Wake Steering Optimisation Using FLORIS

MAE 441/579: Wind Energy
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by
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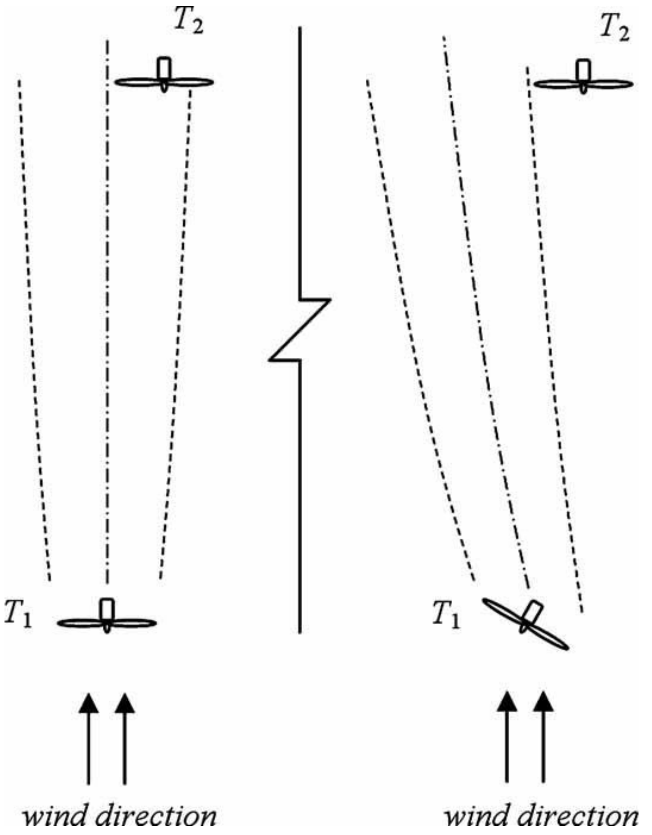
Wake? Why study wake?

- Wakes are mean wind speed decrease (known as wake deficit) and turbulence increase behind a turbine
- Effects of wake exist for several rotor diameters
- Wakes are important in a wind farm where upstream turbines can impact the performances(losses around 40%) and structural loading of downstream turbines

References: [1] WES - Analysis of control-oriented wake modeling tools using lidar field results (copernicus.org)
[2] https://www.osti.gov/etdeweb/servlets/purl/945121

Wake steering

1. Due to yaw offset, a transverse component of thrust force is generated. This component deflects the wake.
2. Power production of yaw misaligned turbine is reduced but it can be overcompensated by the power gains of downstream turbines.
3. Counter rotating vortices shed when turbine is yawed in form of elliptical shapes



Reference: Jiménez, Á., Crespo, A., and Migoya, E.: Application of a LES technique to characterize the wake deflection of a wind turbine in yaw, Wind Energy, 13, 559–572, 2010

Wake models

1. Computationally cheap compared to CFD
2. Fast enough to be optimized in real time
3. Can be used in a optimization models to maximize wind farm power production

Wake models - Computational time - Year

Jensen (Park) Model – 0.0018 s - 1986

Multi-zone wake model – 0.0019 s - 2016

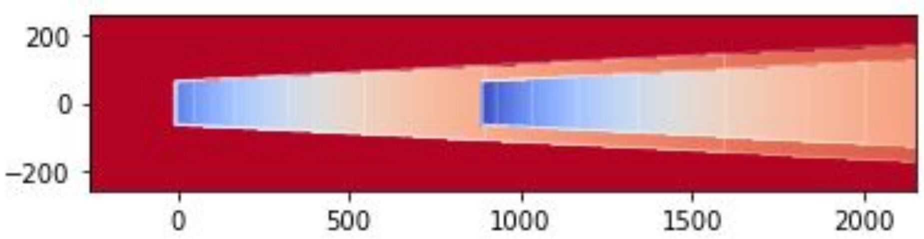
Gaussian wake model – 0.0025 - 2016

Curl model – 1.6 s - 2019

Reference: [WES - Analysis of control-oriented wake modeling tools using lidar field results (copernicus.org)]

Jensen wake model

Visualization of wake profile with a horizontal cut section at turbine height



Tunable parameters -

k- Wake Decay constant

□u is the velocity deficit

Wake linearly expands

$$u(x, r, a) = U_{\infty}(1 - \delta u(x, r, a)),$$

Limitations -

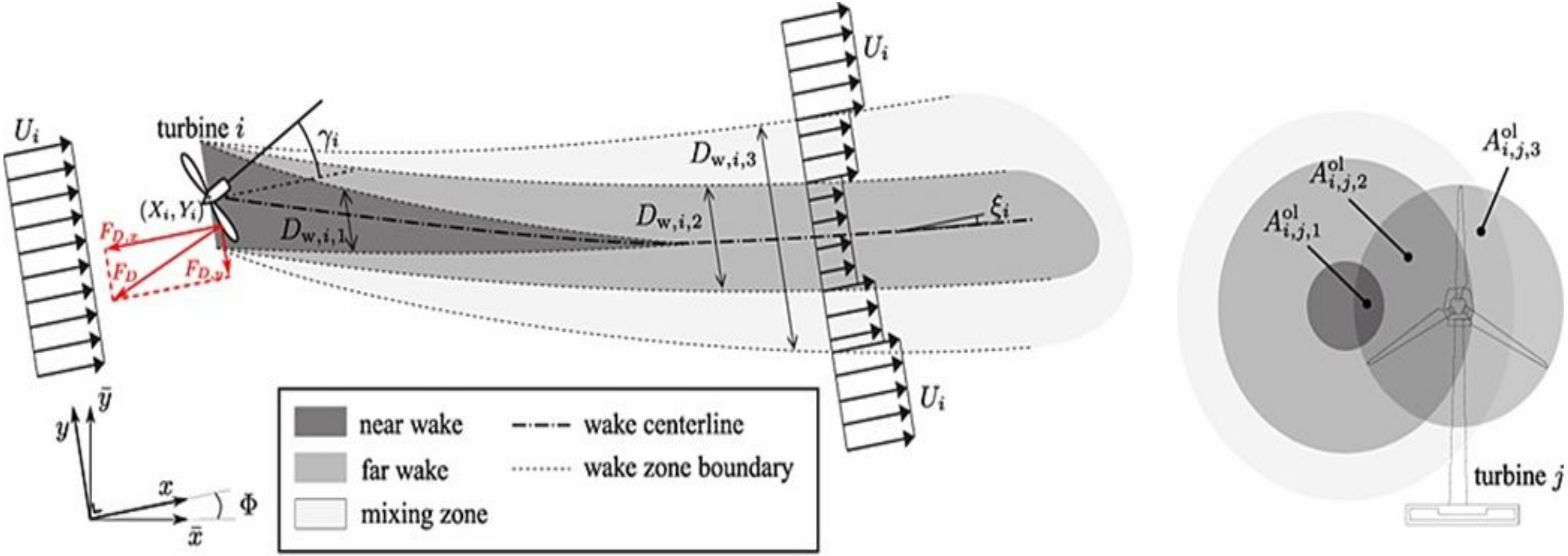
Does not conserve momentum

Does not take into account the added turbulence generated by upstream turbine

$$\delta u = \begin{cases} 2a\left(\frac{D}{D+2kx}\right)^2, & \text{if} \quad r \leq \frac{D+2kx}{2}. \\ 0, & \text{otherwise.} \end{cases}$$

