Complex wake merging phenomena in large offshore wind farms

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2 – National Renewable Energy Lab (NREL)
3 – Technical University of Denmark (DTU)
4 – Vattenfall

Aerial photograph of Lillgrund wind farm

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Scientific questions

- How to properly model wake merging
- Upscaling from single numerical experiments
- Upscaling from observations

Outline

- Lillgrund wind farm
- Large eddy simulation (LES) and analytical (Park) model
- Exact row vs skewed angle

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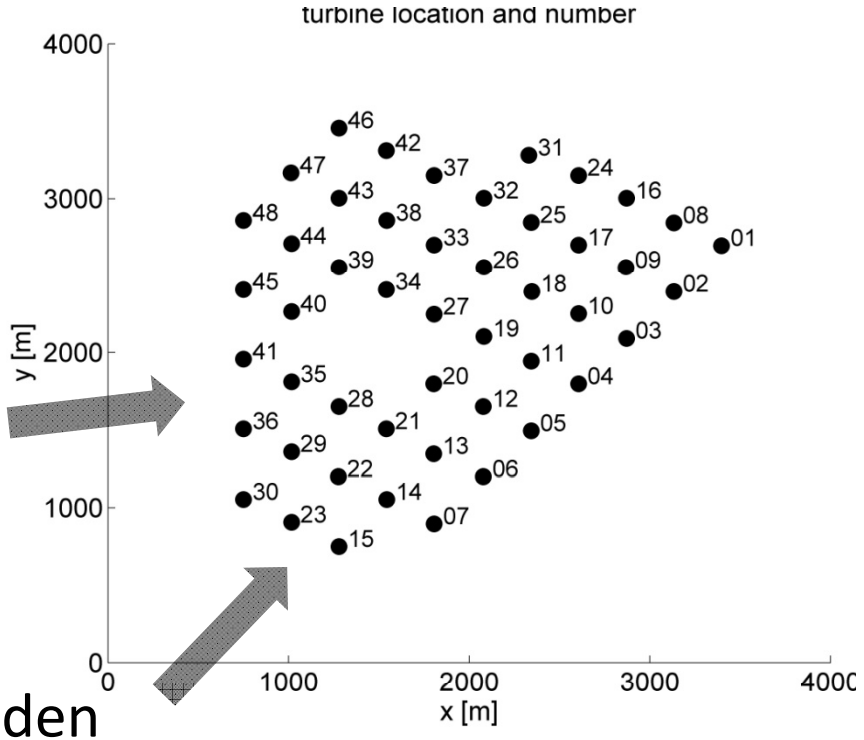
Lillgrund Farm

Aerial photograph of Lillgrund wind farm



- 1st offshore wind farm in Sweden
- 48 2.3 MW (SWT-2.3-93) turbines with 92.6 m rotor diameter (D) and 65 m hub height
- Turbine spacing is 4.3D (exact row)
- U = 9 ms^{-1}, TI = 6%

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Park Model

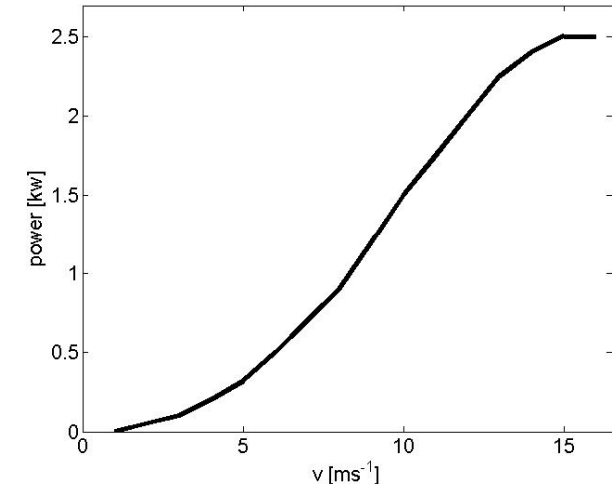
- Thrust curve
- Power curve
- Expansion coefficient

