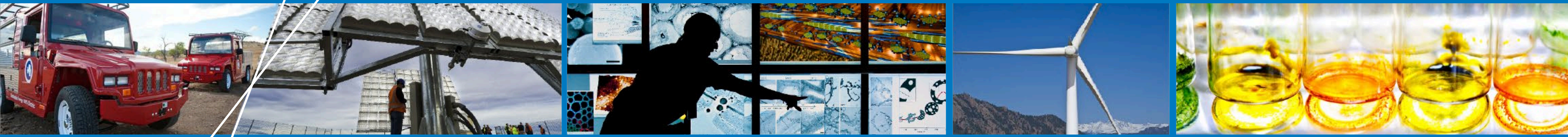
Multidisciplinary Research on Wake Control in Wind Power Plants at NREL



Pieter Gebraad, Paul Fleming, Katherine Dykes
National Renewable Energy Laboratory

Jan-Willem van Wingerden
Delft University of Technology

Windfarms 2015 conference, July 8, 2015, Leuven, Belgium

NREL/PR-5000-65256
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- **Wake modeling and control with SOWFA and FLORIS models**
- **Integrating wakes in wind plant system engineering, using combined optimization of layout and control**

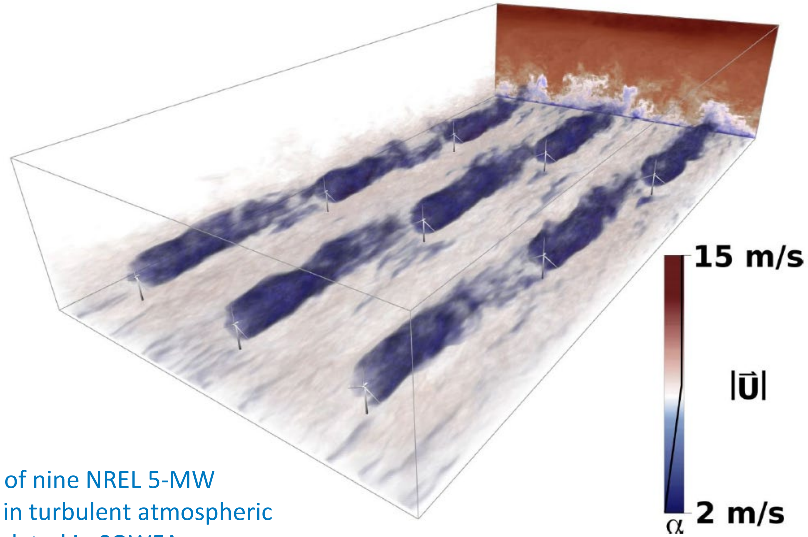
FLORIS = FLOw Redirection and Induction in Steady-state

SOWFA = Simulator fOr Wind Farm Applications

SOWFA Wind Plant Simulator

SOWFA is the National Renewable Energy Laboratory's (NREL's) high-fidelity wind farm simulator and includes:

- A three-dimensional computational fluid dynamics (CFD) solver that calculates the flow around the turbine blades (actuator lines)
- A FAST model of turbine dynamics (power and loads calculation)
- Turbine-level controllers and a supervisory wind plant controller.



An array of nine NREL 5-MW turbines in turbulent atmospheric flow simulated in SOWFA

Photo by Dennis Schroeder, NREL 31716

See also: *National Wind Technology Center Information Portal - SOWFA, https://nwtc.nrel.gov/SOWFA*
Matt Churchfield and Sang Lee

Wake Control Methods

To achieve axial-induction-based wake control:

Increase pitch β *and/or* reduce tip-speed ratio λ (using torque) of upstream turbines.

→ This reduces power production P and reduces the magnitude of rotor thrust F_T

→ Reduces axial induction factor a and increases wake velocity

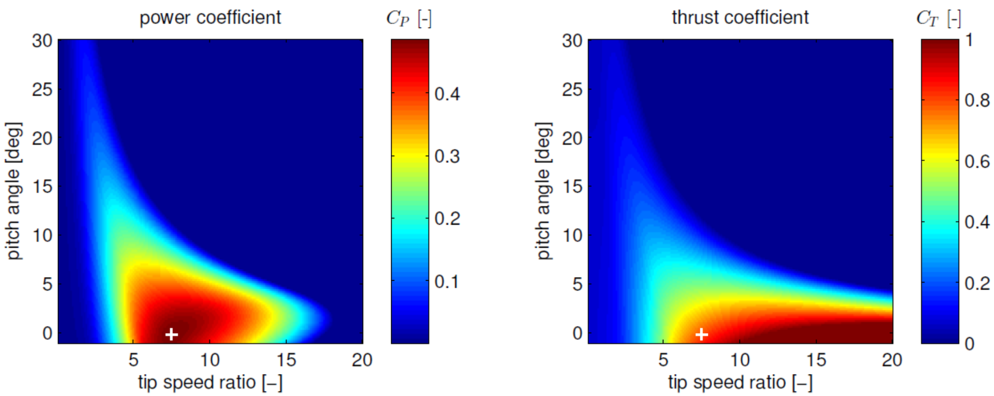
→ Increases power production of downstream turbine.

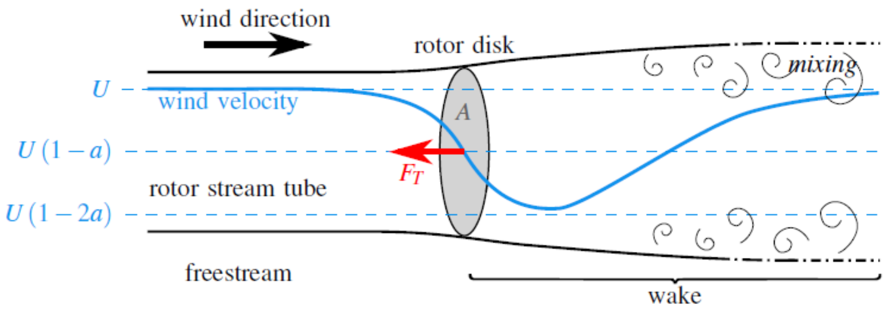
$$\lambda = \frac{\omega R}{U}$$

$$F_T = \frac{1}{2}\rho A C_T(\beta, \lambda) U^2$$

$$P = \frac{1}{2}\rho A C_P(\beta, \lambda) U^3$$

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_T}\right)$$





Wake Control Methods

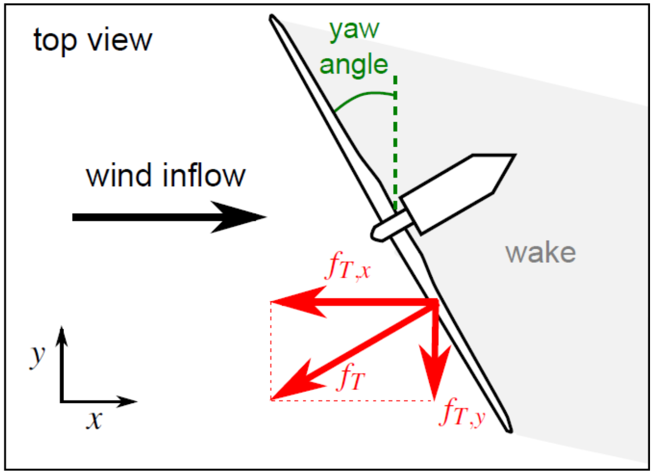
To achieve yaw-based wake control:

Change the yaw angle of the upstream turbine.