Reference: [WES - Analysis of control-oriented wake modeling tools using lidar field results (copernicus.org)]

Multizone wake model



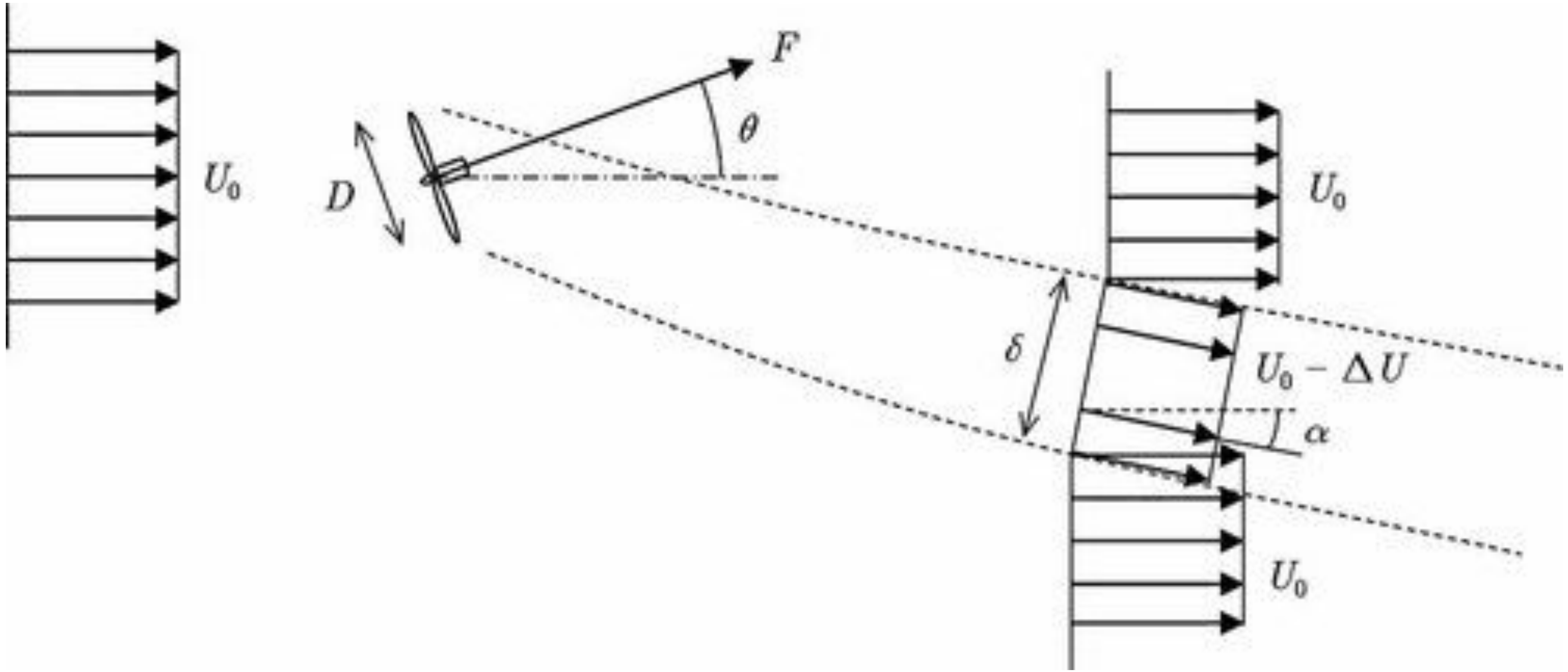
(a) Top view

(b) Cut-through at downstream turbine

Reference: Gebraad, P. M. and Van Wingerden, J.: A control-oriented dynamic model for wakes in wind plants, J. Phys. Conf. Ser., 524, p. 012186, IOP Publishing, 2014

Wake deflection models

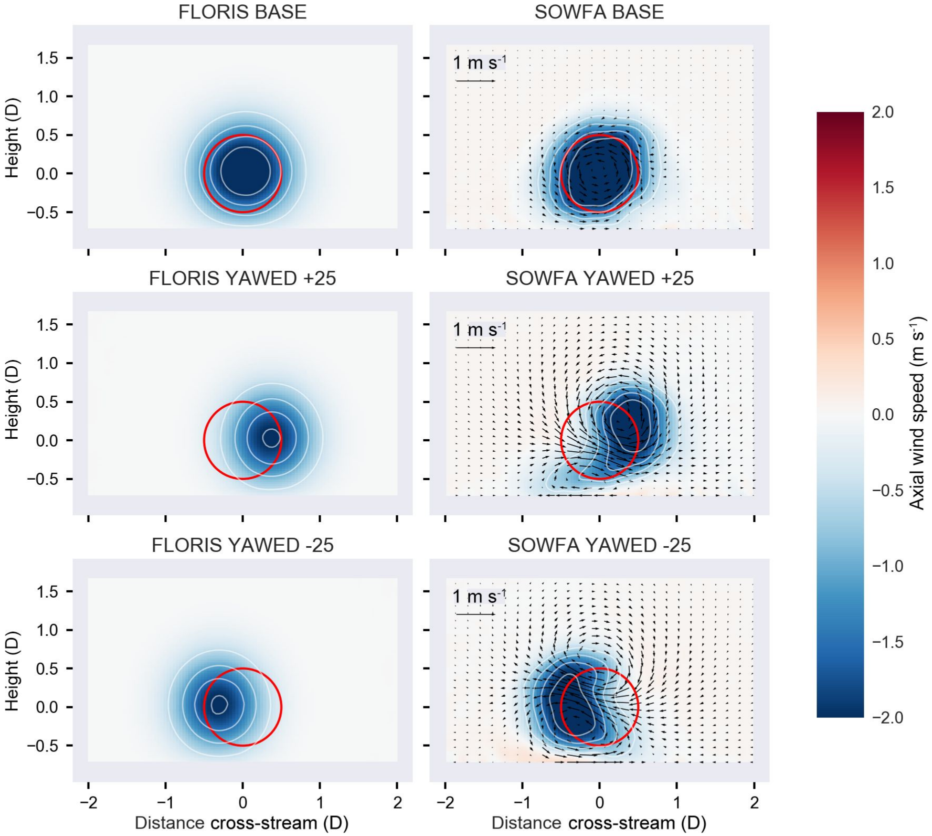
Jimenez and Bastankhah - Predict the wake deflection caused by yawed turbines



