NREL
Transforming ENERGY

Re-thinking plant operation and control – maximizing profitability over the plant lifetime

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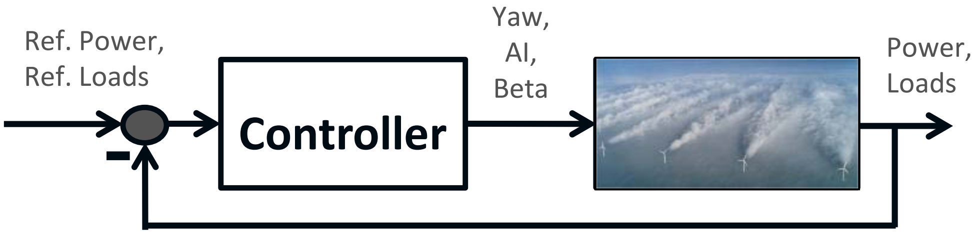
Wind Energy Systems Engineering Workshop

Pamplona, Spain

Controls in Wind Plants

- Recent focus on wind plant controls
- Goals of wind farm control:
  - AEP gains
  - Grid services
  - Load reduction
- How it is being done:
  - Wake steering
  - Axial induction control
  - Individual Pitch Control (IPC)
- General need for controls-oriented models



Horns Rev 1 (Photographer: Christian Steiness)

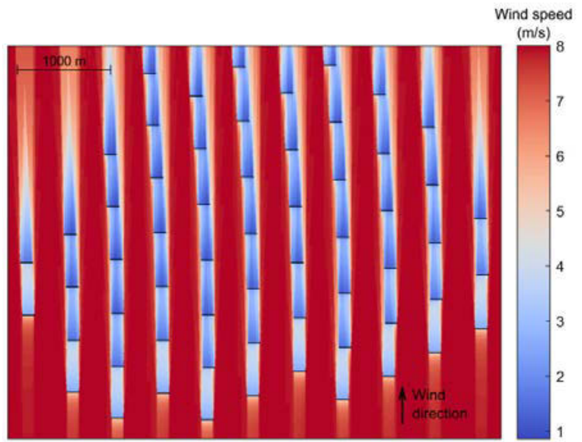
FLORIS: Controls-Oriented Wind Farm Model

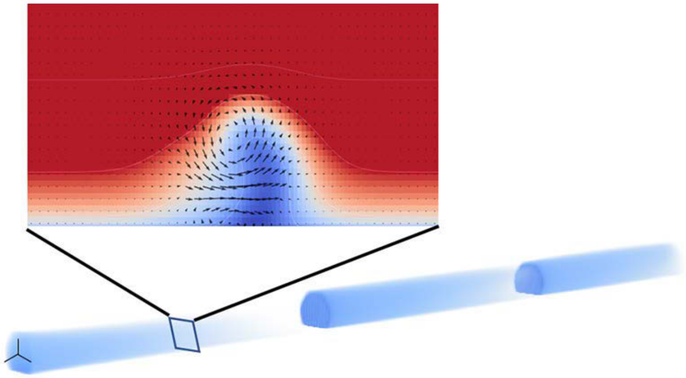
FLORIS framework provides a computationally inexpensive, controls-oriented modeling tool for steady-state characteristics in wind farms.

Available on github (https://github.com/NREL/floris) with several examples.

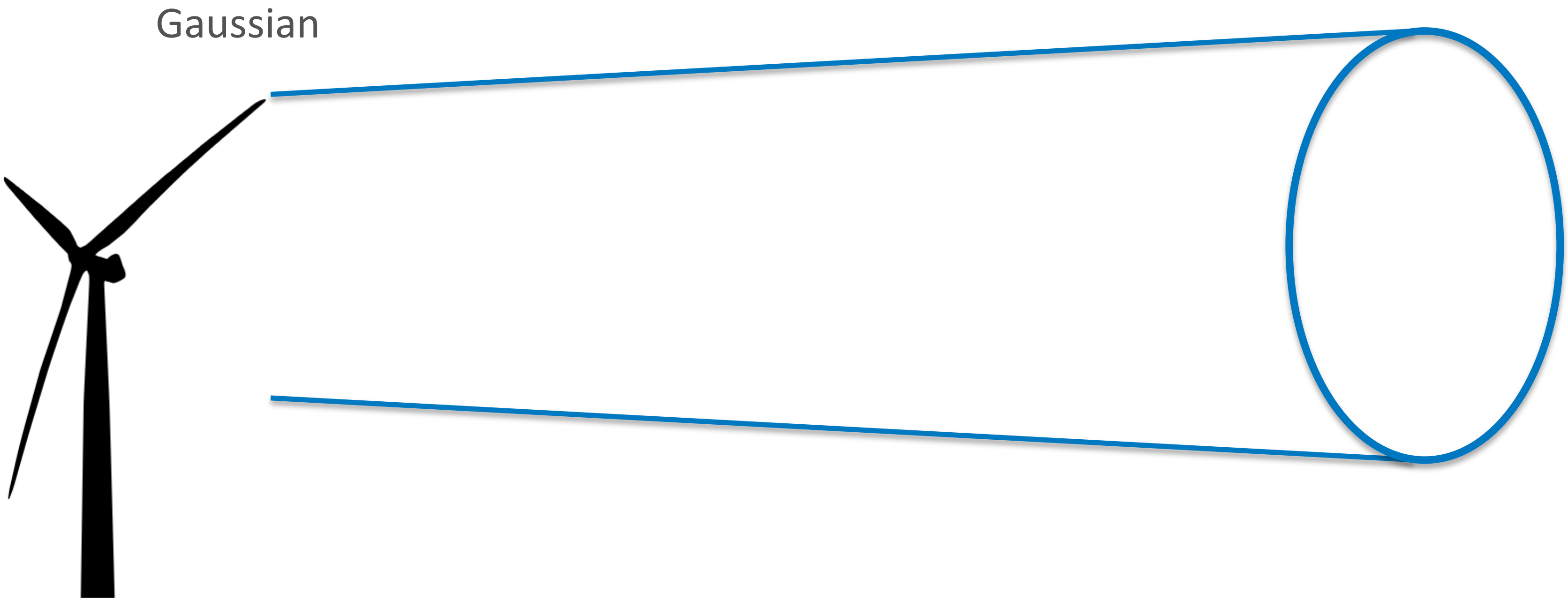
Models currently implemented:

- Jensen model for velocity deficit
- Jimenez model for wake deflection
- Gauss model for deflection and velocity deficit
- Curl model for deflection and velocity deficit