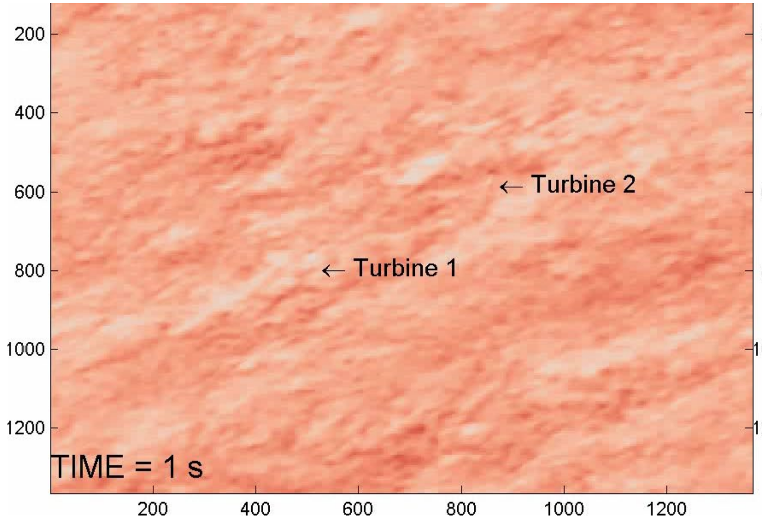
→ This changes direction (and magnitude) of thrust

→ Changes wake direction

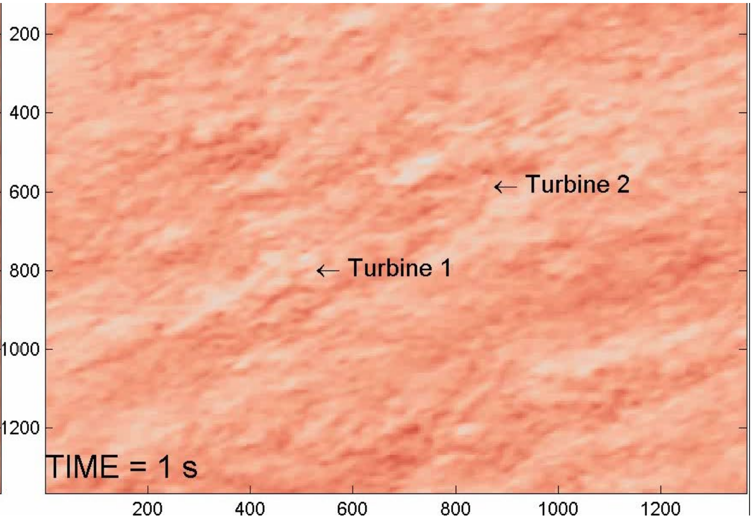
→ Reduces wake overlap with downstream turbine.



Two turbines with zero yaw

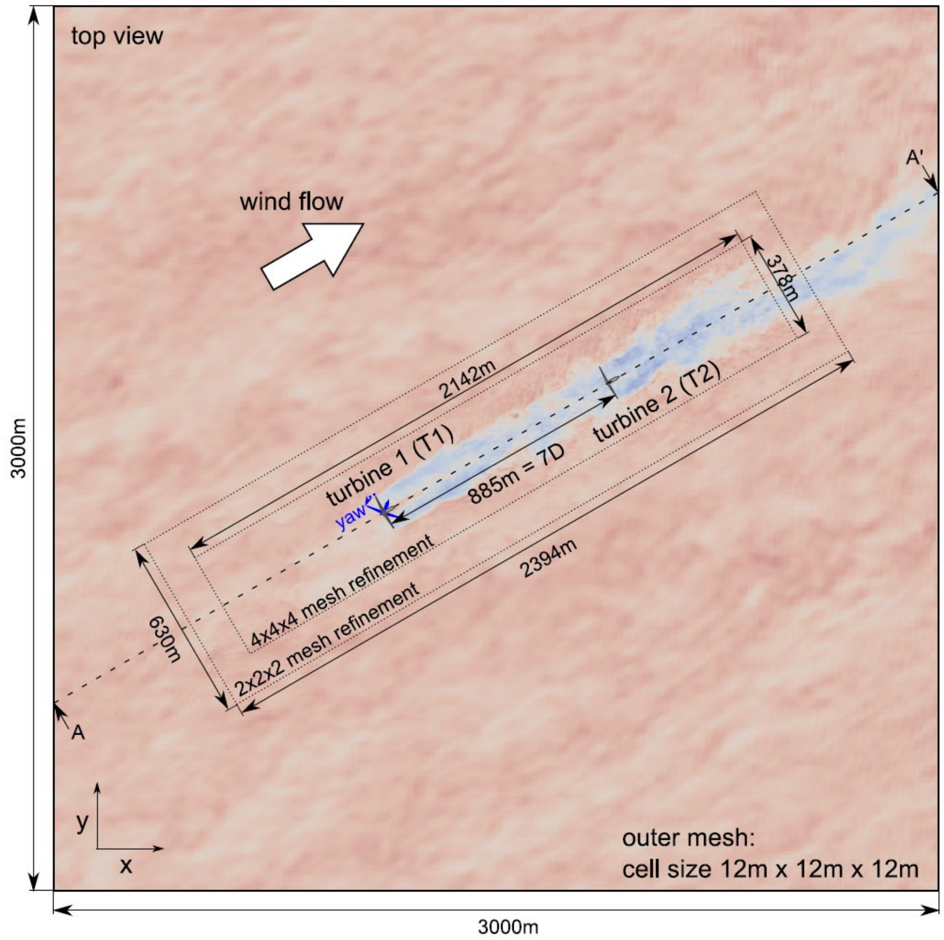


Two turbines: 30° yaw on Turbine 1



See also: *Fleming et al. , 2014. "Simulation Comparison of Wake Mitigation Control Strategies for a Two-turbine Case," Wind Energy.*

Simulation Setup with Two Turbines



SOWFA simulation study of wake control methods.

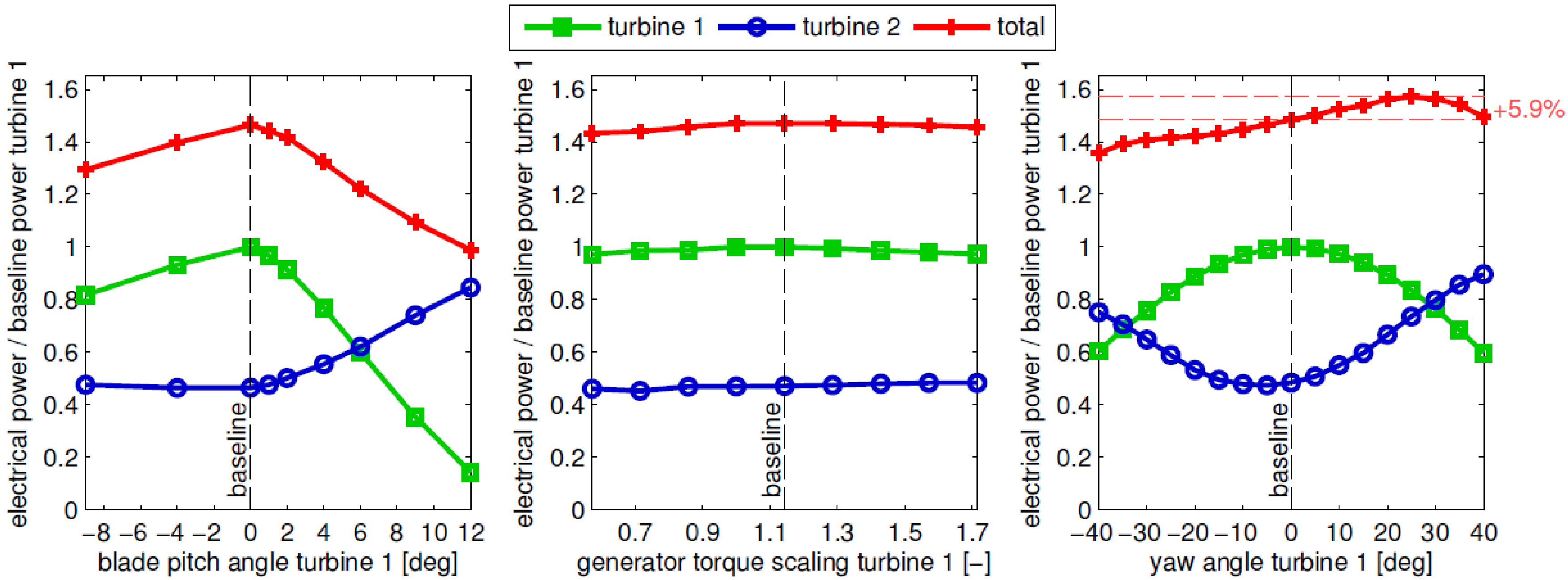
Simulated conditions:

- Two NREL 5-MW turbines aligned in flow
- Inflow speed of 8 meters/second
- Neutral atmospheric stability
- 6% turbulence.