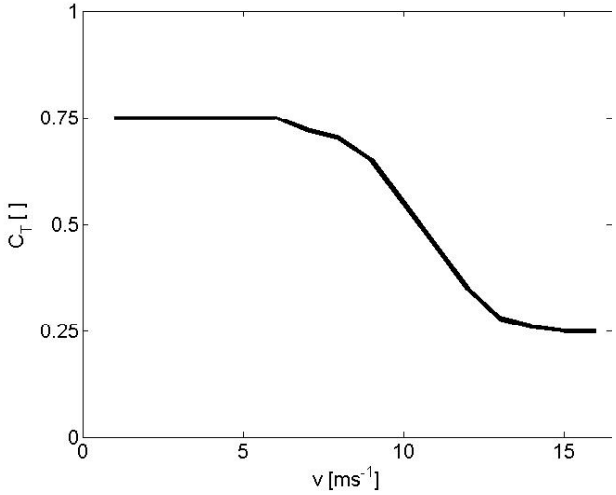
$$D_w(x) = D_{rotor} + 2kx$$

$$\frac{\Delta u(x)}{v_0} = \frac{\sqrt{1-C_T(v_o)}}{\left(1+\frac{2kx}{D_{rotor}}\right)^2}$$

- Katic sum of squares

$$\left(1-\frac{v}{u}\right)^2 = \sum\left(1-\frac{v_i}{v_o}\right)^2$$





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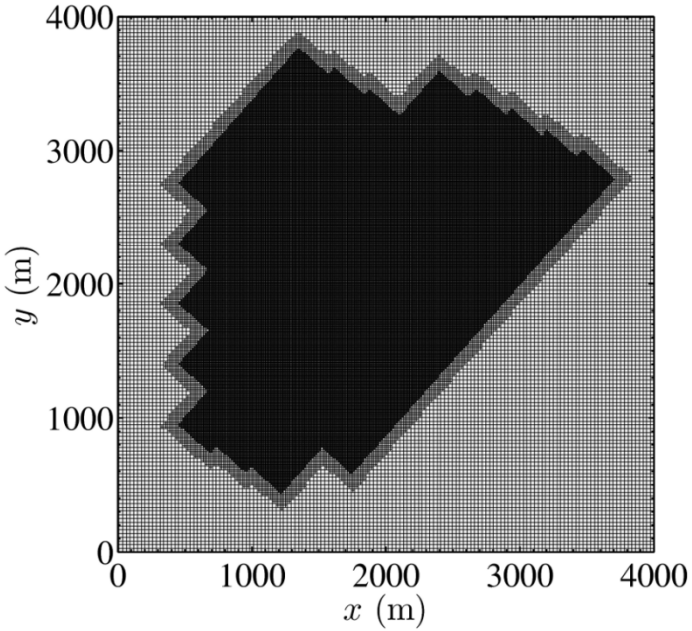
Large eddy simulation (LES)



- Turbines - Actuator line method
- 4 x 4 x 1 km domain size
- Smagorinsky subgrid model (C_s = 0.135)
- Outer resolution Δ=7 m, inner Δ=1.75 m, unstructured grid
- Boundary layer precursor simulation – ‘magic slice’

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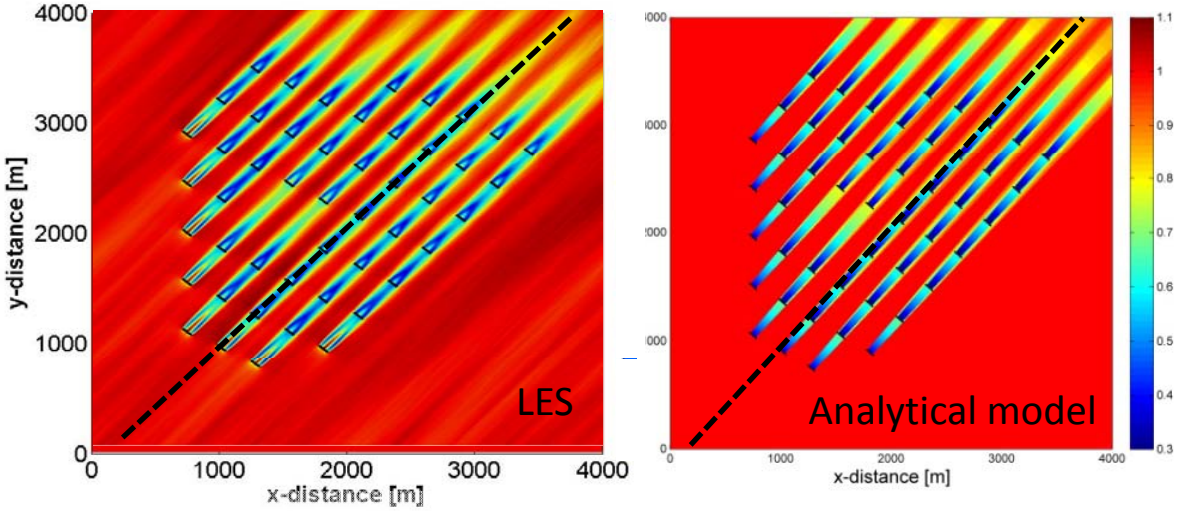
Lillgrund Farm