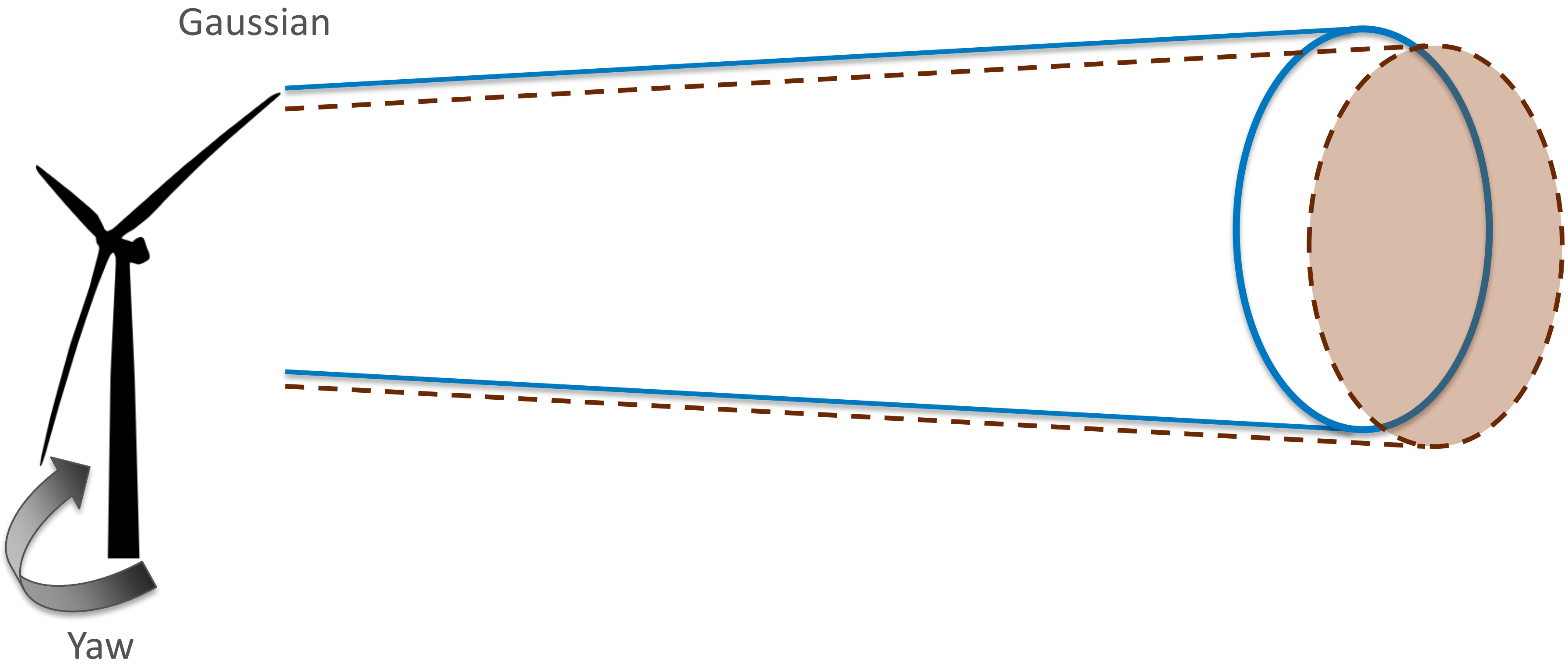




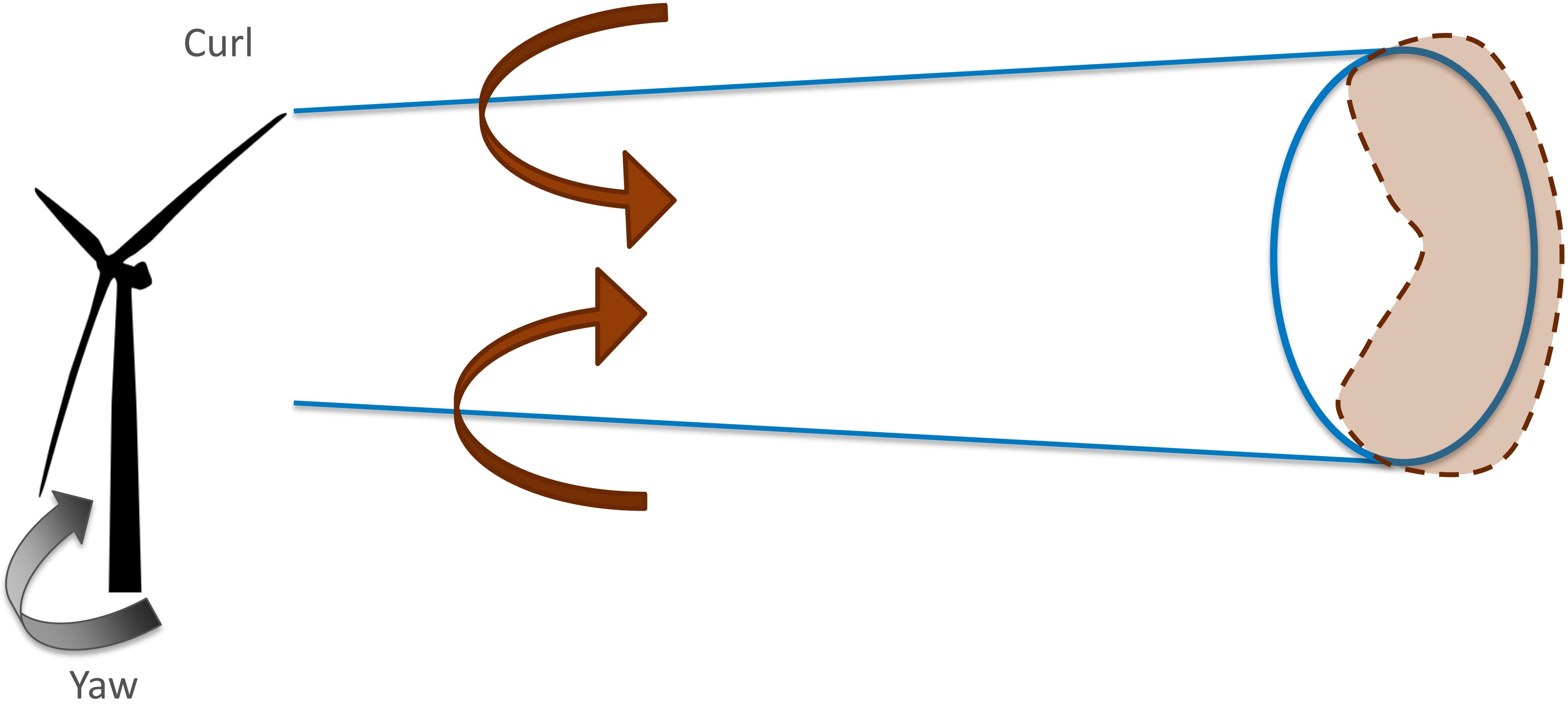
Gaussian Model



Gaussian Model



Aerodynamics of Wake Steering