→ Results in good potential for wake control (slow wake recovery).

See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*

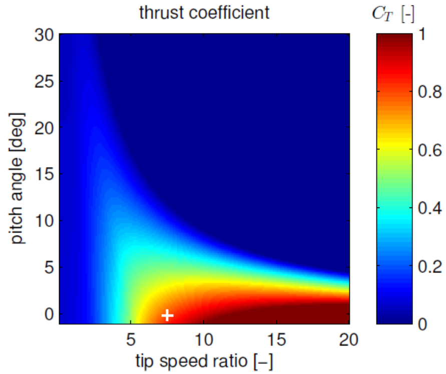
Power Results



- Total power improvement with yaw control
- No power improvement with axial-induction-based control

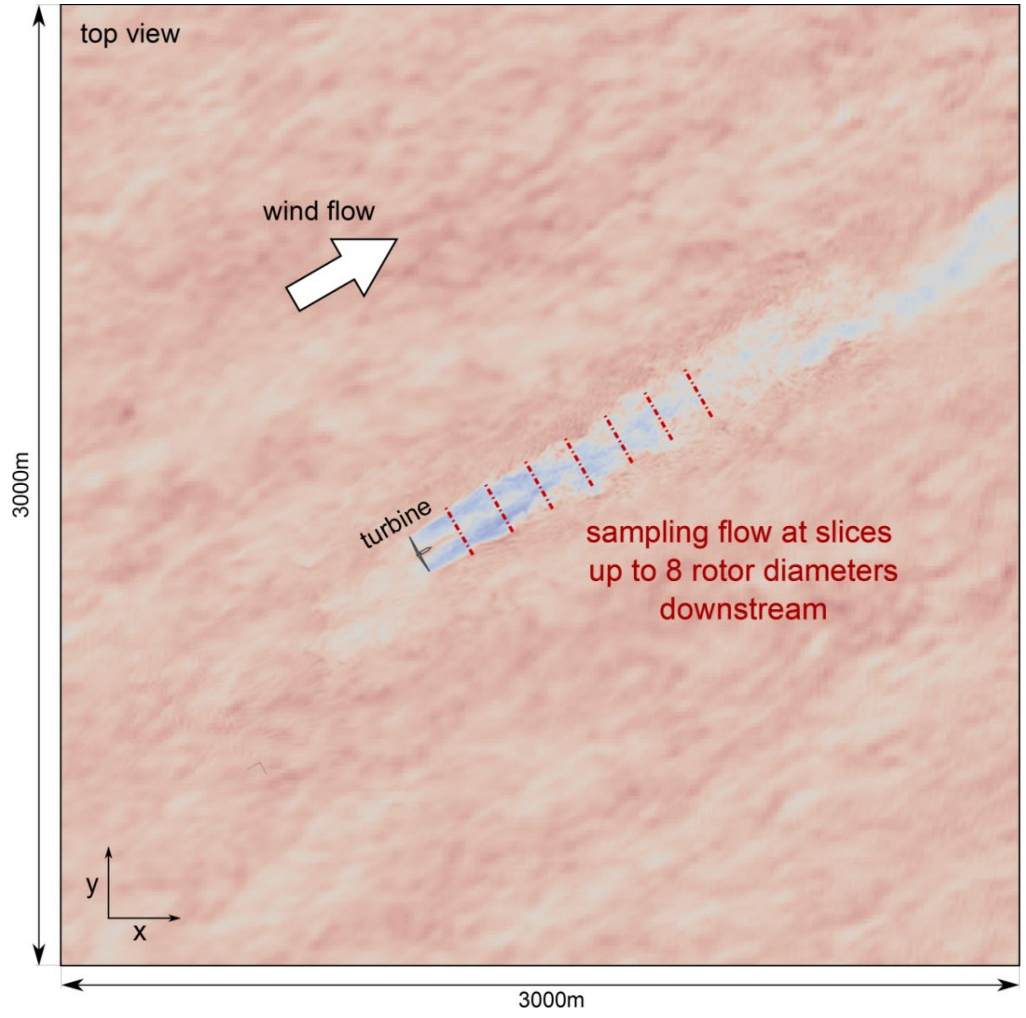
In the next slides, we analyze the wakes in these cases to address the questions:

1. Why are there differences in total power improvement between yaw control and axial-induction-based control methods?
2. Can we achieve total power improvement with axial-induction-based control we move the turbines closer?



See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*

Analyze Wake

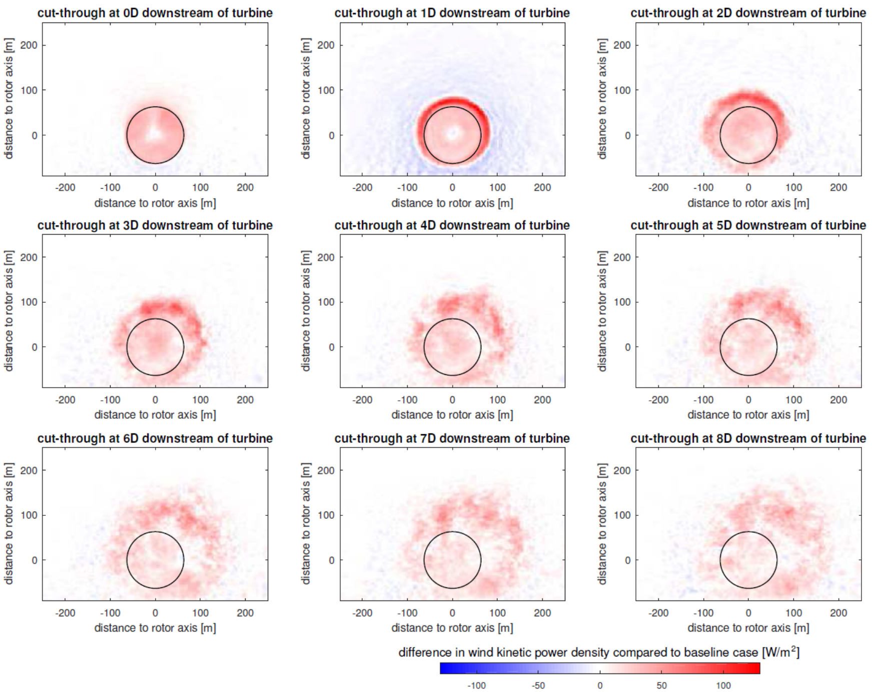


- Sampling flow at several slices downstream of single turbine
- Look at difference in flow for control offsets (pitch, yaw)