Reference: https://wes.copernicus.org/articles/6/701/2021/

Wake asymmetry

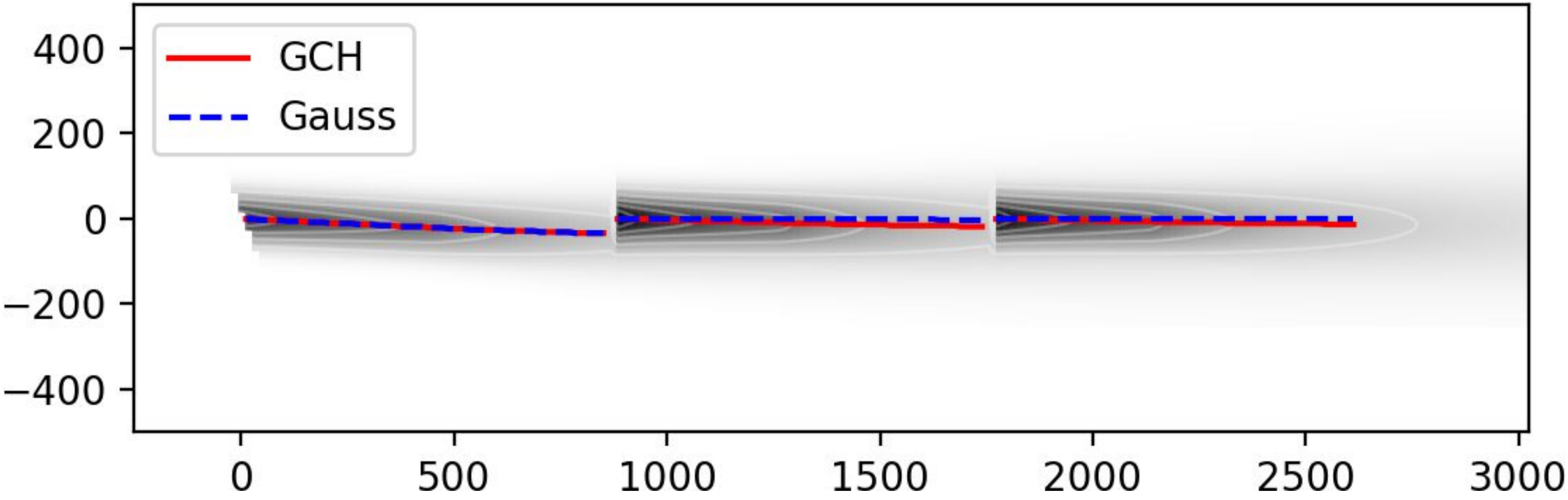
Wake asymmetry - Positive yaw angles and negative yaw angles of same magnitude does not produce same deflection



Reference: https://wes.copernicus.org/articles/6/701/2021/

Secondary steering

Deflected wakes can deflect the wakes of downstream turbine even if they are not yawed

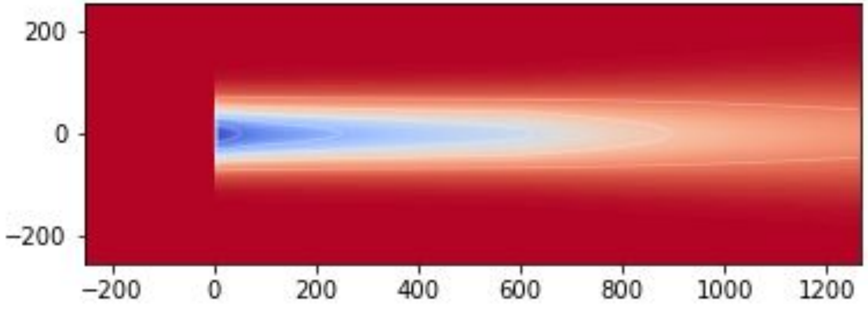


FLORIS results for the three-turbine case shown for the GCH model with the centerline of the wake computed for GCH (red) and the Gaussian model (blue), where the first turbine is yawed 20 degrees.

Reference: https://wes.copernicus.org/articles/6/701/2021/

Gaussian wake model

1. Has velocity deficit, added turbulence (based on turbine operations) and atmospheric stability
2. Momentum is conserved



<u>Assumptions</u>: Wake meandering equal in y,z directions

$$\frac{u(x,y,z)}{U_\infty} = 1 - Ce^{-(y-\delta)^2/2\sigma_y^2} e^{-(z-z_h)^2/2\sigma_z^2}$$

Velocity deficit

C : velocity deficit at the wake center

δ : wake deflection

zh : hub height of the turbine

σy : wake width in the *y* direction

σz : wake width in the *z* direction

Ct : thrust coefficient

$$C = 1 - \sqrt{1 - \frac{(\sigma_{y0}\sigma_{z0})M_0}{\sigma_y \sigma_z}}$$

$$M_0 = C_0(2 - C_0)$$

$$C_0 = 1 - \sqrt{1 - C_T},$$

Reference: [WES - Analysis of control-oriented wake modeling tools using lidar field results (copernicus.org)]

Atmospheric stability

1. TI captures ambient turbulence affecting wake expansion
2. Wind shear and veer are captured as well

Limitations:

Doesn't consider vertical flux and temperature profiles - Stull

3D wake model with shear with power log law

$$\frac{U_{\text{init}}}{U_\infty} = \left(\frac{z}{z_{\text{hub}}}\right)^{\alpha_s}$$

Added Turbulence

$$I = \sqrt{\sum_{j=0}^{N}\left(I_j^+\right)^2 + I_0^2},$$

$$I^+ = A_{\text{overlap}}\left(0.8a_i^{0.73} I_0^{0.35}\left(x/D_i\right)^{-0.32}\right),$$

Wind veer direction across rotor

$$a = \frac{\cos^2\phi}{2\sigma_y^2} + \frac{\sin^2\phi}{2\sigma_z^2}$$

$$b = -\frac{\sin 2\phi}{4\sigma_y^2} + \frac{\sin 2\phi}{4\sigma_z^2}$$

$$c = \frac{\sin^2\phi}{2\sigma_y^2} + \frac{\cos^2\phi}{2\sigma_z^2},$$

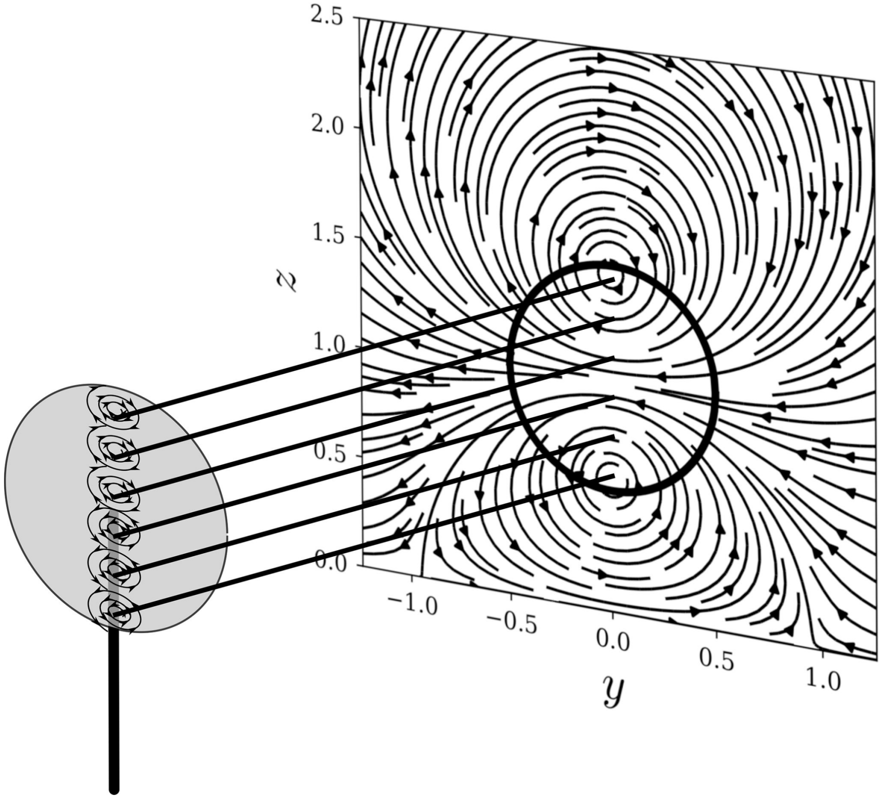
$$\frac{u(x,y,z)}{U_{\text{init}}} = 1 - Ce^{-\left(a(y-\delta)^2 - 2b(y-\delta)(z-z_{\text{hub}}) + c(z-z_{\text{hub}})^2\right)}$$