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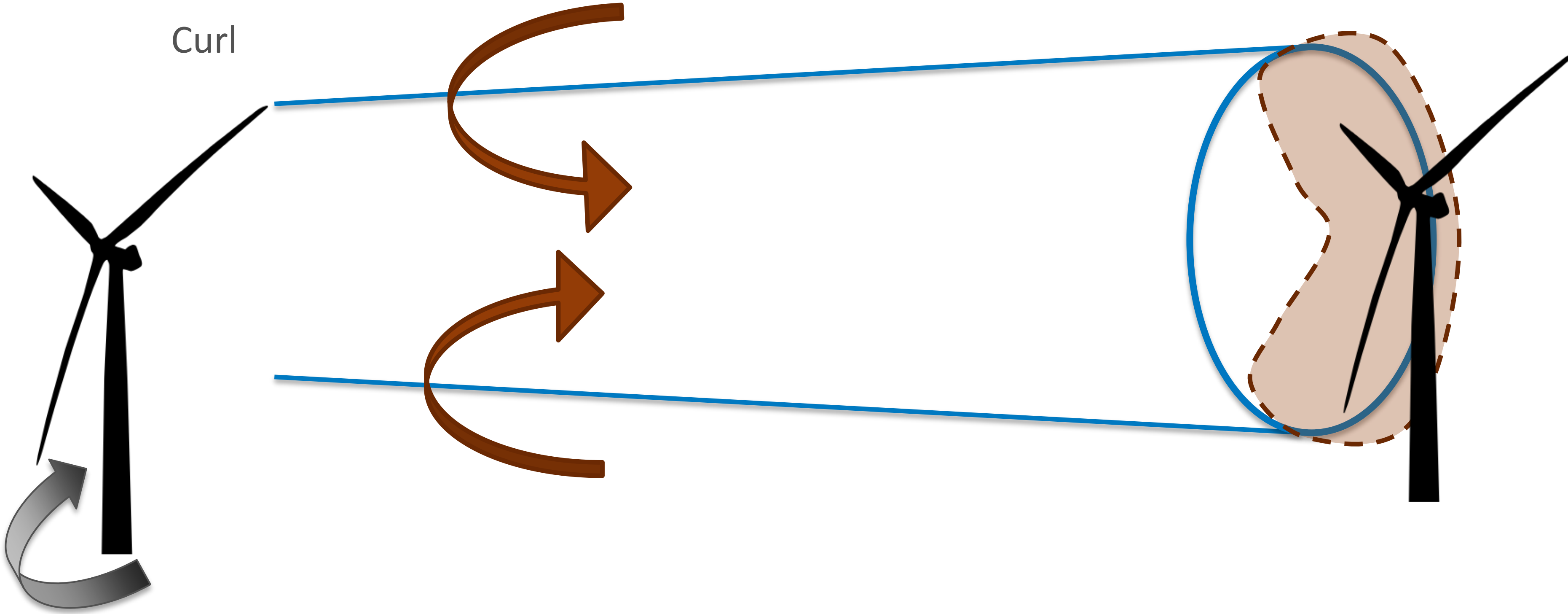
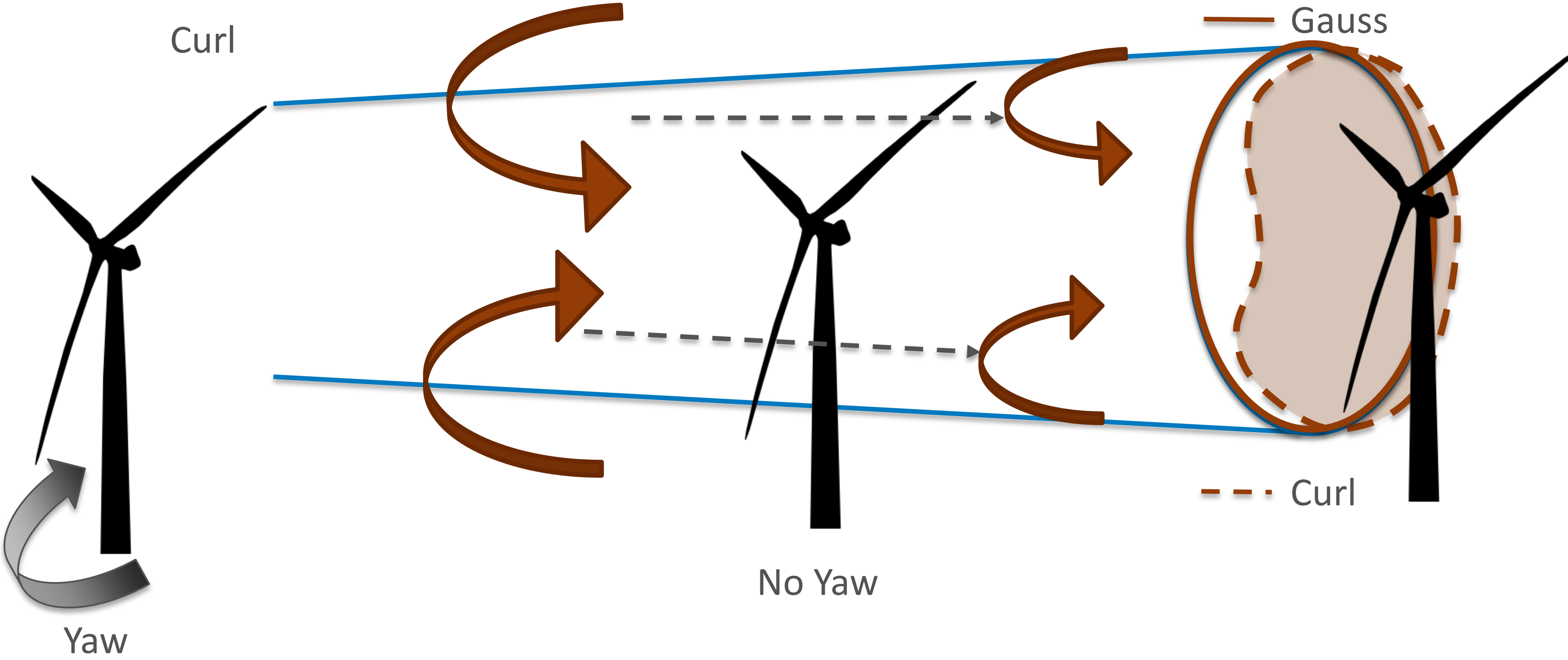