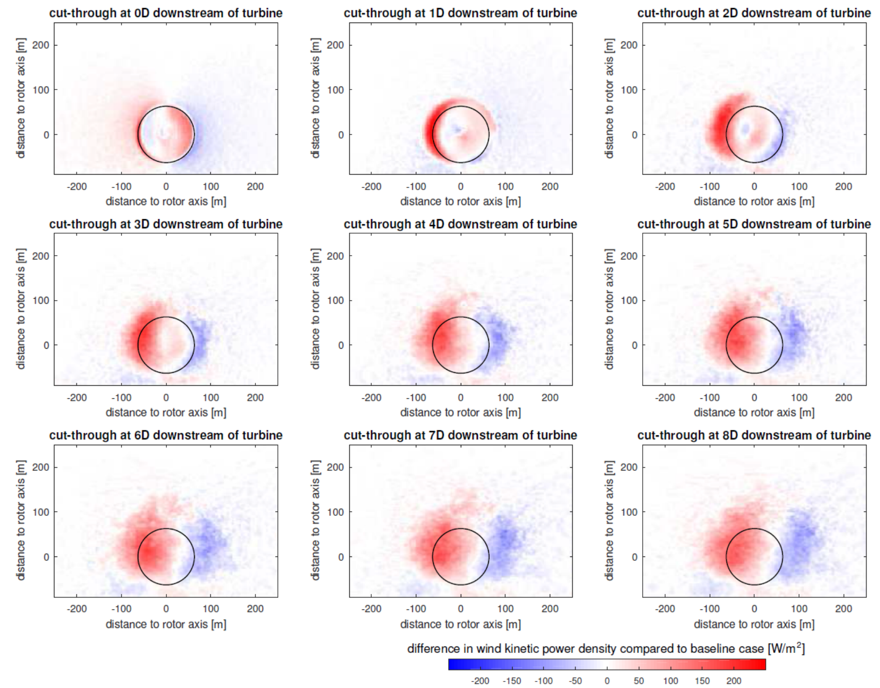
See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*

Analyze Wake

Kinetic power added to the wake:



... by **pitching** 2°

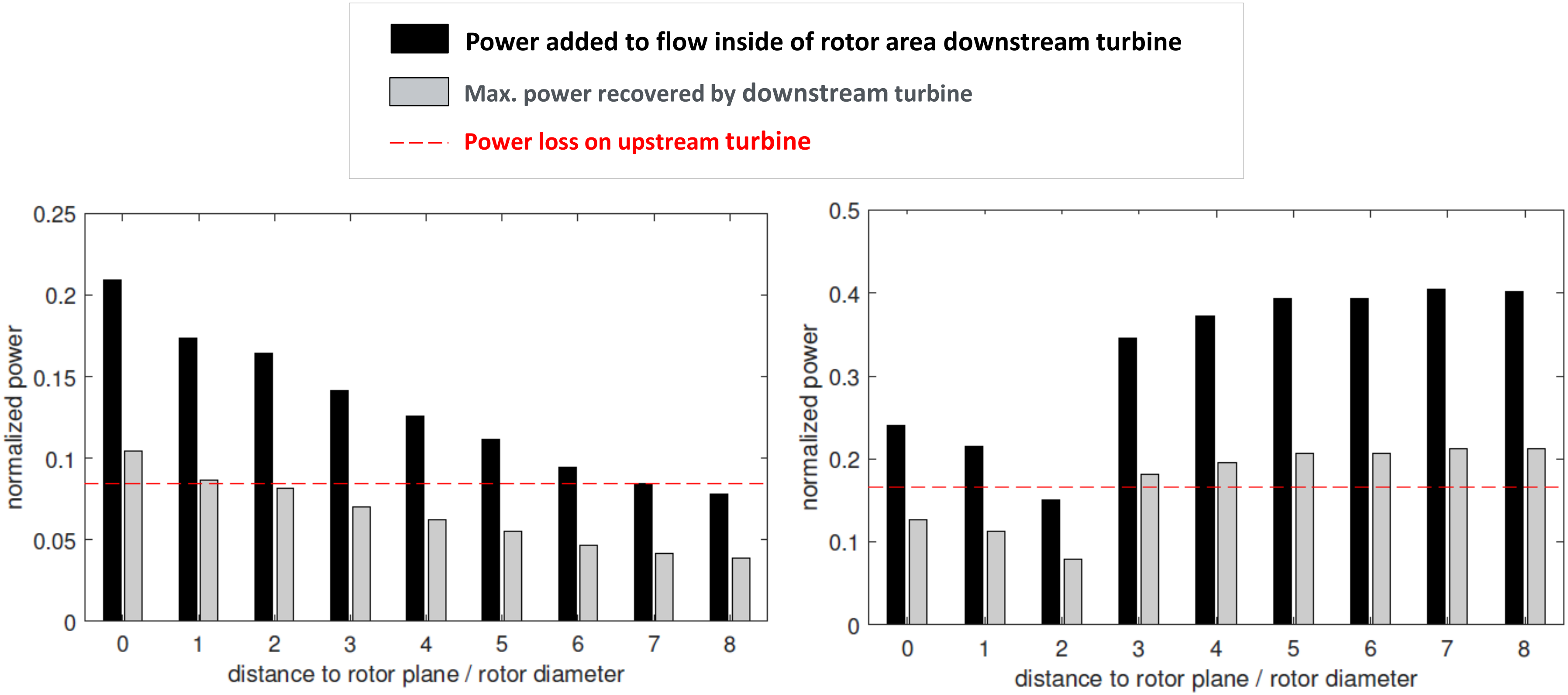


... by **yawing** 25°

See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*

Analyze Wake

Making the power balance:



... by **pitching** 2°

... by **yawing** 25°

See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*

Conclusions

- Larger potential shown for yaw-based wake redirection control than for axial-induction-based control (pitch, torque) in high-fidelity simulation.

- In simulated conditions, axial-induction-based wake control shows no benefit.

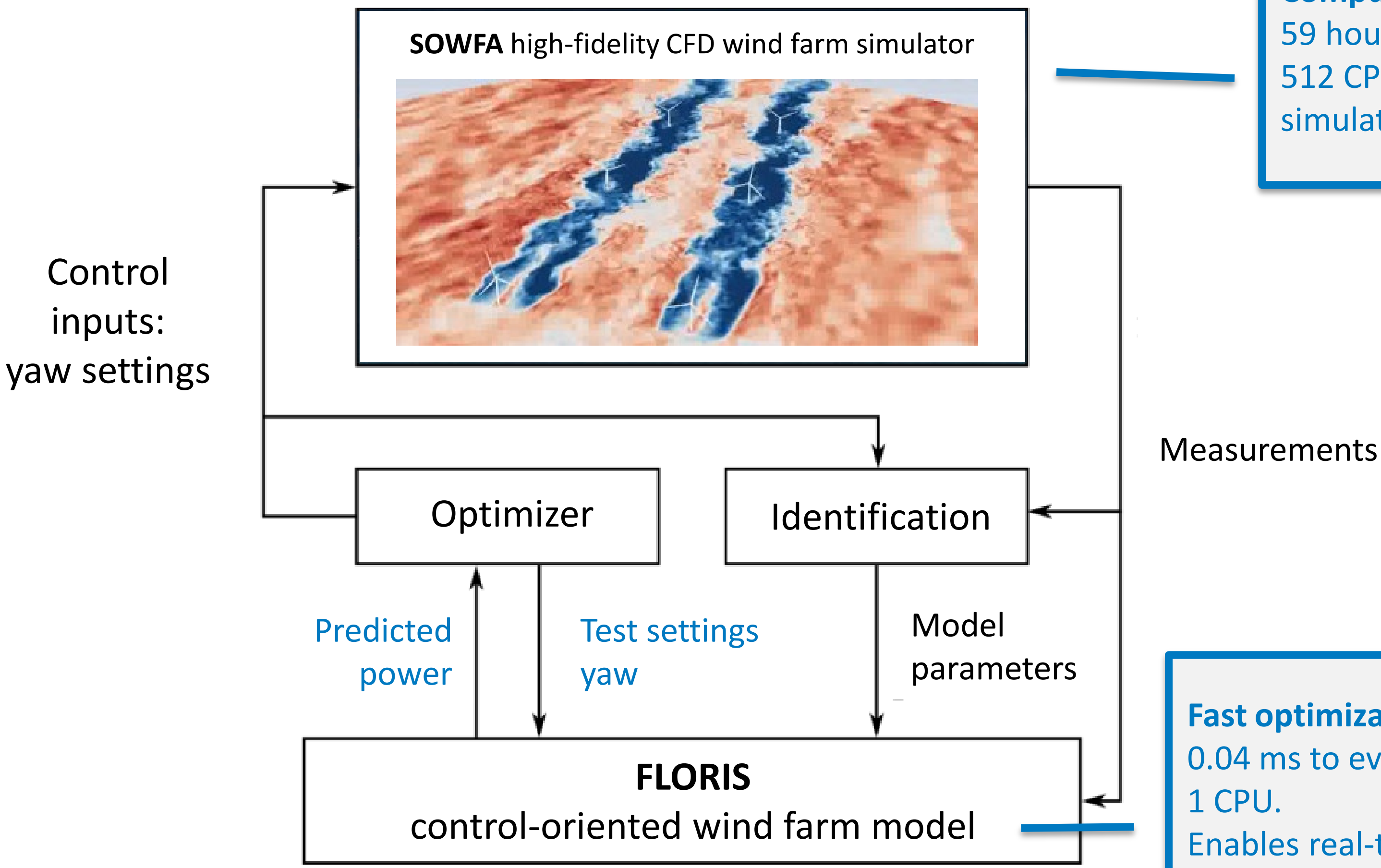
  Causes:
  - Wake expansion
  - Lower thrust → lower turbulence → slower wake recovery

However:

- Potential of techniques depends on:
  - Inflow characteristics
  - Turbine characteristics (C_P and C_T curves).