Reference: [WES - Analysis of control-oriented wake modeling tools using lidar field results (copernicus.org)]

Curl wake model

Solves linearized Navier Stokes Equation - discretized into base and a perturbation solution

$$U\frac{\partial u'}{\partial x} + V\frac{\partial u'}{\partial y} + W\frac{\partial (U+u')}{\partial z} = \nu_{\text{eff}}\left(\frac{\partial^2 u'}{\partial x^2} + \frac{\partial^2 u'}{\partial y^2} + \frac{\partial^2 u'}{\partial z^2}\right).$$



Superposition of vortices to create curl wakes

Reference: Luis A Martínez-Tossas, Jennifer Annoni, Paul A Fleming, and Matthew J Churchfield. The aerodynamics of the curled wake: a simplified model in view of flow control. *Wind Energy Science (Online)*, 2019

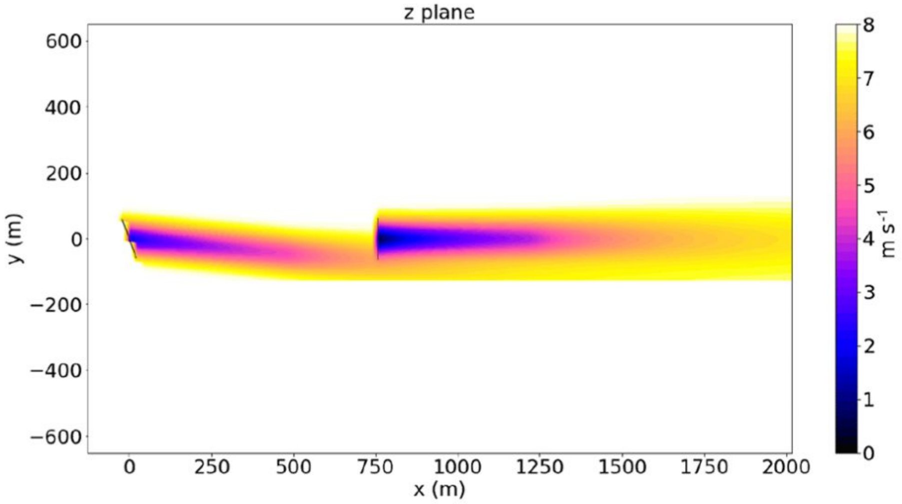
Gaussian Vs Curl wake model

Gaussian model

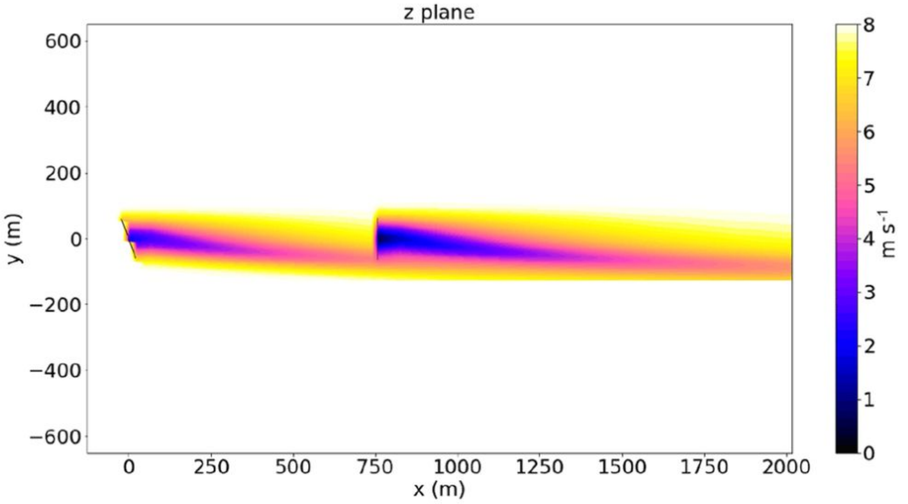
1. Computational power less
2. Assumes wake shape profiles

Curl Wake model

1. Accurate wake profile modelling
2. Wake can take any shape



(a) Gaussian model



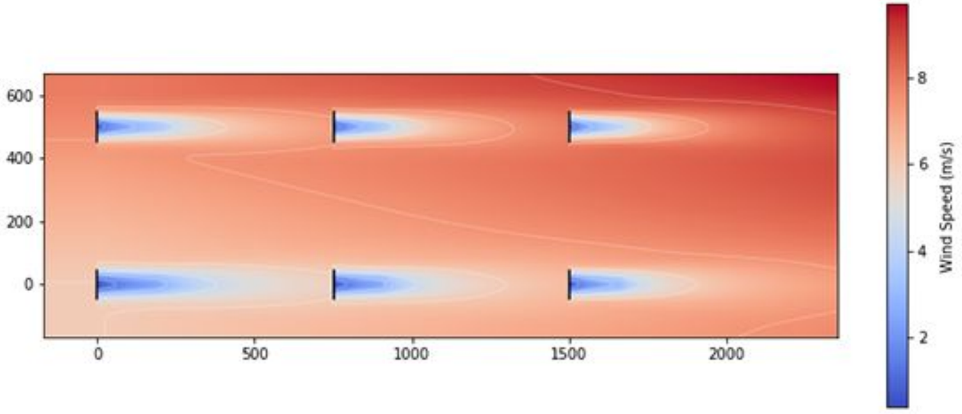
(b) Curled wake model

Image Reference: [WES - The aerodynamics of the curled wake: a simplified model in view of flow control (copernicus.org)]

What is FLORIS ?

FLORIS: FLOw Redirection and Induction in Steady State - software framework for -

- Wind farm optimisation tool
- To maximise profits
- Optimise control strategies like wake steering



NREL FLORIS:
[FLORIS: FLOw Redirection and Induction in Steady State | Wind Research | NREL]

Documentation:
https://floris.readthedocs.io/en/main/index.html

FLORIS Github link:
[NREL/floris: A controls-oriented engineering wake model. Documentation at (github.com)]

Installing Floris

Basic installation

```
# Using pip...
pip install floris          # Latest version
pip install floris==1.1.0  # Specified version number

# Using conda...
conda install floris          # Latest version
conda install floris=1.1.0  # Specified version number
```