Both the Gaussian and Curl model capture
2 turbine effects very well

Aerodynamics of Wake Steering

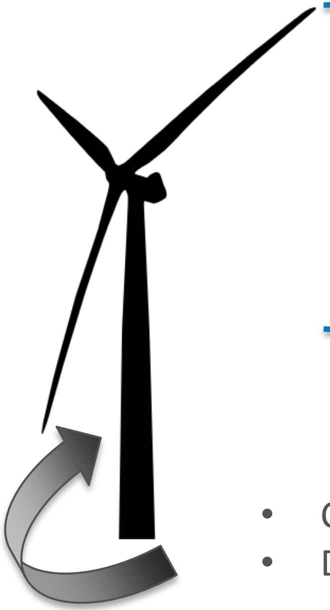


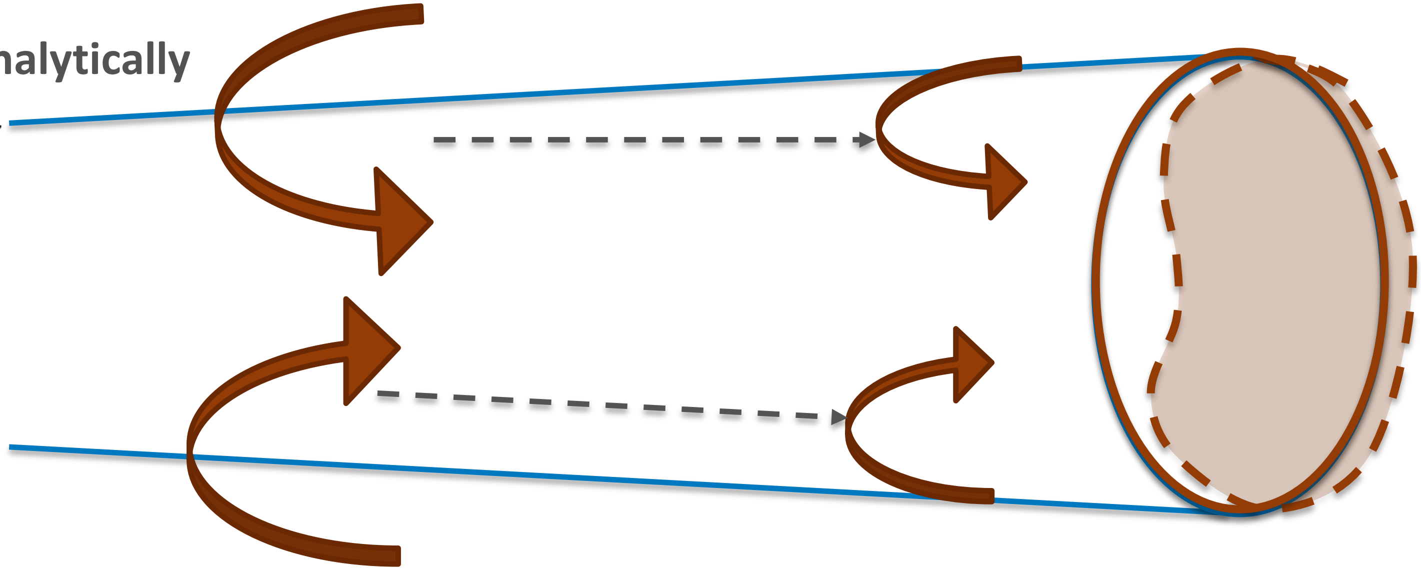
Effects from first turbine persist downstream.

Wake steering is even more beneficial in large rows of turbines (offshore)

Overview of the Curl Model

Find V, W analytically





Yaw

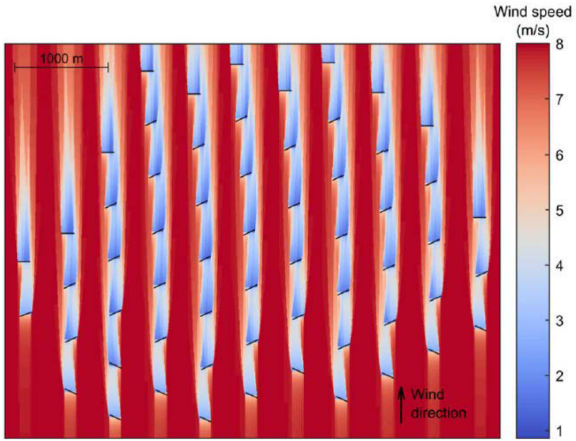
- Curl is a finite difference model that takes O(10s) to run for small wind farms
- Developing a new version that takes into account vortices but runs in fractions of a second
  - Used throughout this presentation
  - Public release later this year

Martínez-Tossas, L. A., Annoni, J., Fleming, P. A., and Churchfield, M. J.: The aerodynamics of the curled wake: a simplified model in view of flow control, Wind Energ. Sci., 4, 127-138, https://doi.org/10.5194/wes-4-127-2019, 2019.

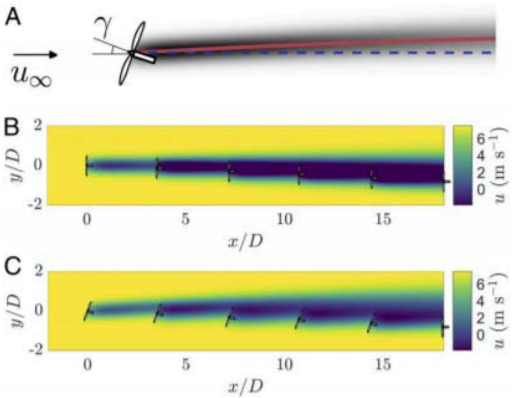
Application of Wake Steering

- Wake deflection can be used in wind turbine arrays/farms to increase AEP
- Gain in downstream turbines can outweigh loss in upstream turbines
- Wake steering is more powerful in low-TI conditions
- Active research into wake steering over recent years

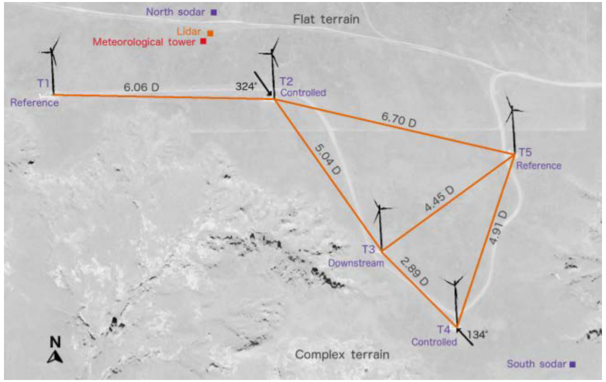
*Not a complete list



(Fleming, et. al., 2016)