See also: *Gebraad et al., 2015. "Comparison of Actuation Methods for Wake Control in Wind Plants," ACC.*
Annoni et al., 2015. "Analysis of Axial-induction-based Wind Plant Control Using an Engineering and a High-order Wind Plant Model," Wind Energy.

Wake Steering Control Using Yaw



Computationally complex:
59 hours of computation on 512 CPUs for a 1,000-s simulation.

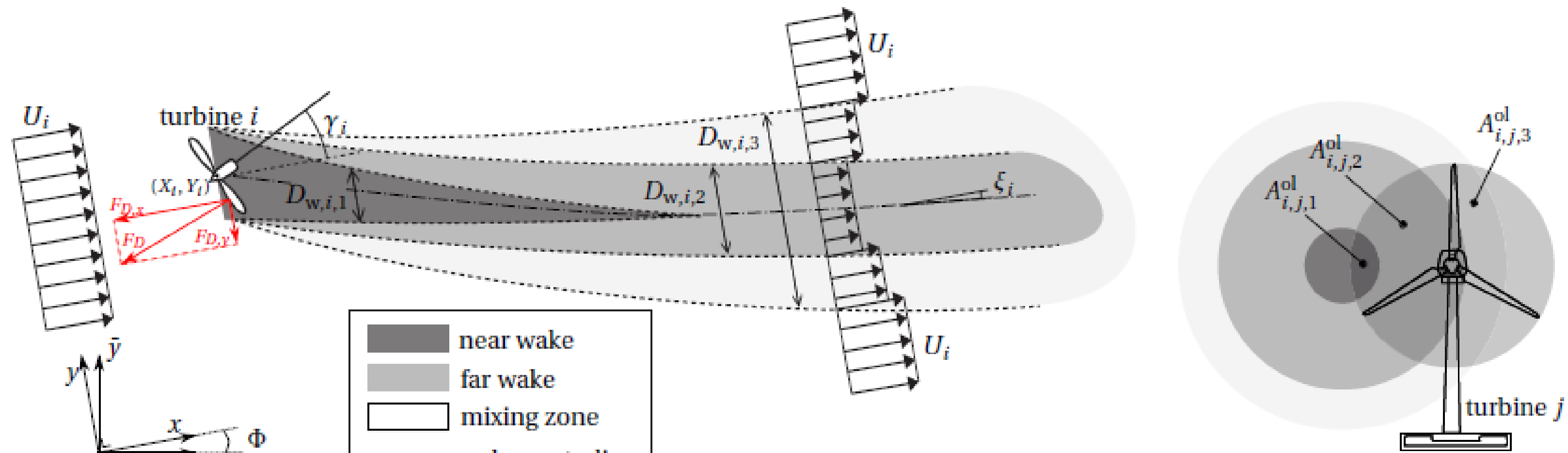
Photo by Dennis Schroeder, NREL 31716

Fast optimization:
0.04 ms to evaluate FLORIS model on 1 CPU.
Enables real-time online optimization.

See also: *Gebraad et al., 2014. "Wind Plant Power Optimization through Yaw Control Using a Parametric Model for Wake Effects – a CFD Simulation Study," Wind Energy.*

Wake Steering Control Using Yaw

- For wake steering control, we use the FLORIS engineering model to predict the effects of control on wake redirection and induction properties.



(a) Top view

(b) Cut-through at downstream turbine

See also: *Gebraad et al., 2014. "Wind Plant Power Optimization through Yaw Control Using a Parametric Model for Wake Effects – a CFD Simulation Study," Wind Energy.*

Wake Steering Control Using Yaw

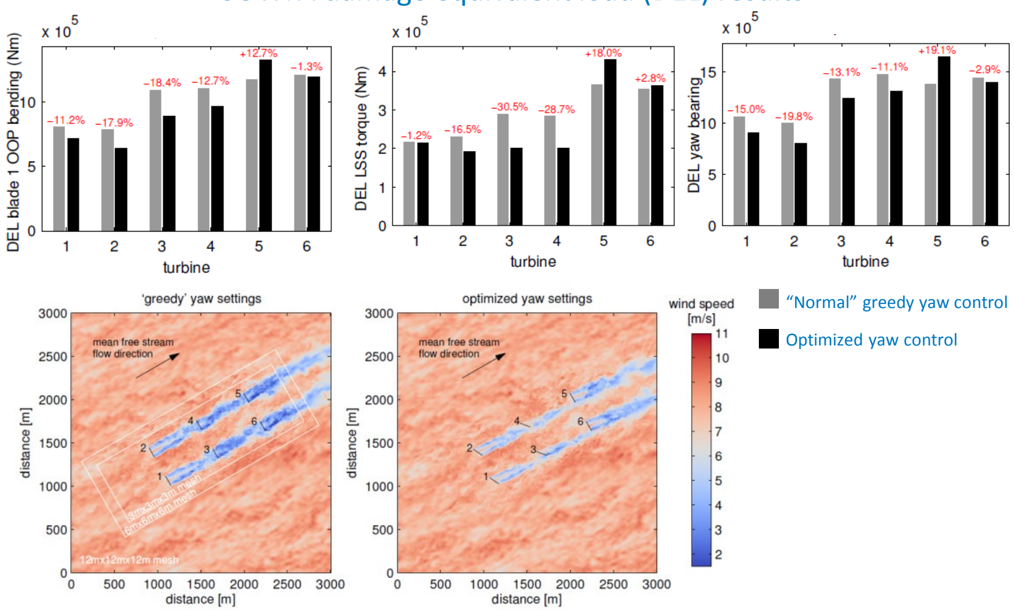
See also: *Gebraad et al., 2014. "Wind Plant Power Optimization through Yaw Control Using a Parametric Model for Wake Effects – a CFD Simulation Study," Wind Energy.*

Data-Driven Wind Plant Control

Load effects:

- Yawing *can* reduce blade loads, depending on direction
- Reducing wake overlap *can* reduce blade loads on downstream turbine
- Possibility to mitigate load increases with individual pitch control
- Now validating with NREL's Control Advanced Research Turbines (CARTs) with lidar

SOWFA damage equivalent load (DEL) results



Flap-wise blade-bending DEL on CART3

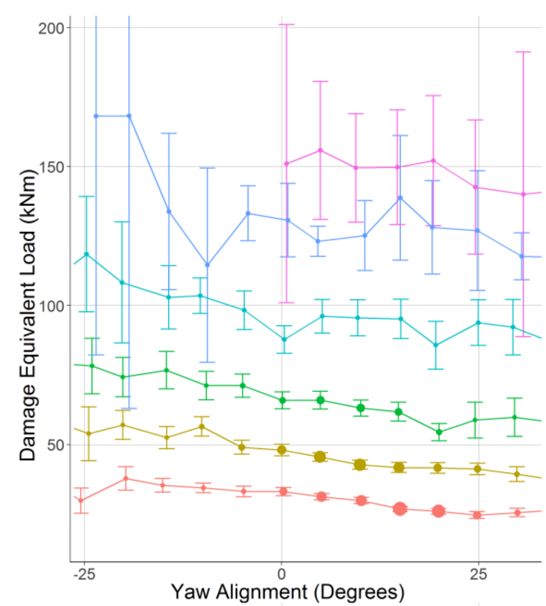


Photo by Lee Jay Fingersh, NREL.