LES Park model



Normalized velocity contours at hub height for the LES (left) and analytical model (right)

Source:

1) Wake merging in large offshore wind farms, EWEA 2012. R.J. Barthelmie Indiana University; C.M. Smith Indiana University; M. Churchfield National Renewable Energy Laboratory; P. Moriarty National Renewable Energy Laboratory

2) Churchfield, M.J., et al. *A large eddy simulation of wind-plant aerodynamics*. in *50th AIAA Aerospace Sciences Meeting*. 2012. Nashville, Tennessee January 9-12, 2012.

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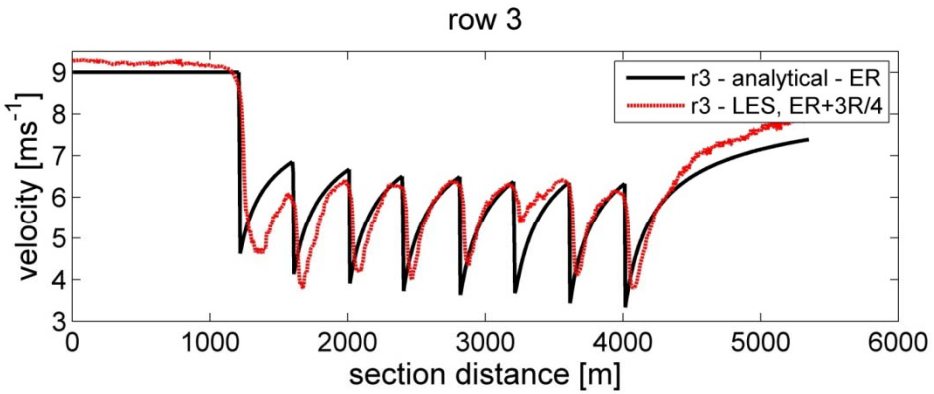
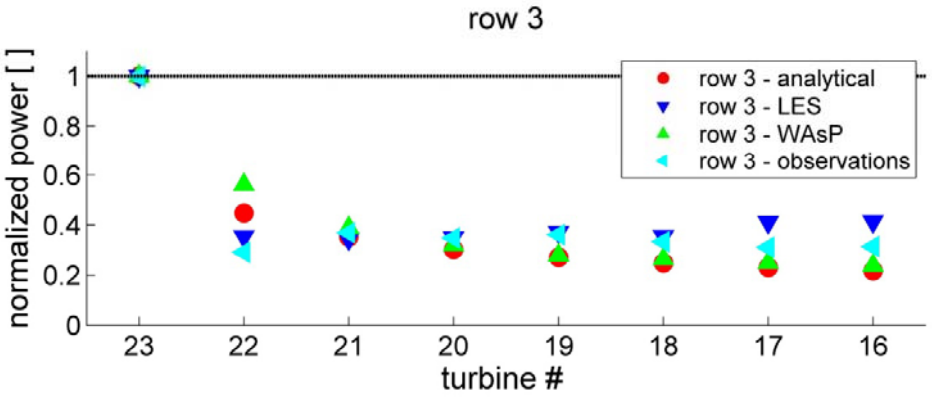
Exact row case