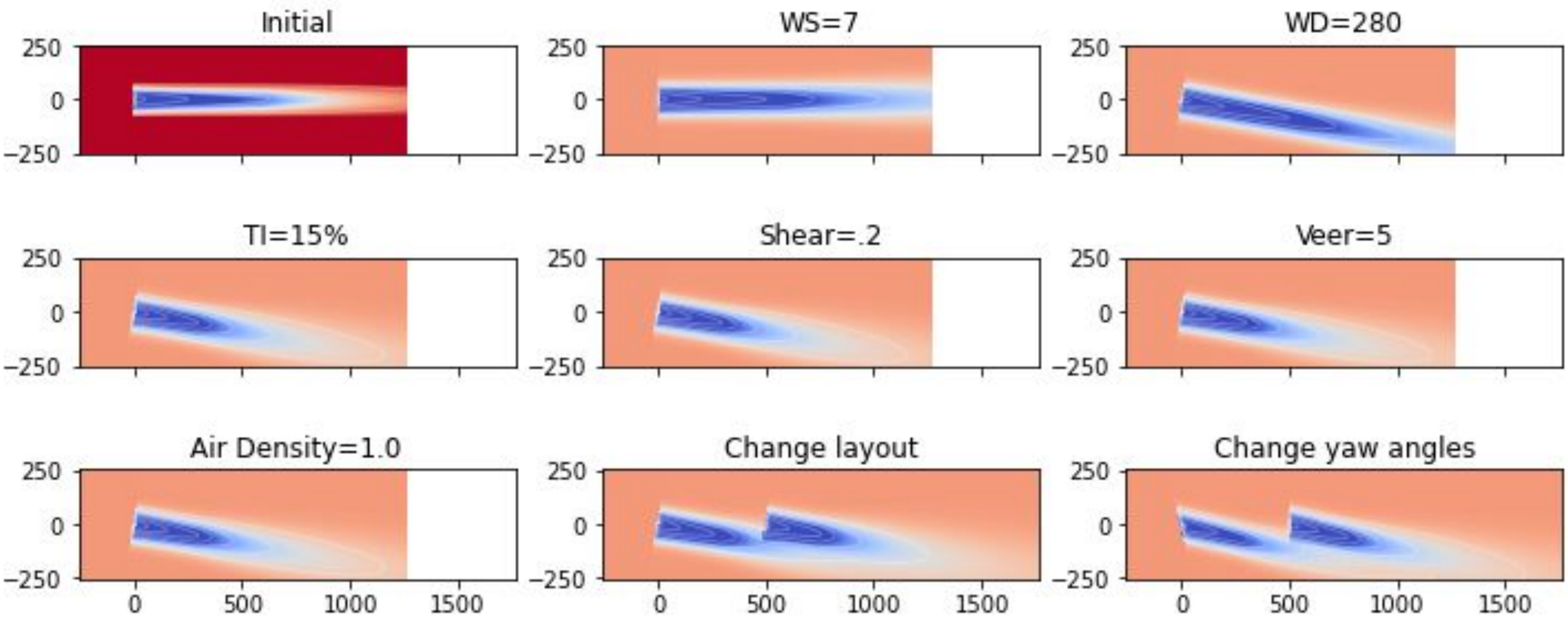
Reference: https://floris.readthedocs.io/en/main/source/examples.html

Basic Example to run Floris

Python code

```python
import matplotlib.pyplot as plt
import floris.tools as wfct

# Initialize the FLORIS interface fi
# For basic usage, the florice interface provides a simplified interface to
# the underlying classes
fi = wfct.floris_interface.FlorisInterface("../example_input.json")

# Calculate wake
fi.calculate_wake()

# Get horizontal plane at default height (hub-height)
hor_plane = fi.get_hor_plane()

# Plot and show
fig, ax = plt.subplots()
wfct.visualization.visualize_cut_plane(hor_plane, ax=ax)
plt.show()
```

Wake Profiles for various wind farm parameters



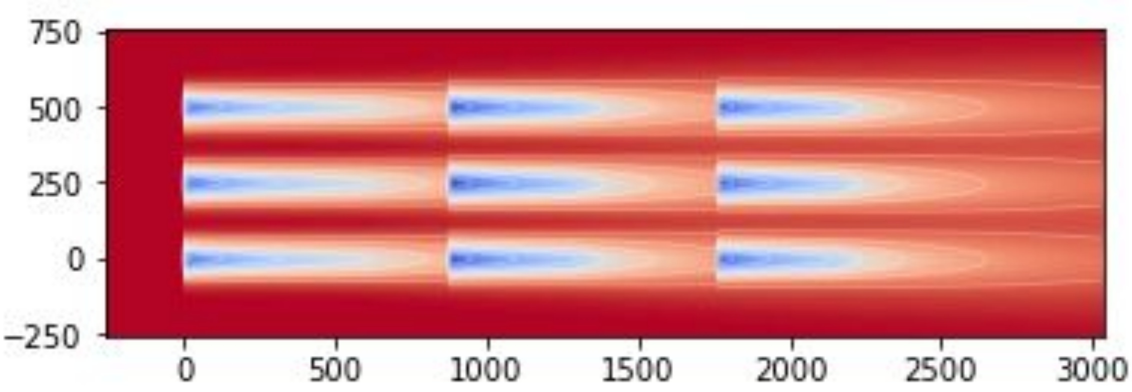
Reference: https://www.nrel.gov/wind/assets/pdfs/systems-engineering-workshop-2019-floris.pdf

Baseline case - 3x3 wind farm

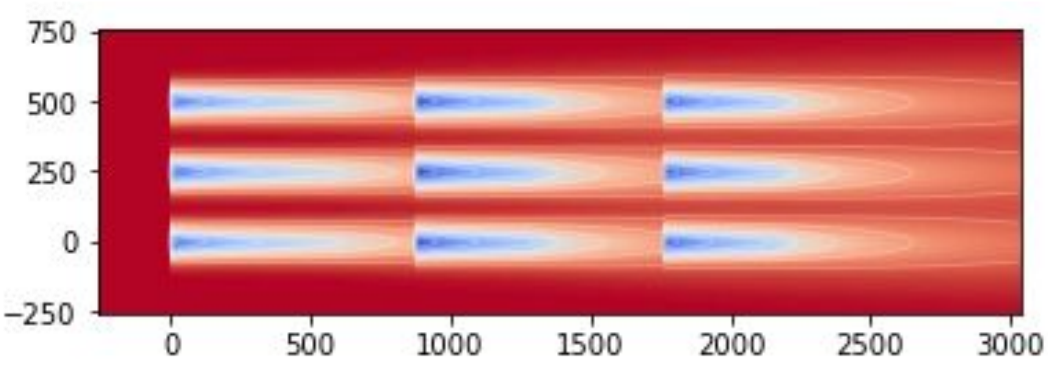
Parameters (Refer: example_input.json)

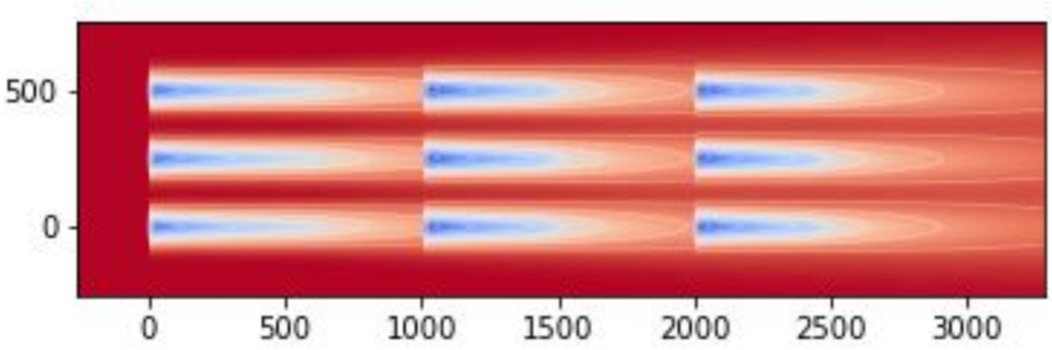
Wind speed	8 m/s
Wind direction	270°
Cut plane height	90 m
Turbulence intensity	0.06
Wind turbine spacing	7D

```
floris.tools.floris_interface.FlorisInterface
height = 90.0 for horizontal plane.
Running FLORIS with no yaw...
Plotting the FLORIS flowfield...
floris.tools.floris_interface.FlorisInterface
height = 90.0 for horizontal plane.
==========================================
Initial Power Output = 9052329.10
==========================================
```