See also: *Fleming et al. , 2014. "Simulation Comparison of Wake Mitigation Control Strategies for a Two-turbine Case," Wind Energy.*
Gebraad et al. , 2014. "Wind Plant Power Optimization through Yaw Control Using a Parametric Model for Wake Effects - a CFD Simulation Study," Wind Energy.

Combined Optimization

- The previous work assumes a fixed plant layout and turbine design
- Perhaps the benefit of wind plant control could be amplified if accounted for during the early phase of design
- A proof-of-concept study was performed in which wind plant controls and layout were optimized

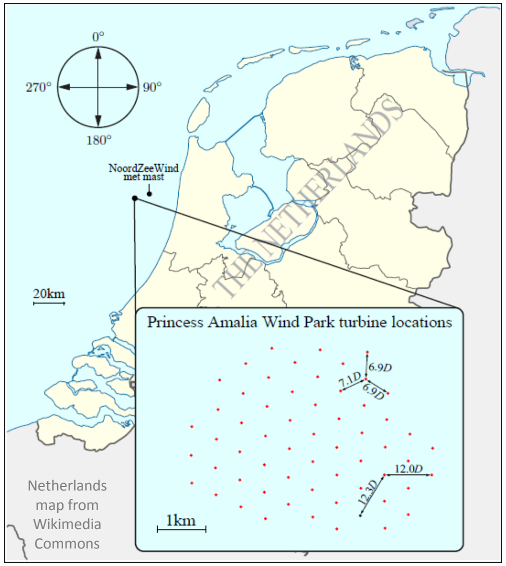
See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

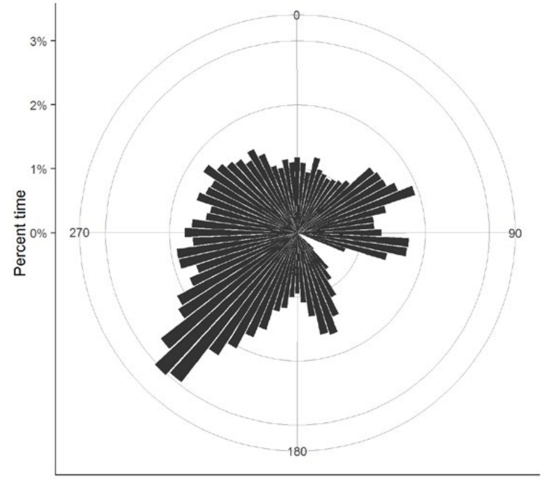
Combined Optimization Case Study: Princess Amalia Wind Park

In this example case, we use **power density of the wind farm (W/m²)** as a proxy to cost of energy.

In the next slides, we compare:

- **Baseline**: fixed (original) positions, turbines all yawed in mean wind direction
- **Optimized yaw**: fixed (original) positions, turbines optimally yawed for each wind direction
- **Optimized location**: position optimized, turbines all yawed in mean wind direction
- **Combined optimization**: simultaneously optimized position and yaw for each wind direction.





wind rose

Note 1: Full paper considered cable length and boundary limitations as well

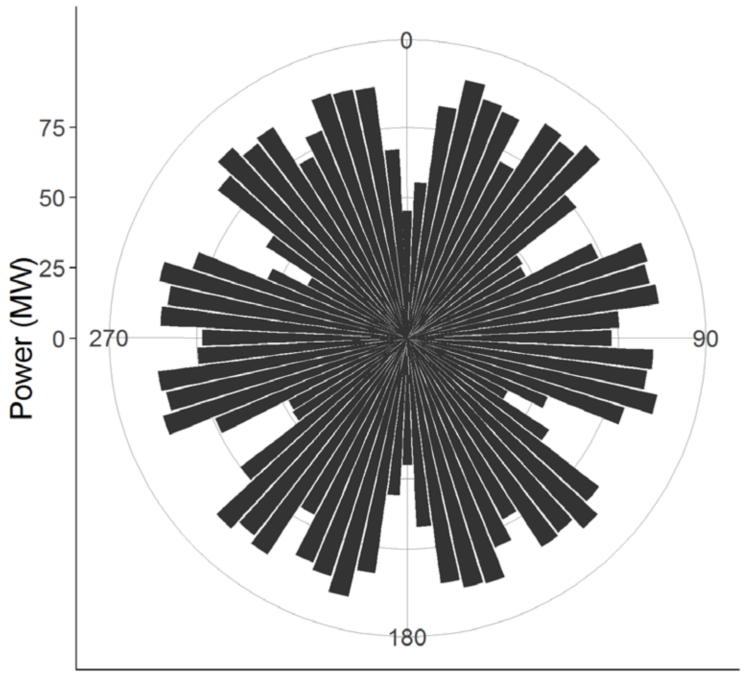
Note 2: NREL's 5-MW turbines were used in place of ~2-MW turbines, making baseline spacings closer

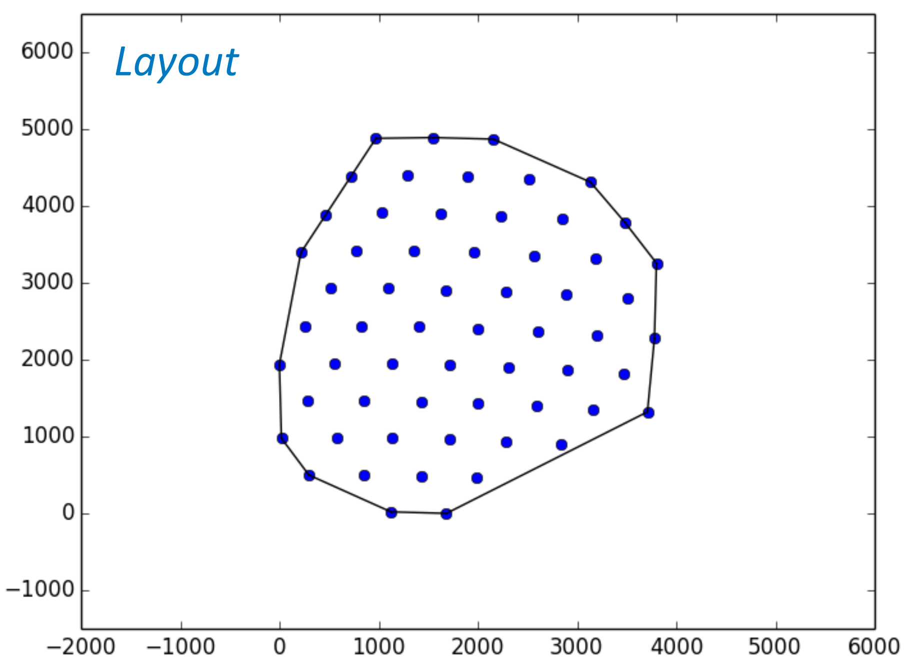
Note 3: Wind rose from nearby Offshore Windpark Egmond aan Zee met mast

See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Princess Amalia Wind Park

	Baseline	Yaw Opt.	Positions Opt.	Combined
Mean power (MW)	78.86	84.91	78.86	78.84
Area (km^2)	14.53	14.53	12.45	8.96
Power density (W/m^2)	5.43	5.84	6.33	8.80