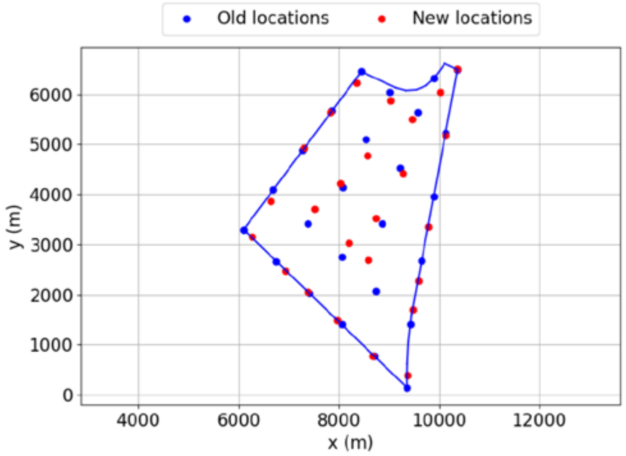
(Howland, et. al., 2018)



(Fleming, et. al., 2019)

Systems Engineering + Wake Steering

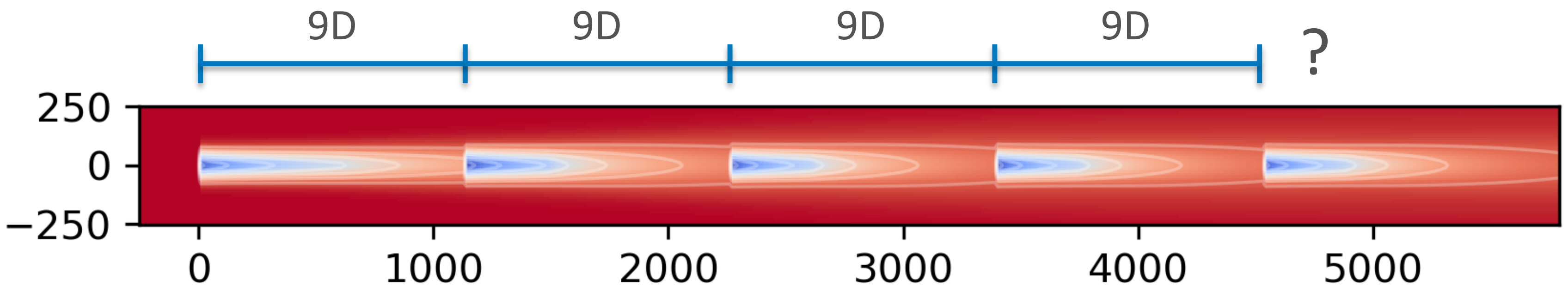
- What becomes possible when you include wake steering in the design process?
  - Increase AEP (regular or tight boundaries)
  - Maintain AEP while minimizing footprint



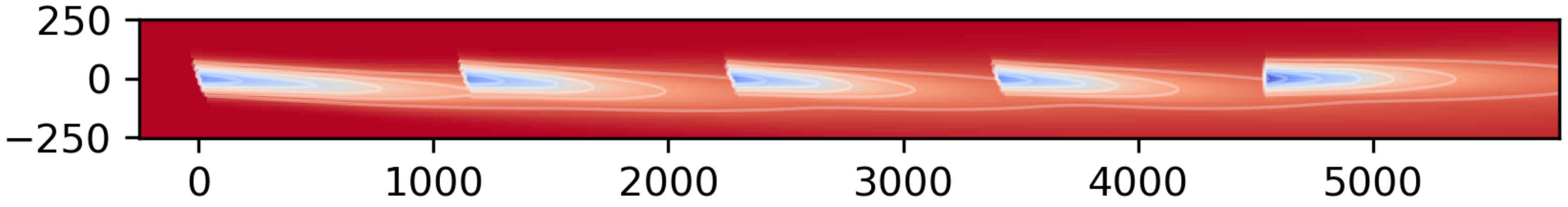
$$\begin{aligned} &\underset{x,y,\gamma}{\text{minimize}} \quad -\sum_{i=1}^{N_{turb}} P_i\left(x_i, y_i, \gamma_i, w_s, w_d, f\right) \\ &\text{subject to} \quad \underline{x} < x_i < \overline{x}, \qquad S_i > 3D, \\ &\qquad\qquad\quad \underline{y} < y_i < \overline{y}, \qquad \underline{\gamma} < \gamma_i < \overline{\gamma} \end{aligned}$$

$$\begin{aligned} &\underset{x,y,\gamma}{\text{minimize}} \quad -\frac{1}{A(x,y)}\sum_{i=1}^{N_{turb}} P_i\left(x_i, y_i, \gamma_i, w_s, w_d, f\right) \\ &\text{subject to} \quad \underline{x} < x_i < \overline{x}, \qquad S_i > 3D, \\ &\qquad\qquad\quad \underline{y} < y_i < \overline{y}, \qquad \underline{\gamma} < \gamma_i < \overline{\gamma}, \\ &\qquad\qquad\quad \sum_{i=1}^{N_{turb}} P_i > P_{init} \end{aligned}$$