Row 3 Velocity



Row 3 Power



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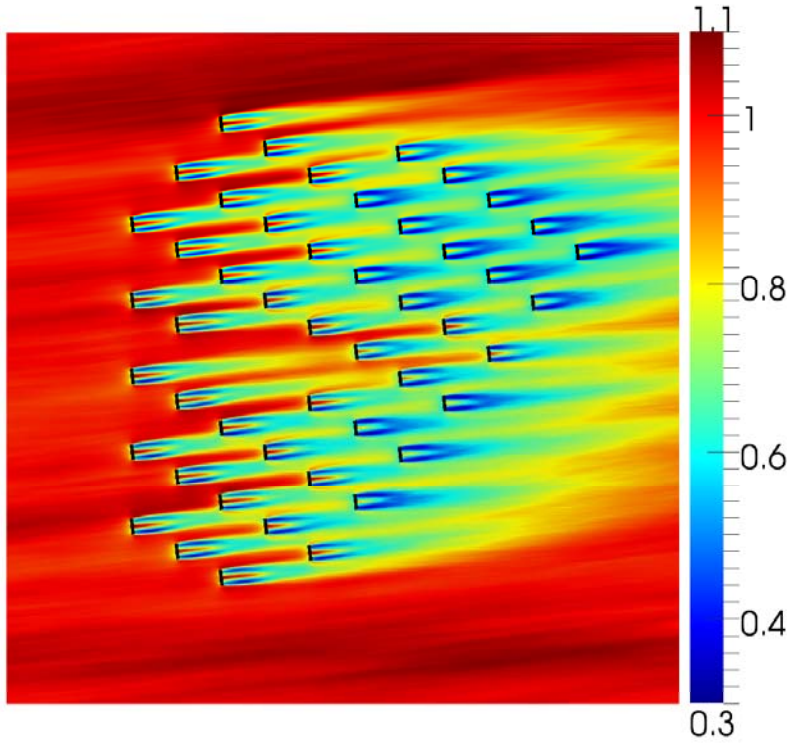
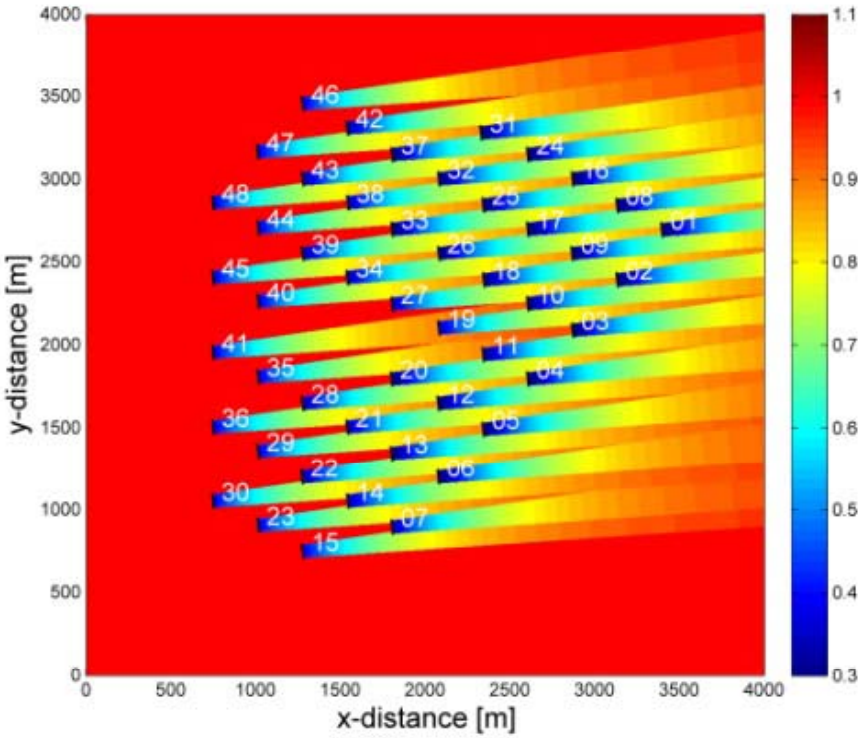
Skewed angle case