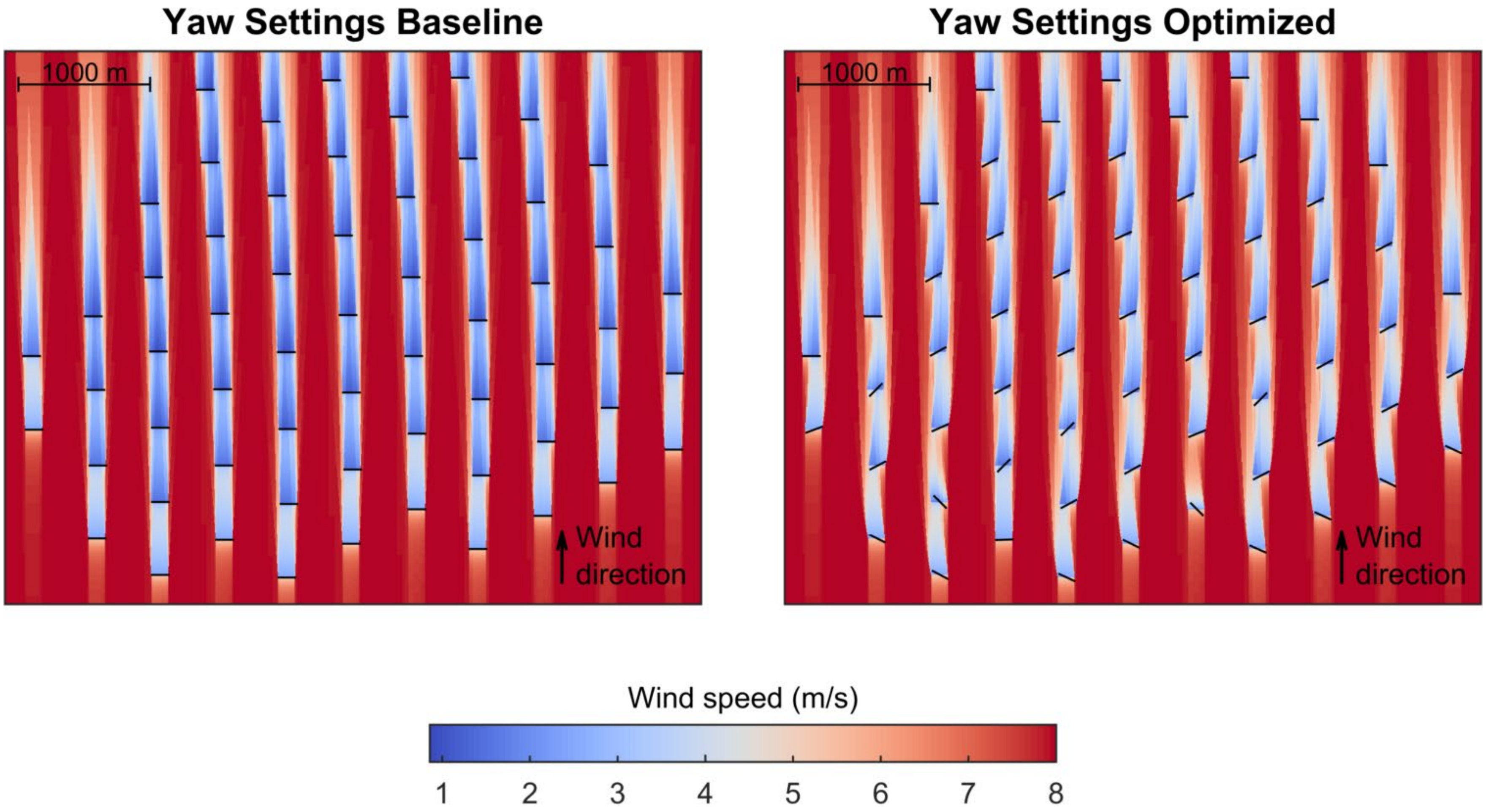




See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Princess Amalia Wind Park

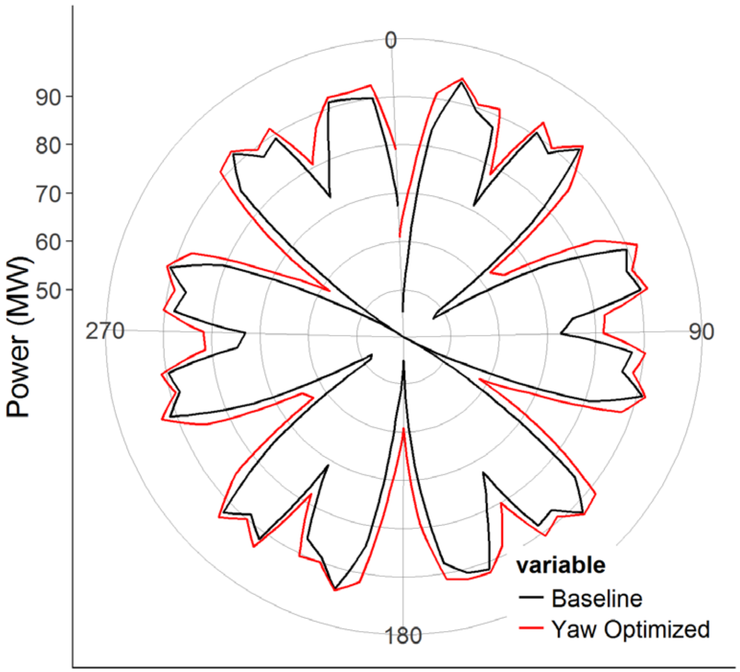
Yaw optimization for 180° wind direction, based on FLORIS:

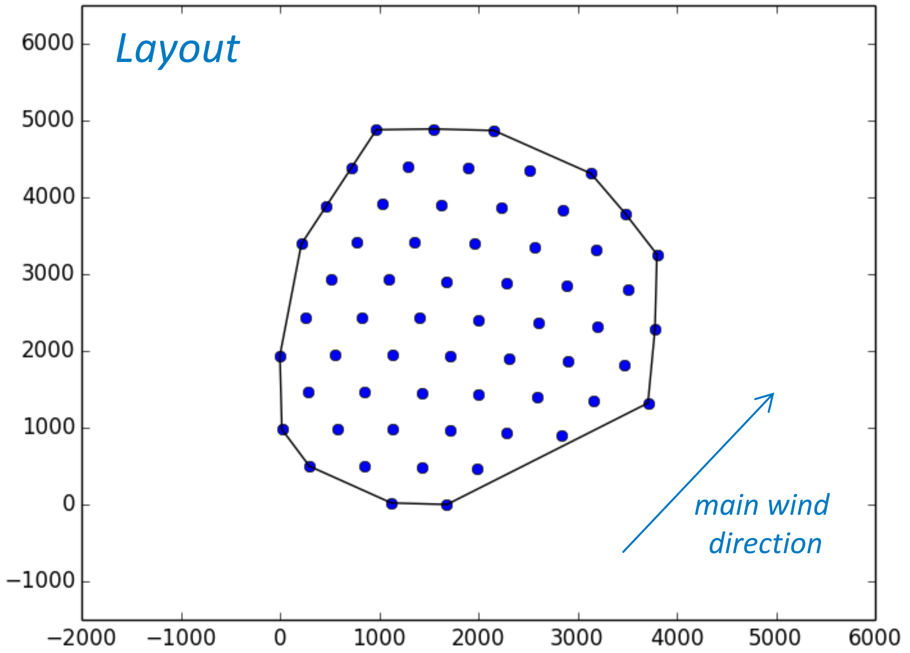


See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Princess Amalia Wind Park

	Baseline	**Yaw Opt.**	Positions Opt.	Combined
Mean power (MW)	78.86	84.91	78.86	78.84
Area (km^2)	14.53	14.53	12.45	8.96
Power density (W/m^2)	5.43	5.84	6.33	8.80