Increased spacing - 3x3 wind farm





Wake losses are less

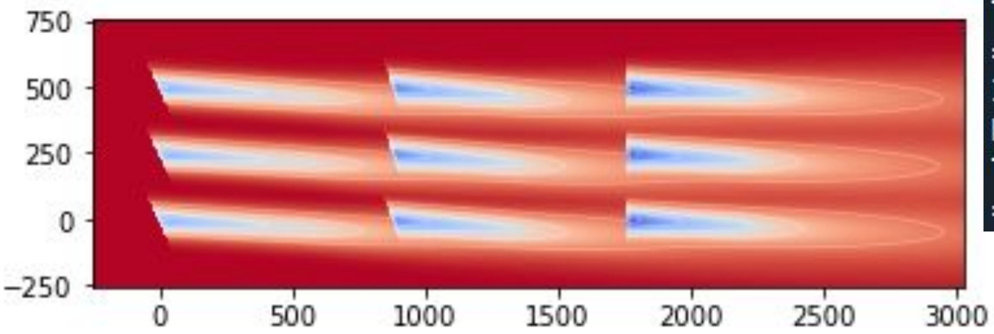
Power gain = 6.9%

```
floris.tools.floris_interface.FlorisInterface
height = 90.0 for horizontal plane.
Running FLORIS with no yaw...
Plotting the FLORIS flowfield...
floris.tools.floris_interface.FlorisInterface
height = 90.0 for horizontal plane.
==========================================
Initial Power Output = 9052329.10
==========================================
Plotting the FLORIS flowfield with no yaw...
==========================================
New Power Output = 9675427.08
==========================================
Plotting the FLORIS flowfield with no yaw...
```

Optimised yaw - 3x3 wind farm

Parameters (Refer: example_input.json)

Wind speed	8 m/s
Wind direction	270°
Cut plane height	90 m
Turbulence intensity	0.06
Wind turbine spacing	7D



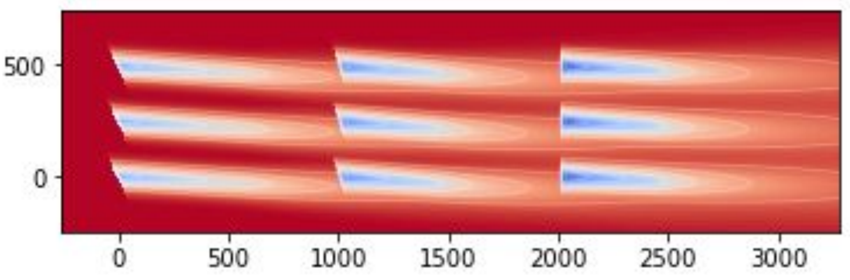

```
==========================================
yaw angles =
Turbine  0 = 25.0  deg
Turbine  1 = 19.49474461529016  deg
Turbine  2 = 0.0  deg
Turbine  3 = 25.0  deg
Turbine  4 = 18.343158207649804  deg
Turbine  5 = 1.782844436048123e-26  deg
Turbine  6 = 25.0  deg
Turbine  7 = 18.03066636141671  deg
Turbine  8 = 3.252606516704605e-17  deg
==========================================
Initial Power Output = 9052329.10
Power output with wake steering = 10728465.49
Total Power Gain = 18.5%
==========================================
```

Optimised yaw increasing turbine spacing - 3x3 wind farm

Parameters (Refer: example_input.json)

Wind speed	8 m/s
Min/Max yaw angle	0/25°
Wind direction	270°
Cut plane height	90 m
Turbulence intensity	0.06
Wind turbine spacing	8D

```
==========================================
yaw angles =
Turbine  0 = 25.0  deg
Turbine  1 = 17.752217912332437  deg
Turbine  2 = 0.0  deg
Turbine  3 = 25.0  deg
Turbine  4 = 17.62629163021377  deg
Turbine  5 = 1.0460845366789476e-16  deg
Turbine  6 = 24.701301448267202  deg
Turbine  7 = 16.517407044011374  deg
Turbine  8 = 1.456768662532798e-25  deg
==========================================
Initial Power Output = 9675427.08
Power output with wake steering = 11116100.85
Total Power Gain = 14.9%
==========================================
```



Power comparison varying wind turbine spacing

Spacing of 7D

```
==========================================
yaw angles =
Turbine  0 = 25.0  deg
Turbine  1 = 19.49474461529016  deg
Turbine  2 = 0.0  deg
Turbine  3 = 25.0  deg
Turbine  4 = 18.343158207649804  deg
Turbine  5 = 1.782844436048123e-26  deg
Turbine  6 = 25.0  deg
Turbine  7 = 18.03066636141671  deg
Turbine  8 = 3.252606516704605e-17  deg
==========================================
Initial Power Output = 9052329.10
Power output with wake steering = 10728465.49
Total Power Gain = 18.5%
==========================================
```

Spacing of 8D

```
==========================================
yaw angles =
Turbine  0 = 25.0  deg
Turbine  1 = 17.752217912332437  deg
Turbine  2 = 0.0  deg
Turbine  3 = 25.0  deg
Turbine  4 = 17.6262916302137 7  deg
Turbine  5 = 1.0460845366789476e-16  deg
Turbine  6 = 24.701301448267202  deg
Turbine  7 = 16.517407044011374  deg
Turbine  8 = 1.456768662532798e-25  deg
==========================================
Initial Power Output = 9675427.08
Power output with wake steering = 11116100.85
Total Power Gain = 14.9%
==========================================
```

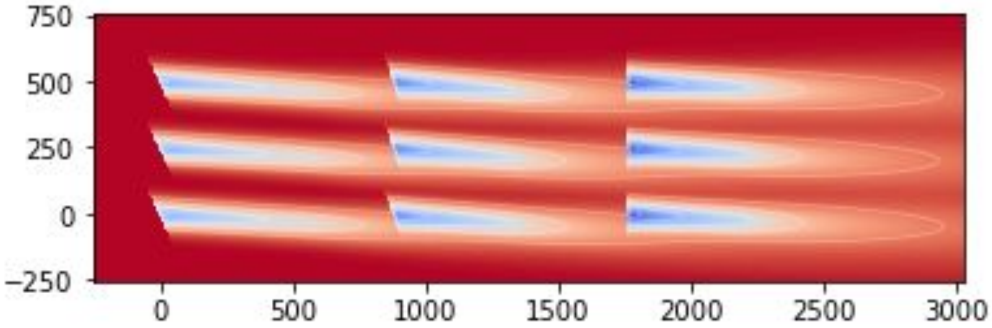
Individual turbine power output for spacing of 7D