LES



Park model



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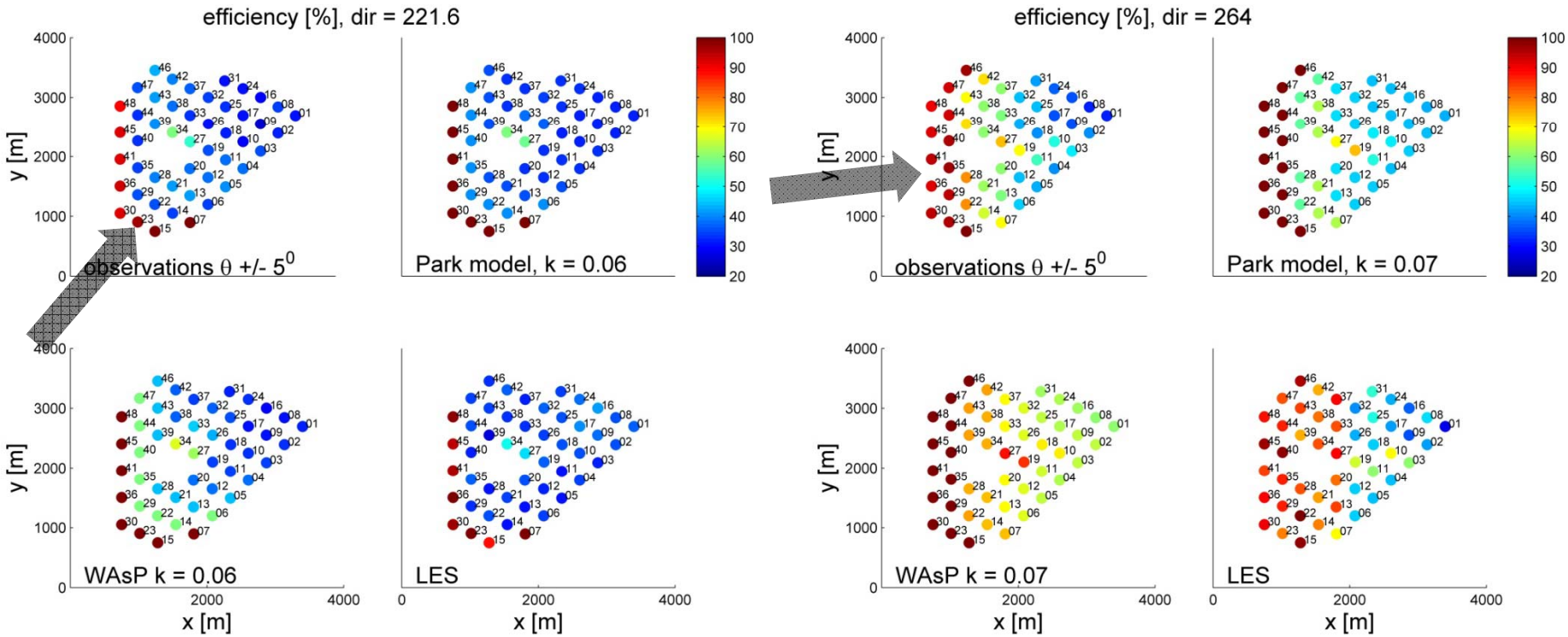
Efficiency

Exact row

Skewed angle



- Wake effects
- Upstream heterogeneity

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Total power production

	$\theta = 222^0$	$\theta = 264^0$
Obs (+/- 5^0)	1.00	1.00
Park (k = 0.06/0.07)	0.98	0.98
LES (TI = 6%)	1.08	1.25
WAsP (k = 0.04)	0.92	0.96

- Adjustable expansion coefficient
- Upscaling from single experiments/observations
- $\Sigma P_i \ (\theta=222^0) \ / \ \Sigma P_i \ (\theta=264^0) = 0.72$

