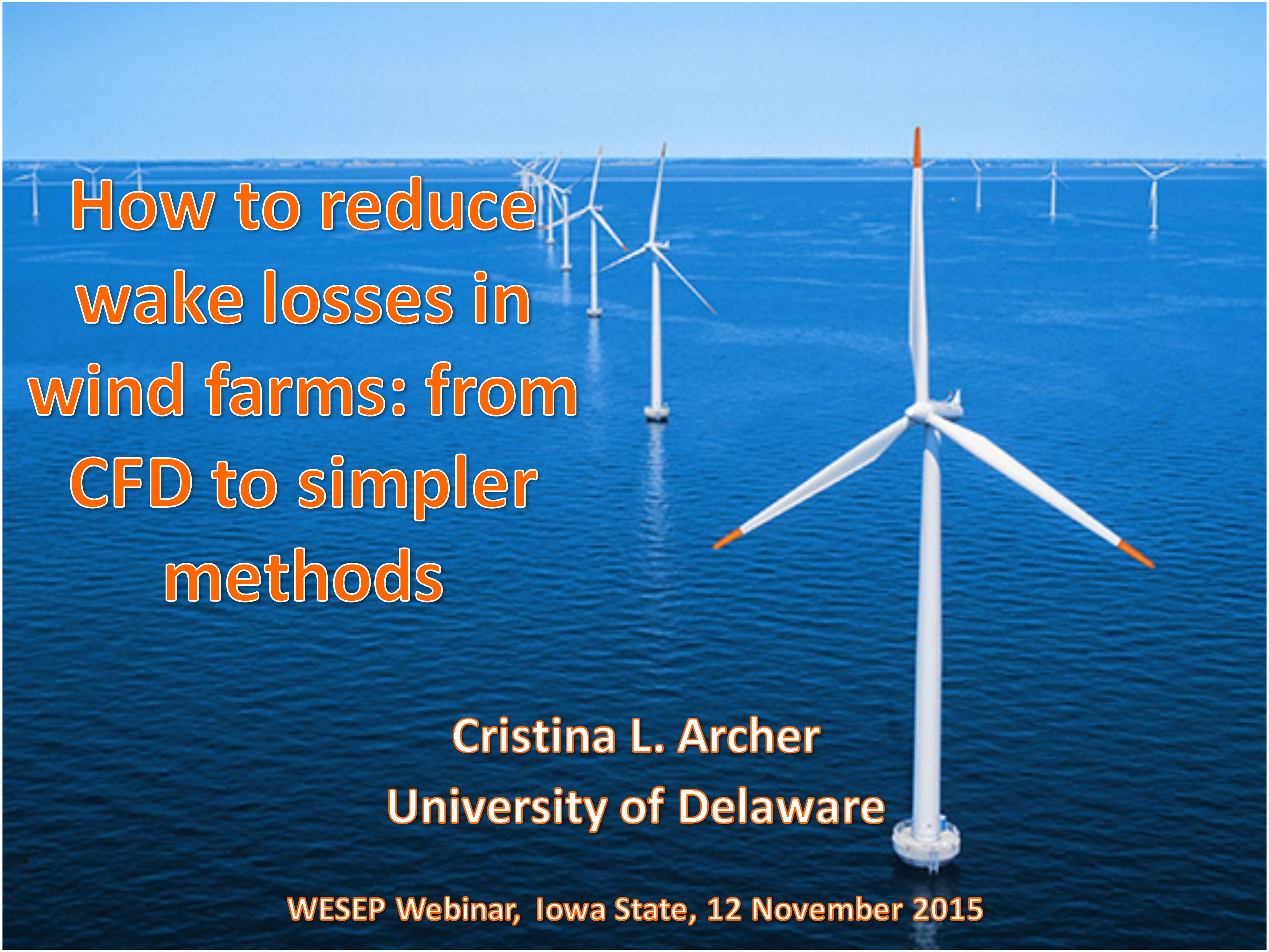
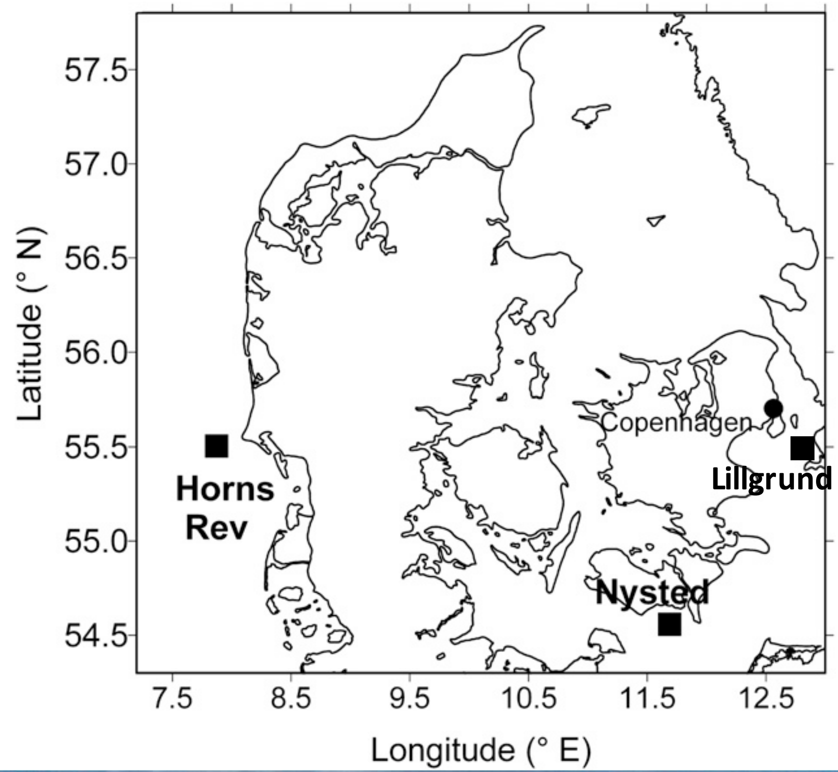