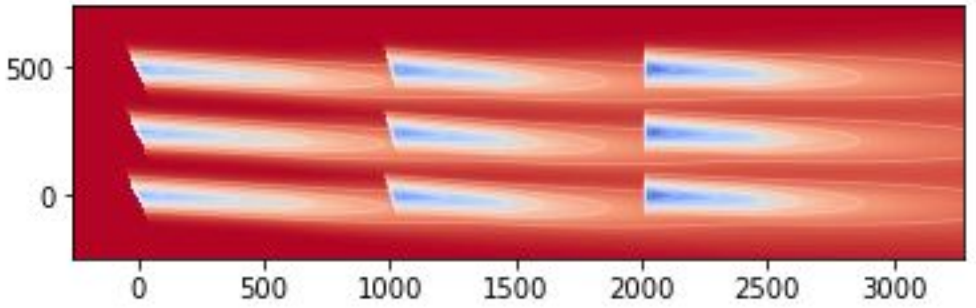
```
=================================
Initial Power output individual
Turbine  0 = 1695368.6455472684
Turbine  1 = 616485.226366925
Turbine  2 = 704025.578728817
Turbine  3 = 1695368.5157089536
Turbine  4 = 617320.0581111772
Turbine  5 = 705440.8333813363
Turbine  6 = 1695368.5157535109
Turbine  7 = 617712.6795726656
Turbine  8 = 705239.0431098198
=================================
```

```
=================================
Power output with wake steering
Turbine  0 = 1409447.771337561З
Turbine  1 = 959193.640053284
Turbine  2 = 1144535.3169808695
Turbine  3 = 1409447.7593912906
Turbine  4 = 1015479.095602687
Turbine  5 = 1172698.007283363
Turbine  6 = 1409447.7609801886
Turbine  7 = 1033306.1598301253
Turbine  8 = 1174909.983532359
=================================
```

Case study conclusion

1. The output power is more for 8D due to more turbine spacing allowing wake recovery
2. For 7D spacing, even though power gain is more than 8D. One needs to evaluate the cost of turbine life with yawing
3. FLORIS software framework evaluate other parameters like wind turbine spacing, turbine life with optimal yaw angles

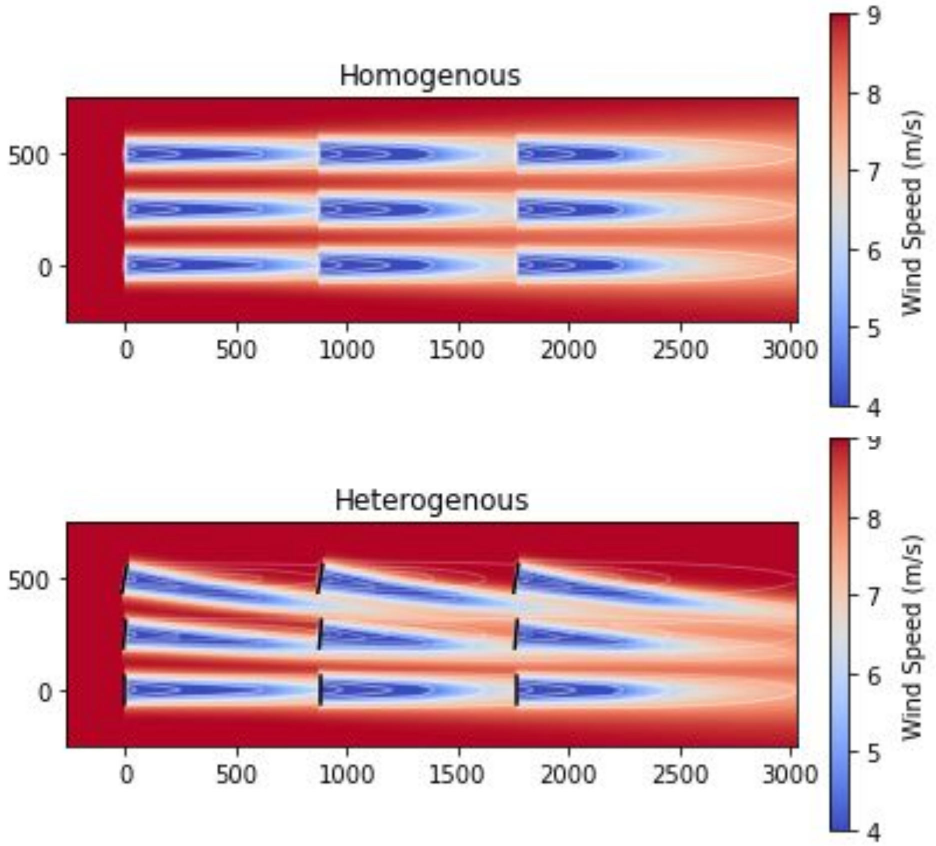




Heterogeneous flow

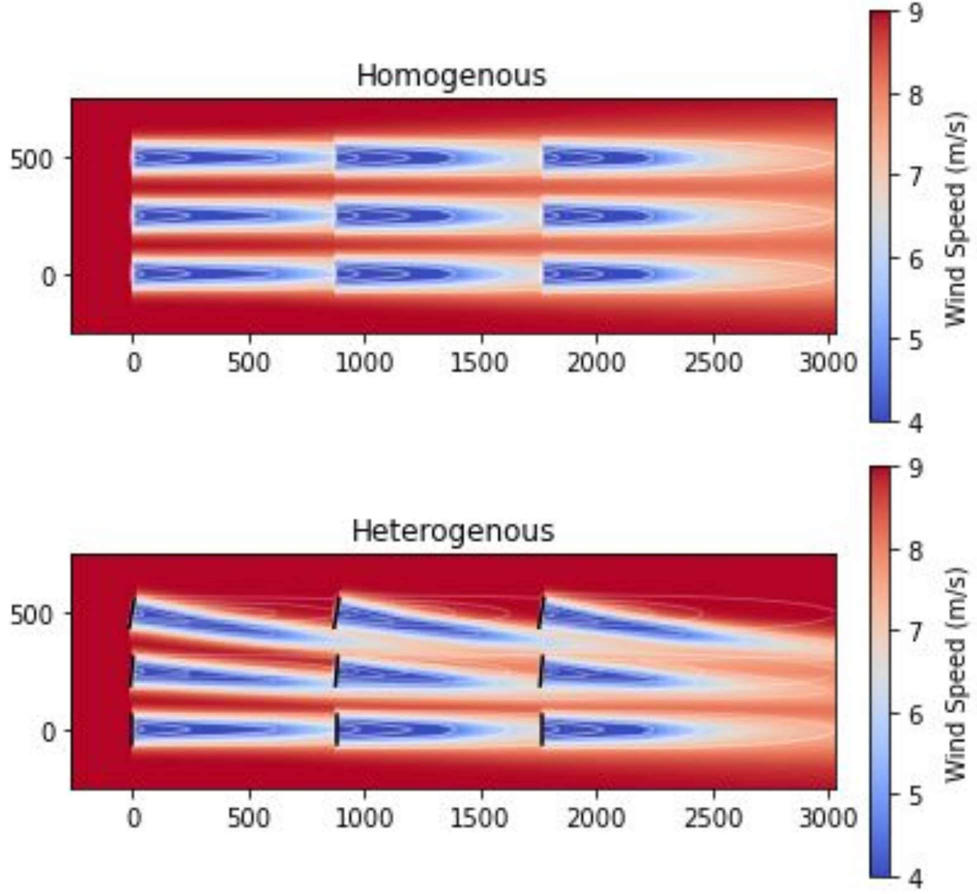
Parameters (Refer: example_input.json)