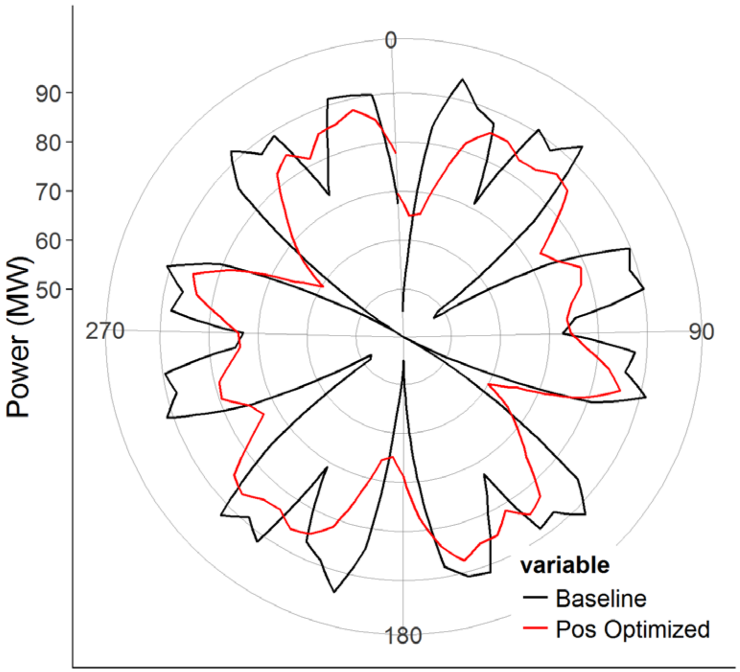


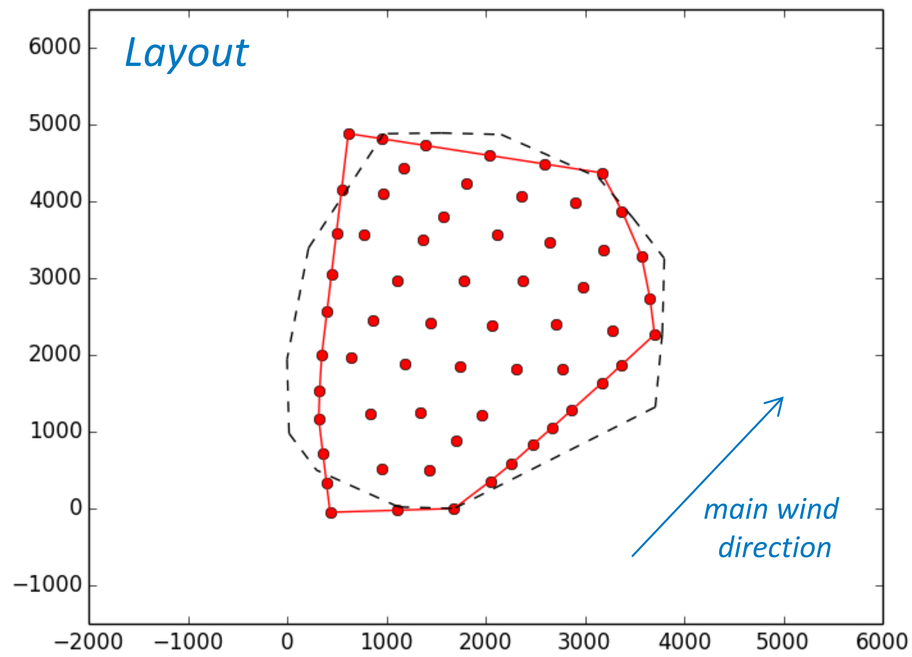


See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Princess Amalia Wind Park

	Baseline	Yaw Opt.	**Positions Opt.**	Combined
Mean power (MW)	78.86	84.91	78.86	78.84
Area (km^2)	14.53	14.53	12.45	8.96
Power density (W/m^2)	5.43	5.84	6.33	8.80

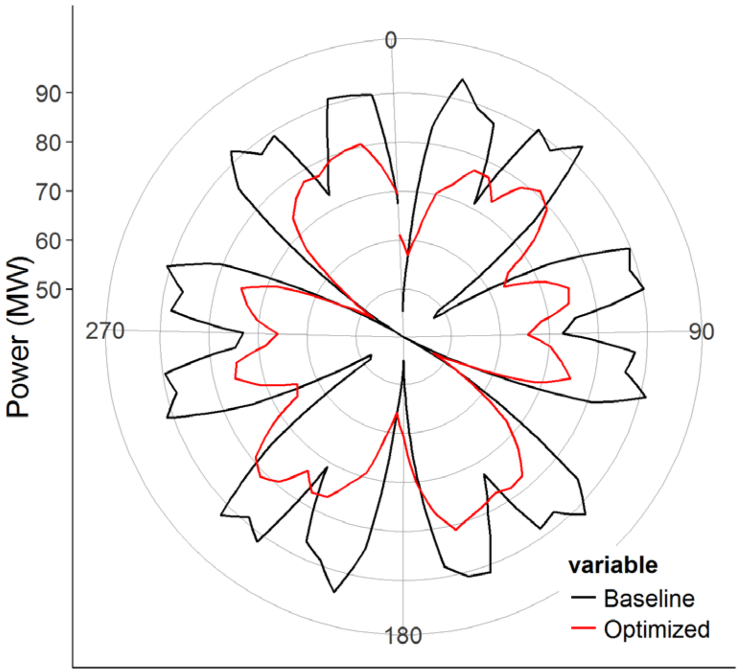


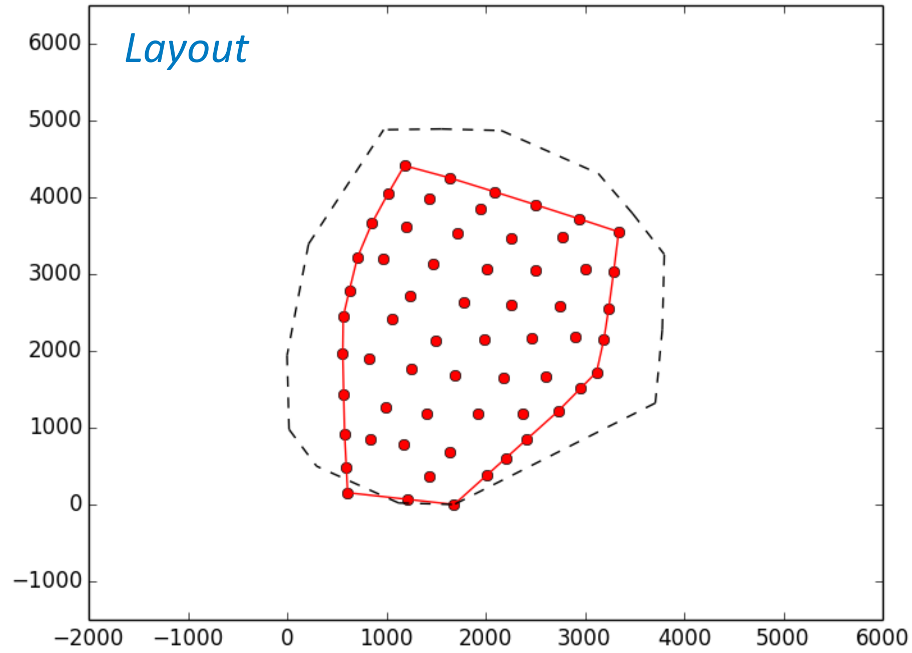


See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Princess Amalia Wind Park

	Baseline	Yaw Opt.	Positions Opt.	**Combined**
Mean power (MW)	78.86	84.91	78.86	78.84
Area (km^2)	14.53	14.53	12.45	8.96
Power density (W/m^2)	5.43	5.84	6.33	8.80





See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*

Combined Optimization Case Study: Results

- Coupling yaw control and position density provided a 40% increase in power density over layout optimization alone and 50% more than yaw control alone
- Proof-of-concept study demonstrated that the potential of wind plant control can be greatly expanded if included in the design phase
- Current work: we are extending FLORIS to be able to optimize annual energy production instead of power density

See also: *Fleming et al., 2015. "Wind Plant System Engineering through Optimization of Layout and Yaw Control," Wind Energy.*