Illustrative Example

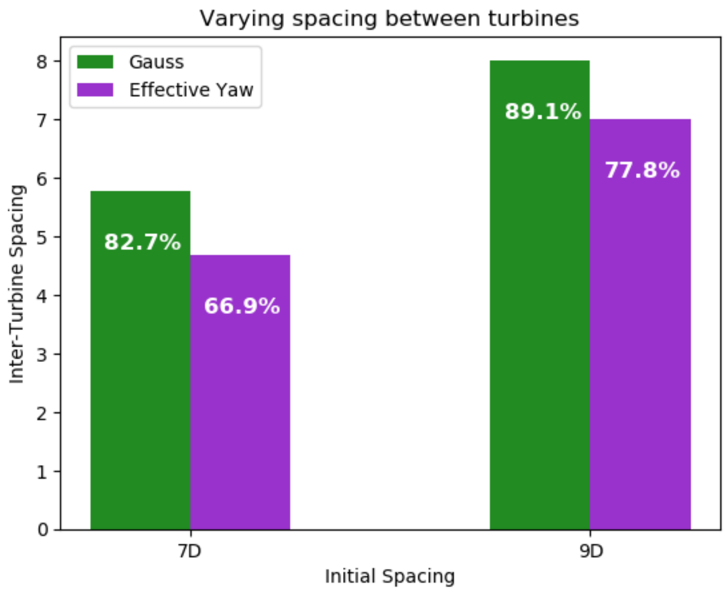


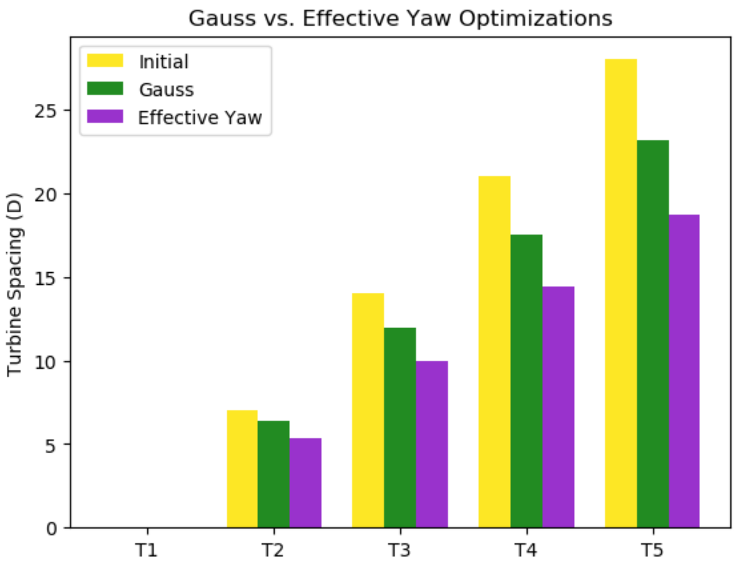
Baseline power: 5.46 MW



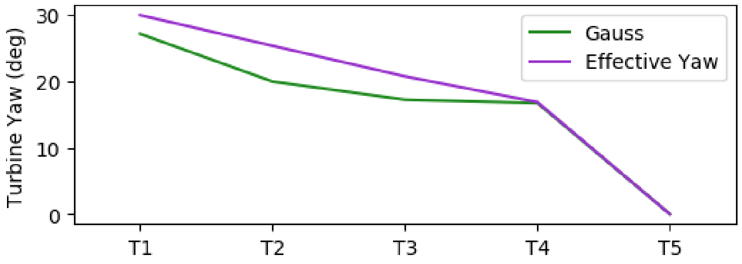
Yawed power: 5.80 MW

Individual Spacing Optimization Results

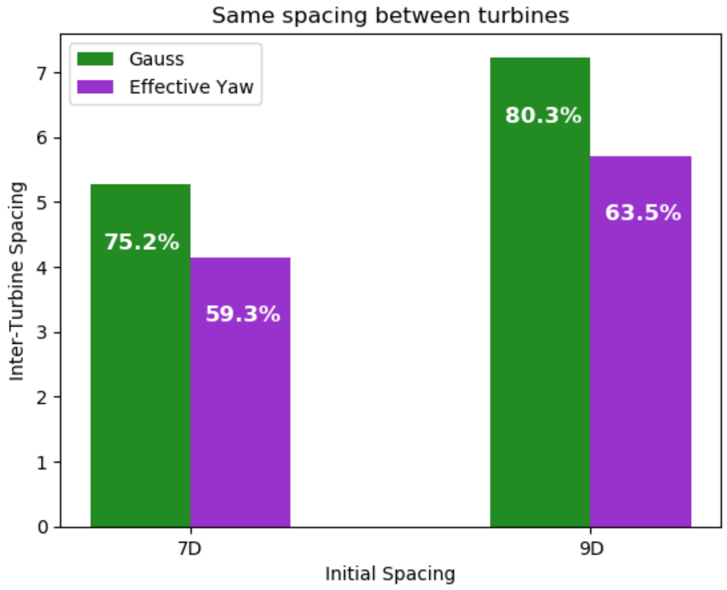


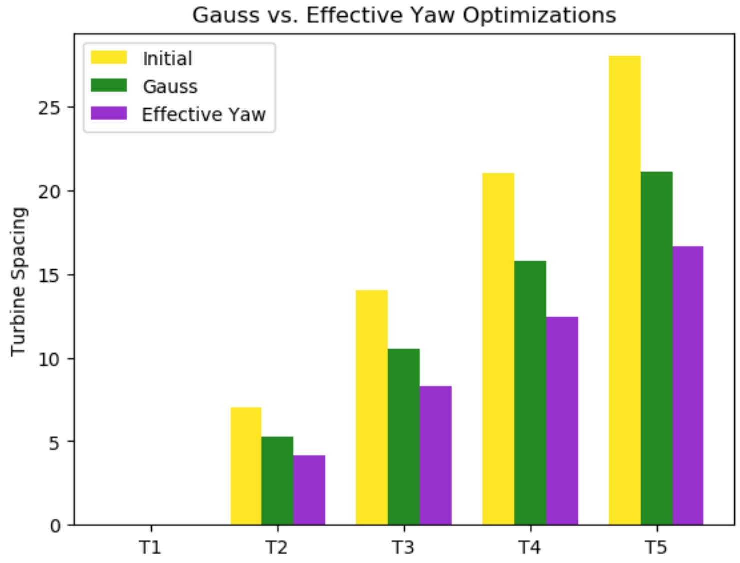


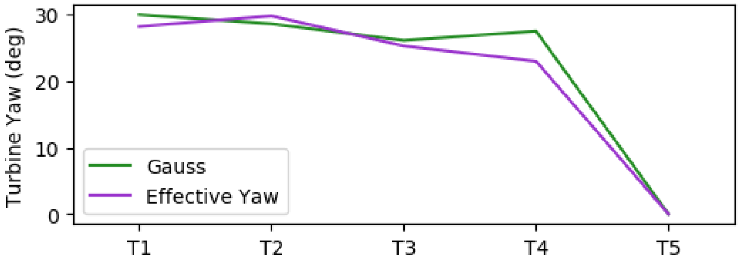
- Significant reduction in average spacing of turbines