Wind speed	8 m/s
Min/Max yaw angle	0/0°
Wind direction	270°
Cut plane height	90 m
Turbulence intensity	0.06
Wind turbine spacing	7D



Heterogeneous flow 7D 3x3 wind farm

```
            Current function value: -1.067
            Iterations: 14
            Function evaluations: 151
            Gradient evaluations: 14
==========================================
yaw angles =
Turbine  0 = 25.0  deg
Turbine  1 = 19.999725316607382  deg
Turbine  2 = 0.0  deg
Turbine  3 = 13.840694198790535  deg
Turbine  4 = 7.421265183725226  deg
Turbine  5 = 2.0199750324186770e-28  deg
Turbine  6 = 3.663195112499273e-17  deg
Turbine  7 = 1.4272665593176763  deg
Turbine  8 = 2.1684043447541695e-17  deg
==========================================
Total Power Gain = 6.8%
==========================================
Plotting the FLORIS flowfield with yaw...
power opt =  18405313.370802958
power intital =  17235319.565929826
```



Yaw induced turbine loads/Fatigue via wake steering

1. SOWFA tool are used to compute effects of wake steering on wind turbine loading
2. Studies indicate yaw misalignment reduces fatigue loads variation on turbine[1]
3. However there is increased load variations on the non-rotating turbine parts[2]

Reference:

[1] Paul A.Fleming et al., Evaluating techniques for redirecting turbine wakes using SOWFA, Renewable Energy, https://doi.org/10.1016/j.renene.2014.02.015

[2] Kragh K, Hansen M. Load alleviation of wind turbines by yaw misalignment, Wind Energy. http://dx.doi.org/10.1002/we.1612

Yaw induced turbine loads/Fatigue via wake steering

Full results of simulations. Turbine wake redirection is summarized by the wake center 7 rotor diameters downstream from the turbine, bold indicates the larger offset.

	Amount	Horizontal wake-offset abs (x/D)	Vertical wake-offset abs (z/D)	Power	Blade OOP	Drivetrain	Tower	Yaw bearing
	Baseline	**0.08**	0.03	0.0%	+0.0%	+0.0%	+0.0%	+0.0%
Yaw-Based	−40°	**0.33**	0.02	−39.4%	+5.6%	−17.3%	−20.3%	−13.9%
	−35°	**0.32**	0.03	−31.2%	+8.9%	−10.7%	−17.7%	−0.7%
	−30°	**0.27**	0.00	−23.8%	+9.5%	−6.1%	−15.2%	−6.7%
	−25°	**0.24**	0.02	−16.8%	+14.2%	−0.8%	−14.9%	−8.0%
	−20°	**0.17**	0.02	−11.2%	+11.7%	+2.3%	−7.7%	−9.8%
	−15°	**0.10**	0.02	−6.0%	+7.2%	+1.5%	−10.5%	−3.5%
	−10°	**0.05**	0.02	−2.6%	+8.6%	+1.0%	−10.3%	−2.8%
	−5°	**0.03**	0.02	−0.4%	+5.3%	+0.8%	−5.9%	−3.1%
	5°	**0.17**	0.05	−0.3%	−4.0%	−1.6%	−0.1%	−5.1%
	10°	**0.24**	0.06	−2.6%	−5.2%	+1.3%	+0.1%	−9.7%
	15°	**0.30**	0.06	−5.7%	−9.9%	−0.4%	−3.2%	−11.1%
	20°	**0.35**	0.05	−10.6%	−13.3%	−1.0%	−6.0%	−14.4%
	25°	**0.43**	0.08	−16.2%	−14.4%	−6.2%	−7.4%	−14.8%
	30°	**0.49**	0.05	−23.3%	−17.1%	−10.2%	−12.7%	−8.1%
	35°	**0.51**	0.05	−31.3%	−20.1%	−14.9%	−7.9%	−13.5%
	40°	**0.54**	0.10	−40.1%	−24.4%	−22.2%	−7.1%	−1.5%

Fatigue loads: output power, blade out-of-plane (OOP) bending moment, drivetrain torsion, tower side-e-side bending, and the yawing and tilting moments experienced at the yaw bearing

Reference: https://doi.org/10.1016/j.renene.2014.02.015Get

Fatigue sustainability via additive manufacturing

Blade Material: Low cost thermoplastics skin reinforced by 3D printed skeleton structures

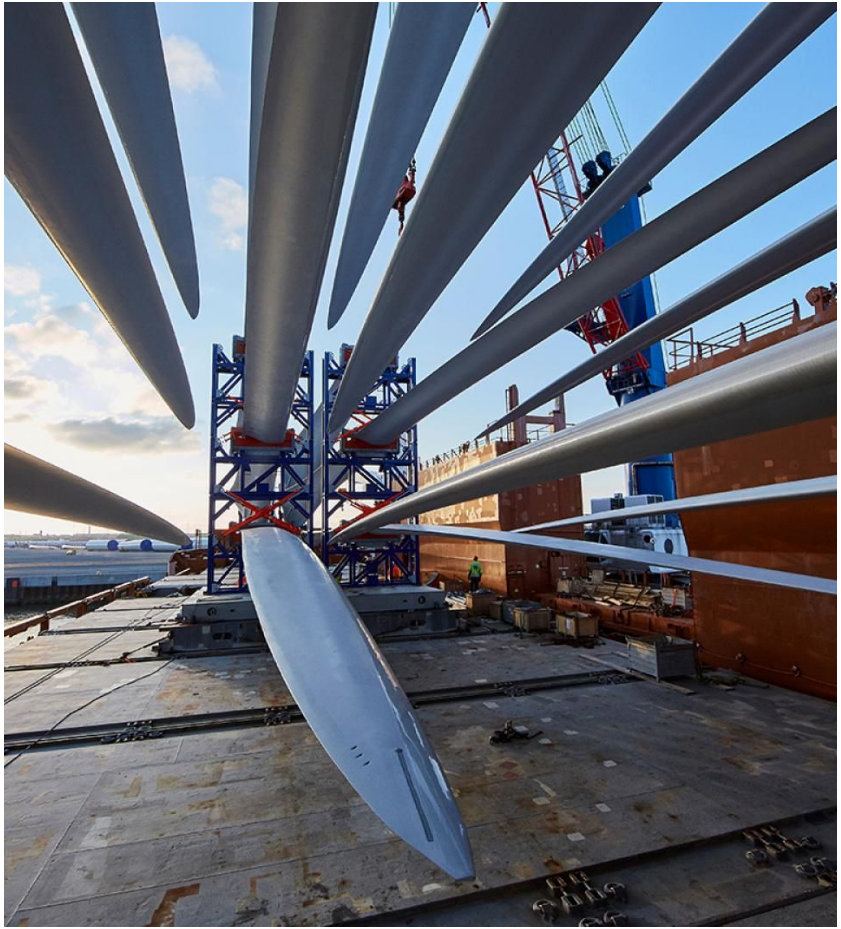
- Sustain higher fatigue loads
- Light weight
- More rotor diameter or power output
- Low maintenance and electricity cost

Facts:
10-15 meters of blade capture 40% of energy
Blade tip travel 1/4th speed of sound

Reference: Tipping Point: 3D-Printed Blade Parts Can Help Take Wind Power To The Next Level | GE News

OAK RIDGE National Laboratory

NREL Transforming ENERGY



Questions?