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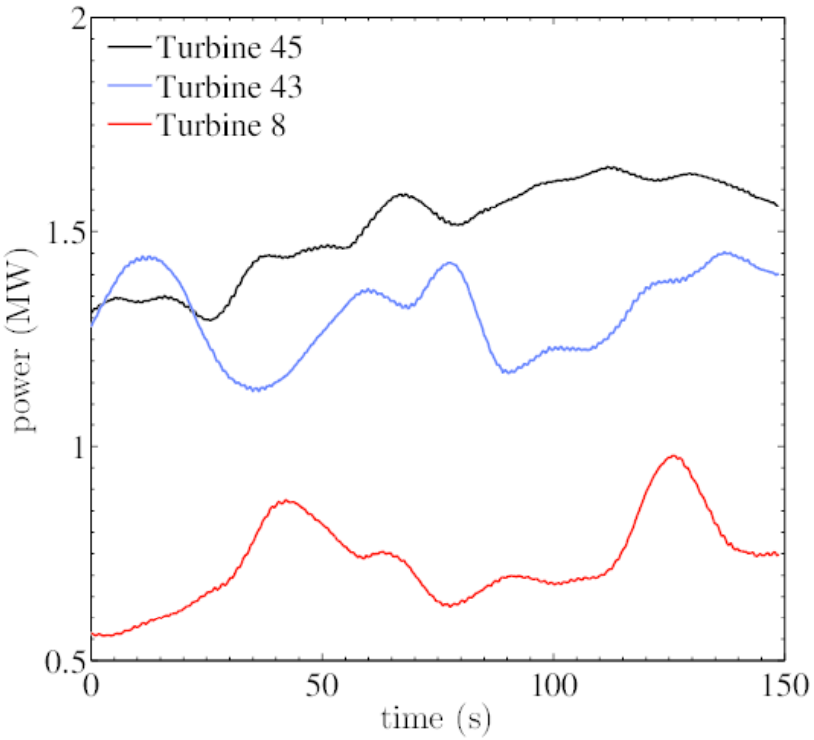
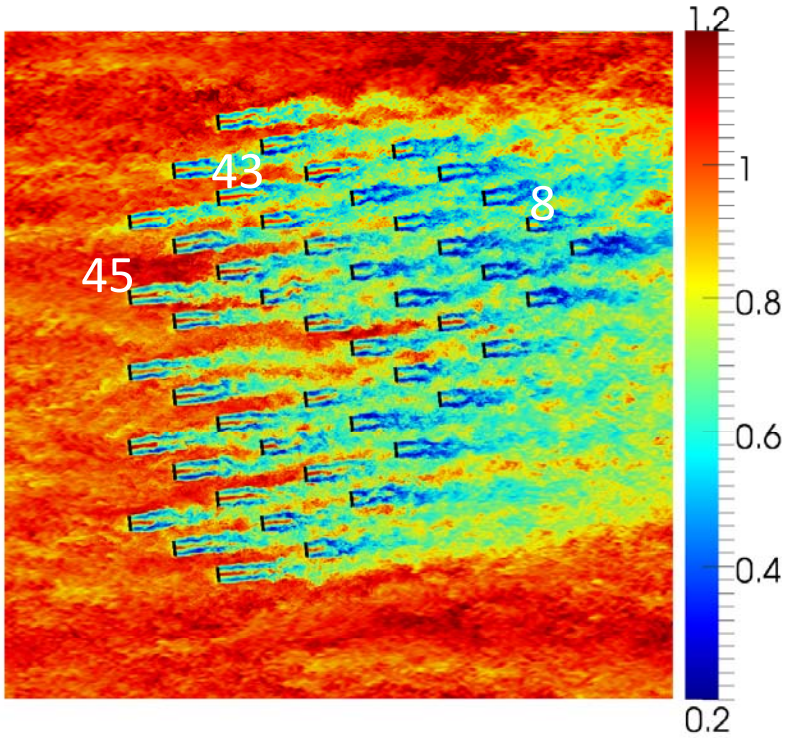
LES



Power history



Instantaneous velocity contour

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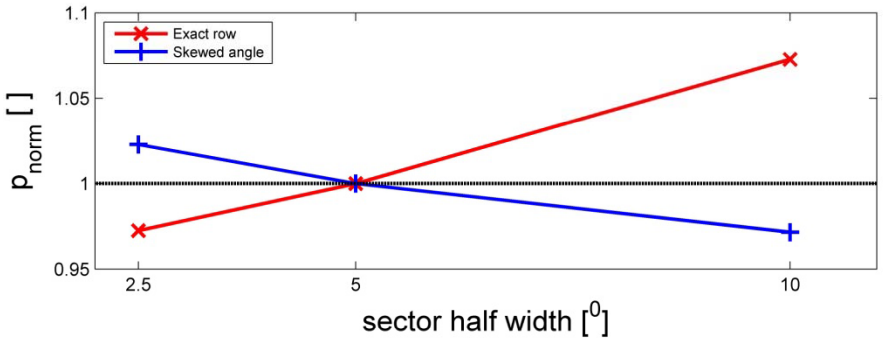
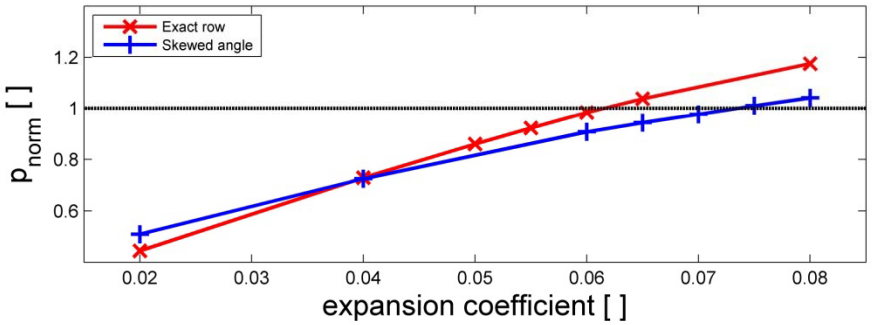
Total power production

