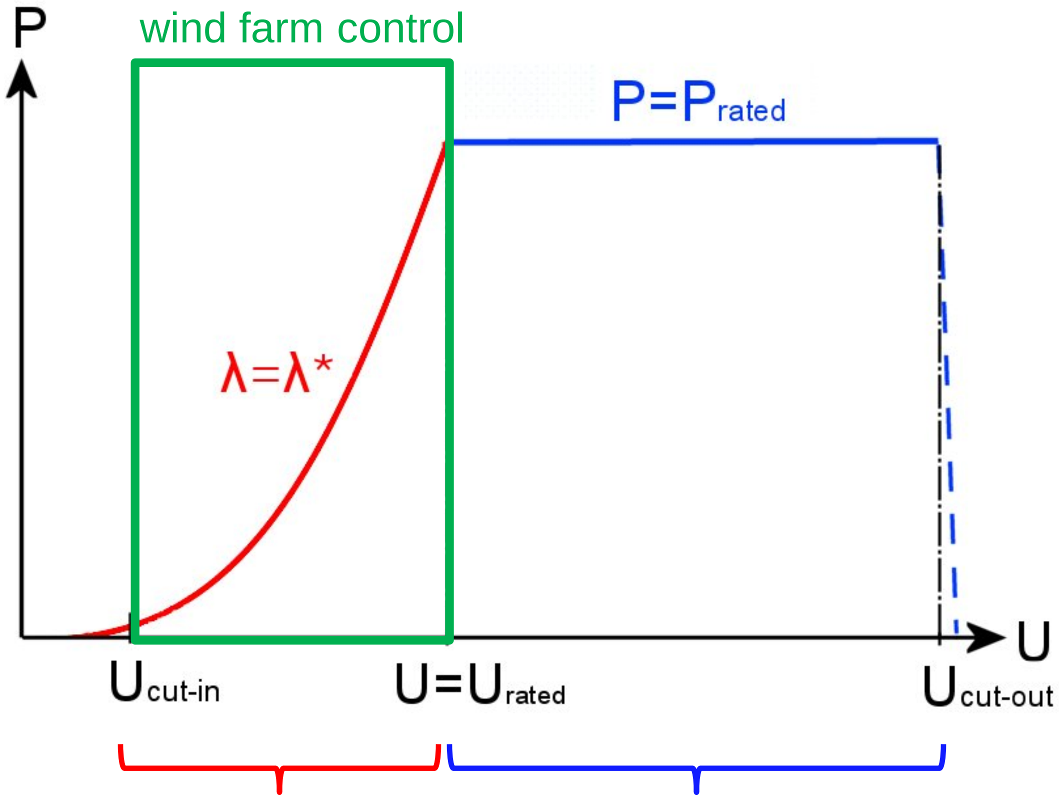


x/D=5



Background

Basic ***individual*** wind turbine control



Relevant region for wind farm control

under rated wind speed

λ-control

(rotational speed)

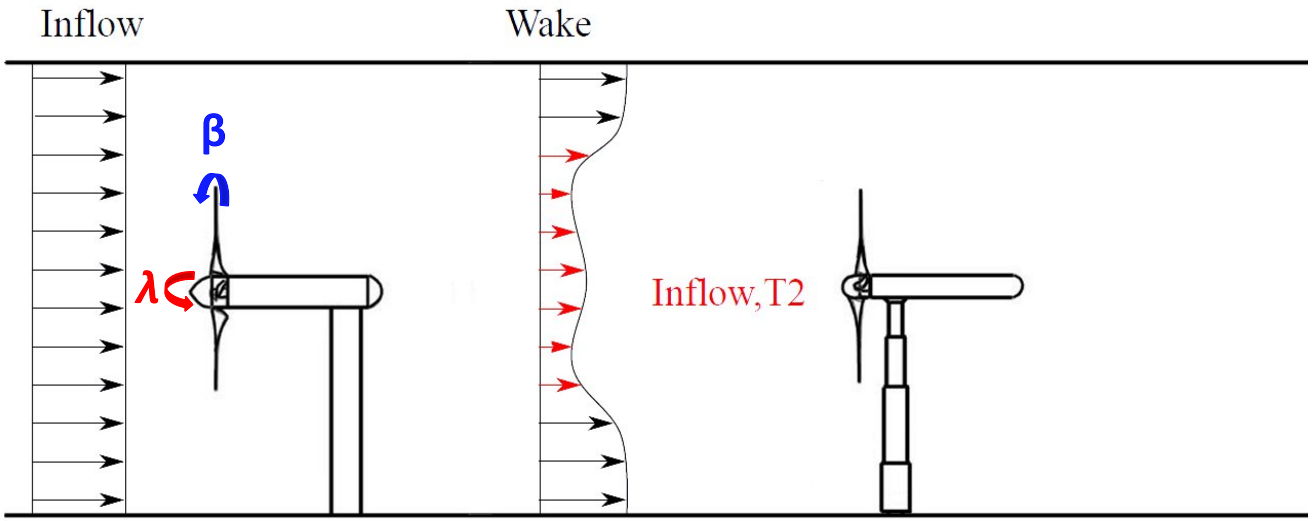
above rated wind speed

β-control

(pitch angle)

Background

Concepts of **wind farm control / wake control**



⇨ Reduce energy capture of upstream turbine to the benefit of the downstream turbines

Background

Further wind turbine control goals

- Fatigue load reduction
- Resonance avoidance
- Gust load alleviation
  (extreme loads)
- Periodic disturbance reduction
  (wind shear, tower shadow effect)
- Actuator duty cycles reduction
- …

*(**Source:** C.L. Bottasso, «Wind turbine control – short course»;*
http://www.aero.polimi.it/~bottasso/DownloadArea.htm)