Constant Spacing Optimization Results

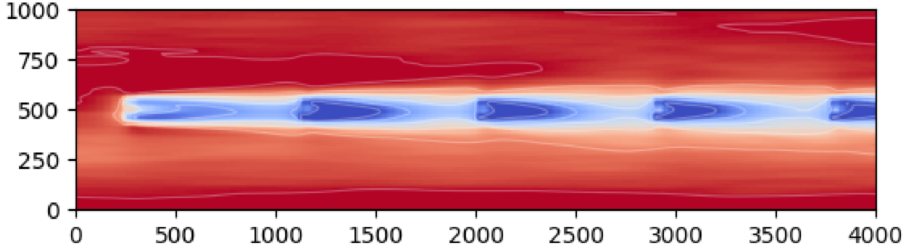


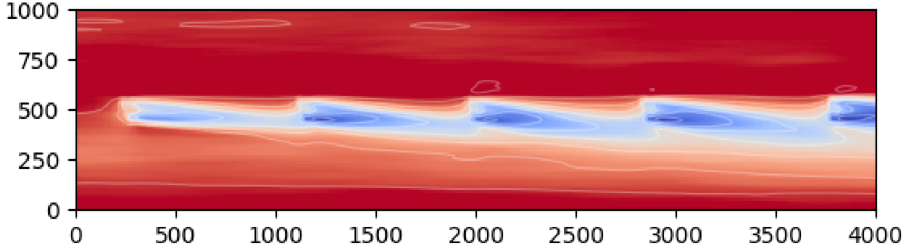


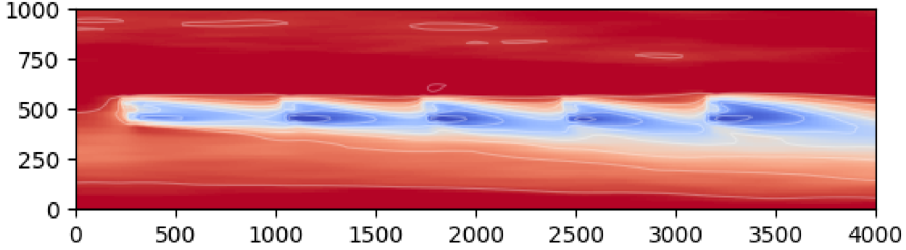


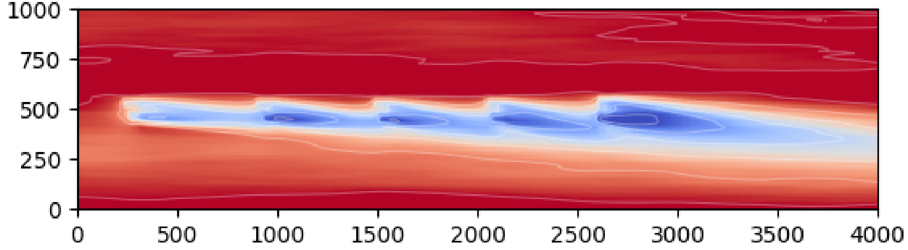
- Effective yaw model gives a more aggressive approach

Validation Against SOWFA

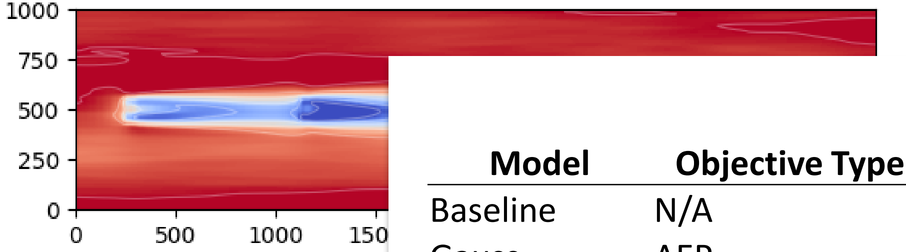


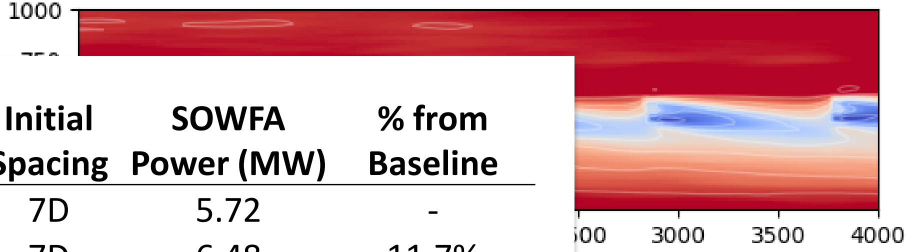




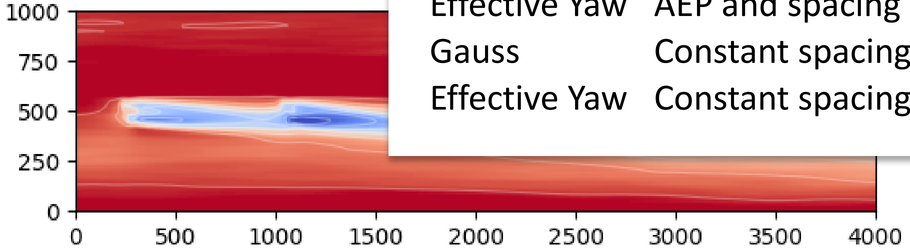


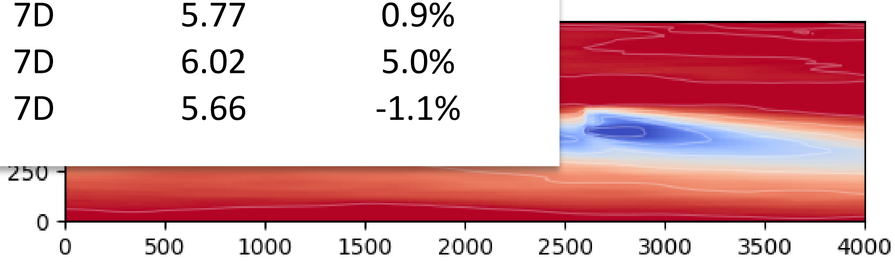
Validation Against SOWFA





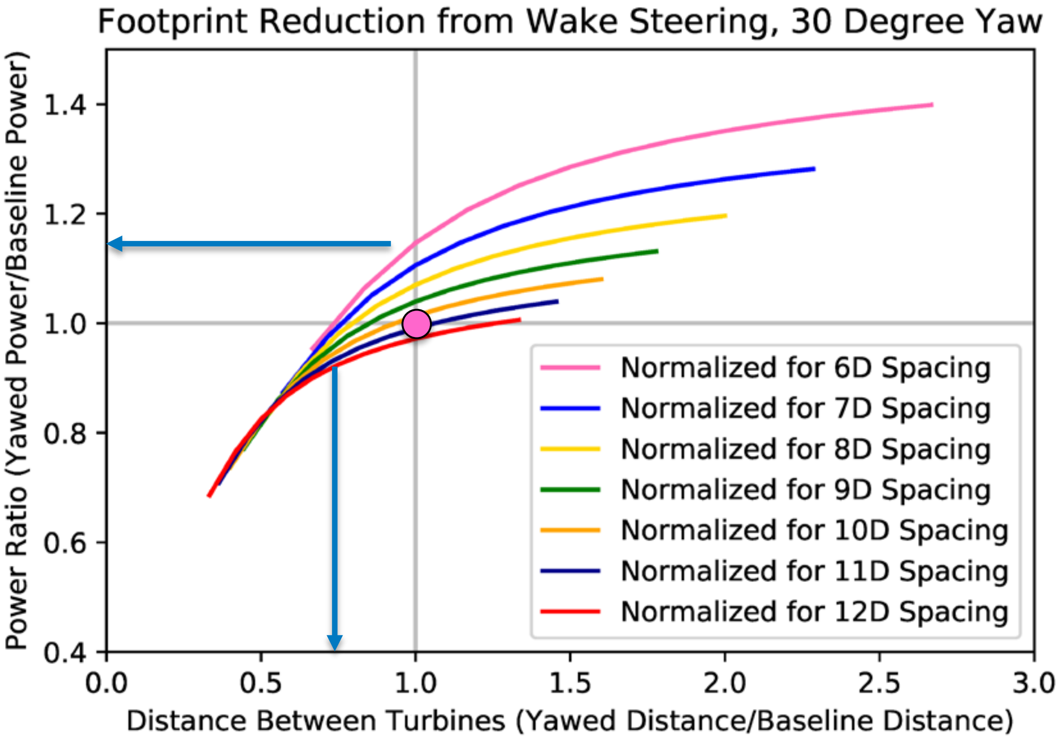
Model	Objective Type	Initial Spacing	SOWFA Power (MW)	% from Baseline
Baseline	N/A	7D	5.72	-
Gauss	AEP	7D	6.48	11.7%
Effective Yaw	AEP	7D	6.68	14.4%
Gauss	AEP and spacing	7D	6.02	5.0%
Effective Yaw	AEP and spacing	7D	5.77	0.9%
Gauss	Constant spacing	7D	6.02	5.0%
Effective Yaw	Constant spacing	7D	5.66	-1.1%