Observations - averaging sector width



Park model - expansion coefficient



- Sector width - +/- 5%
- Choose k = 0.06 exact row
  and k = 0.07 skewed angle

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Expansion coefficient

Offshore wakes might be narrower than previously thought, especially in off-axis wind directions

$$k = k(\theta, v, TI)$$

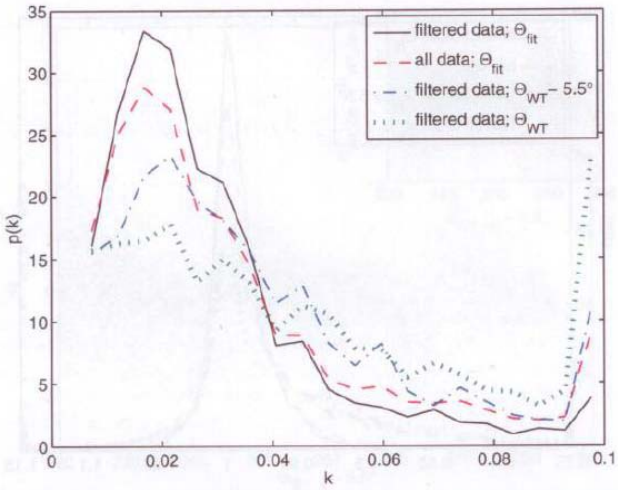

Figure 8. Distribution p(k) of wake-decay parameters obtained from best fit to all (f1)–(f3) filtered 10 min events (solid), best fit to all, i.e. non-filtered, 10 min events (dashed), one-parameter fit to all (f1)–(f3) filtered 10 min events with pre-assigned wind direction Θ = ΘWT − 5.5° (dash-dotted) and one-parameter fit to all (f1)–(f3) filtered 10 min events with pre-assigned wind direction Θ = ΘWT (dotted)

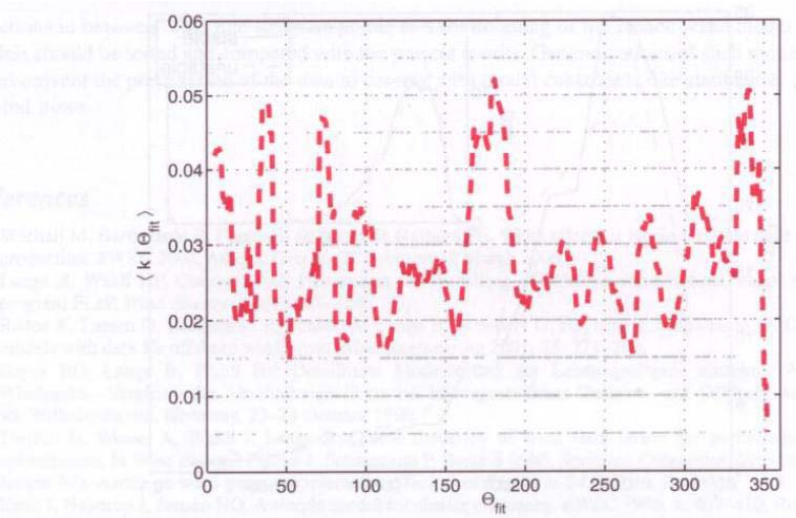

Figure 9. Wake-decay parameter k apportioned on the wind direction Θfit. The conditional average ⟨k|Θfit⟩ (thick red line) is calculated as a moving average with 10° width

Source: Jochen Cleve, G. Martin, P. Enevoldsen, B. Birkemose, and L. Jensen, 2009, Model-based analysis of wake-flow data in the Nysted offshore wind farm. *Wind Energy*. **12**, p. 125-135.