Influence of Initial Conditions on What Can be Achieved

- Performed sweep of different optimization initial conditions
- Trends show closer-spaced turbines have more potential for footprint reduction while maintaining same AEP output
- Lower yaw angles give larger spacings more potential



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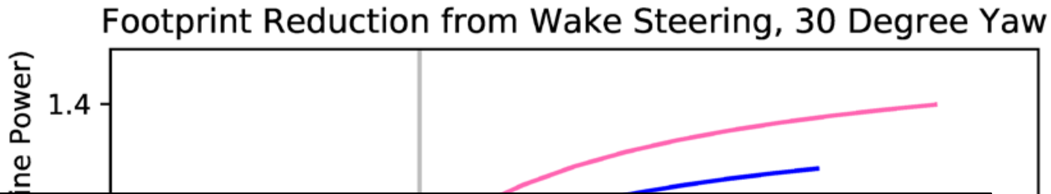
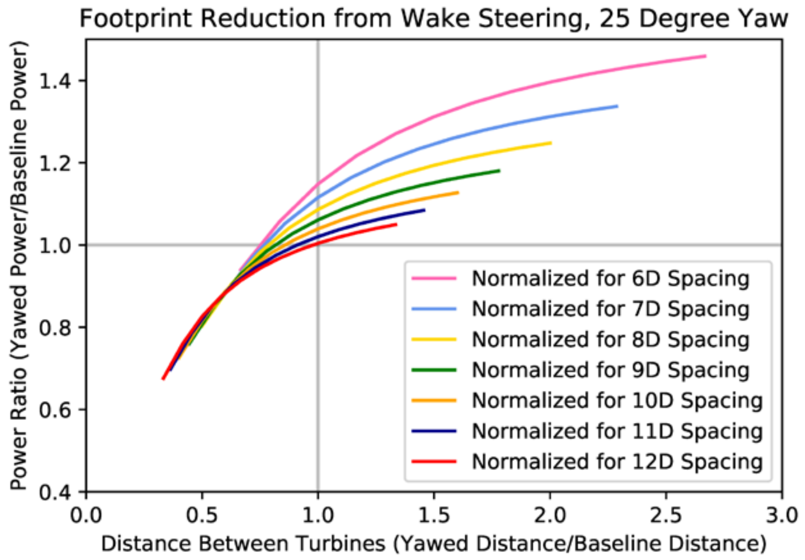
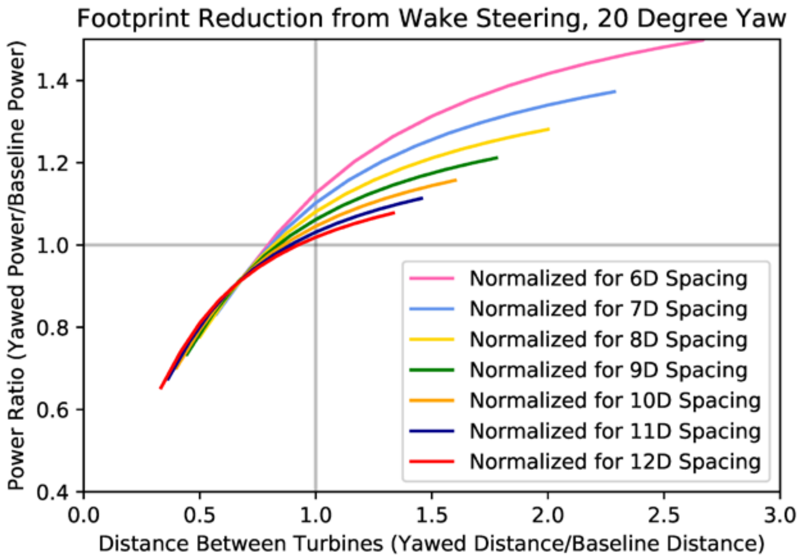
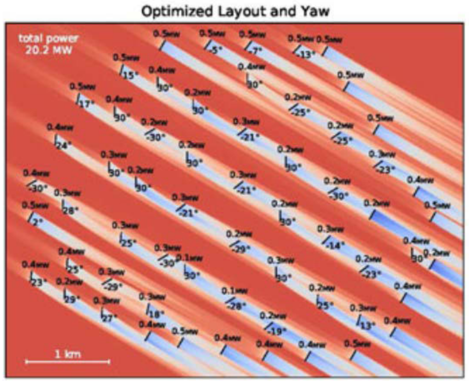




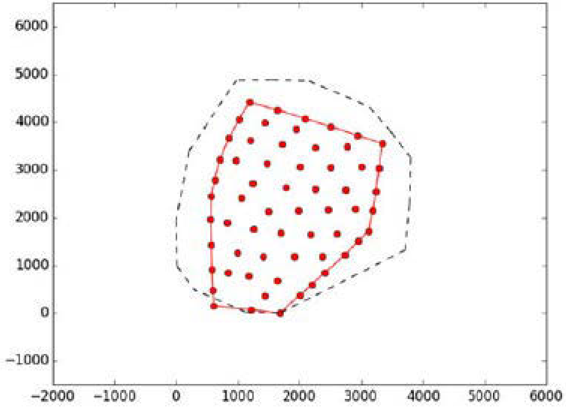


Summary

- Limited previous work of wake steering + layout has been completed in literature
- Improving FLORIS' modelling of yawing turbine effect for deeper arrays
- New FLORIS code has optimization module
    - Under continuing development
- Gaining further intuition into wake steering + layout
- Opportunities for co-design optimizations, tying together controls, layout, cabling, lease area, loads, etc.



(Gebraad, et. al., 2016)



(Fleming, et. al., 2016)

Thank you

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