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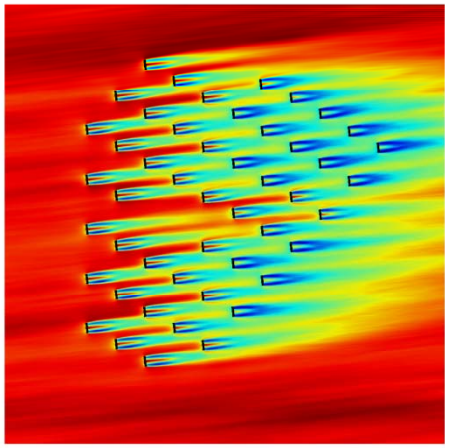
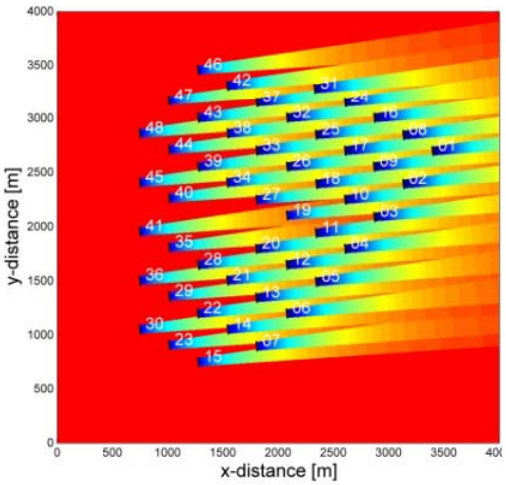
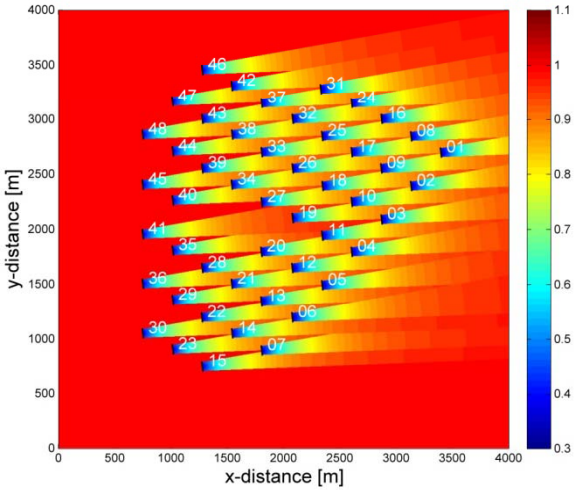
Skewed angle case



LES



k = 0.04
narrow wakes
slow recovery



k = 0.06
wide wakes
fast recovery

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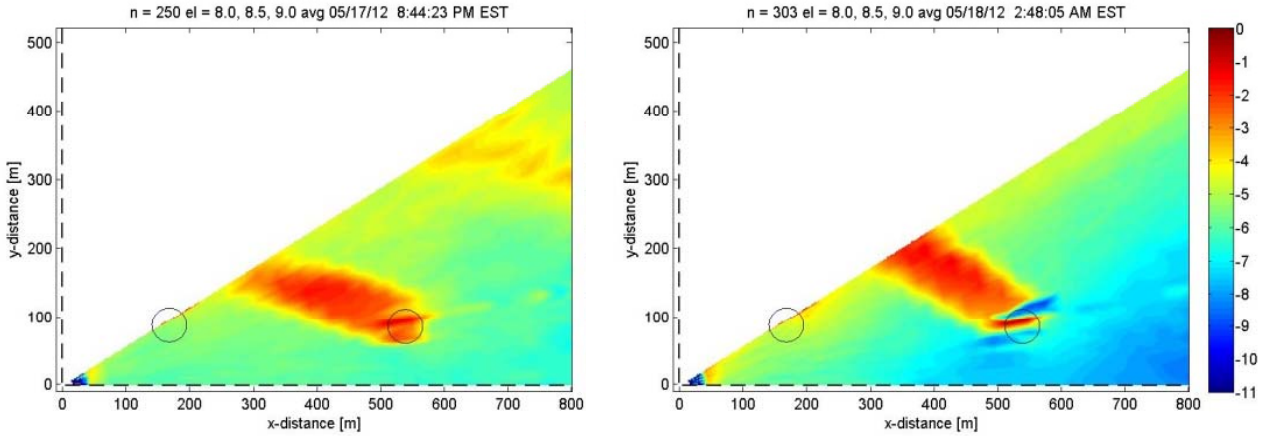

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Grants: DE-EE0005379, NSF 1067007, FloDesign