How to reduce wake losses in wind farms: from CFD to simpler methods
Cristina L. Archer
University of Delaware
WESEP Webinar, Iowa State, 12 November 2015

# Outline

- Introduction to wind farm losses:
  - What are wind turbine wakes?
  - Why wind turbine wakes cause losses?
- Understanding wake impacts with CFD:
  - Wind farm layout;
  - Atmospheric stability.
- The Geometric Model (GM):
  - GM validation;
  - Optimizing wind farm layout with GM.

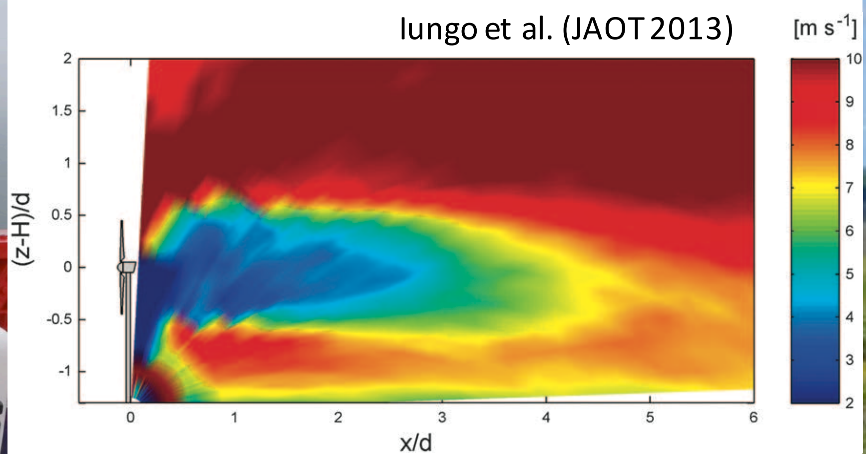
# Horns Rev photos

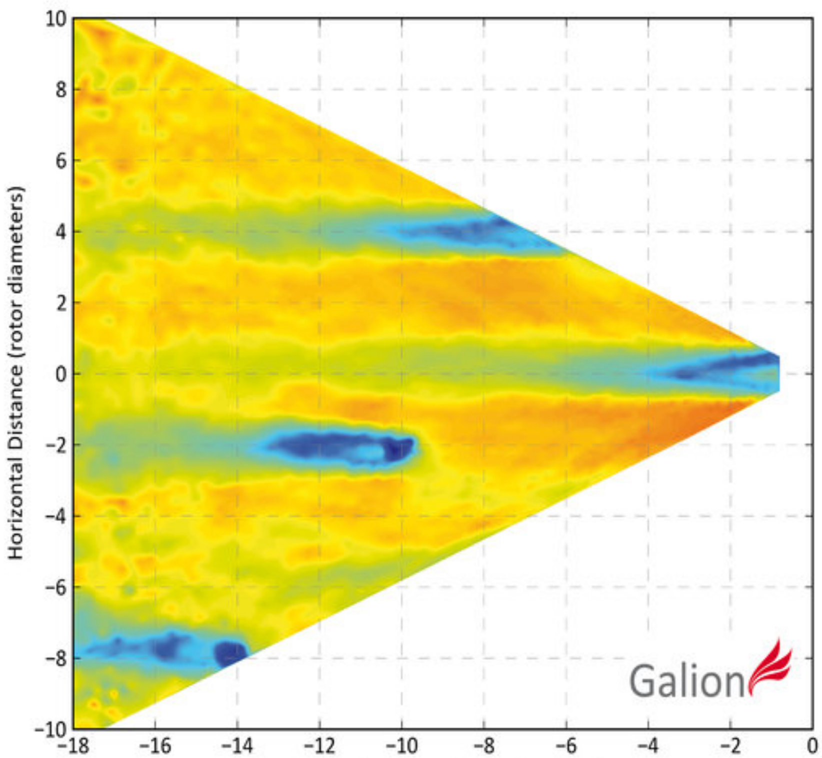

12 February 2008
~10:10 UTC

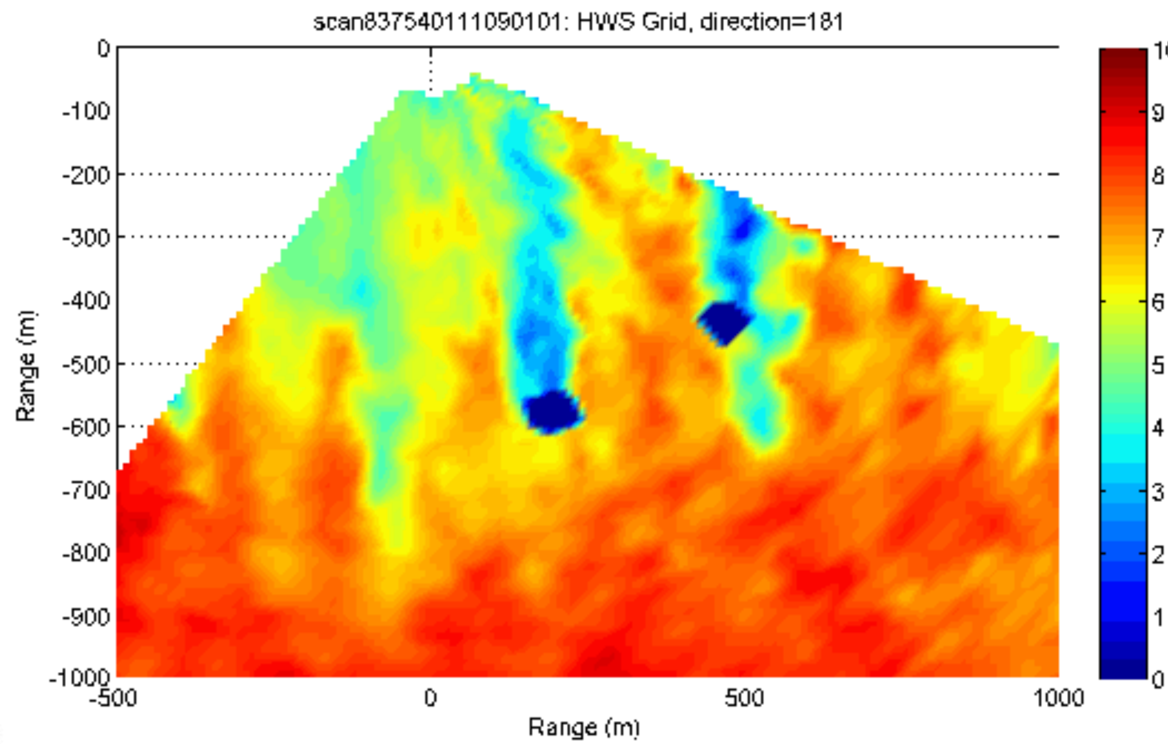

Photos by Christian Steiness

# Lidars: wind speed deficit in wakes

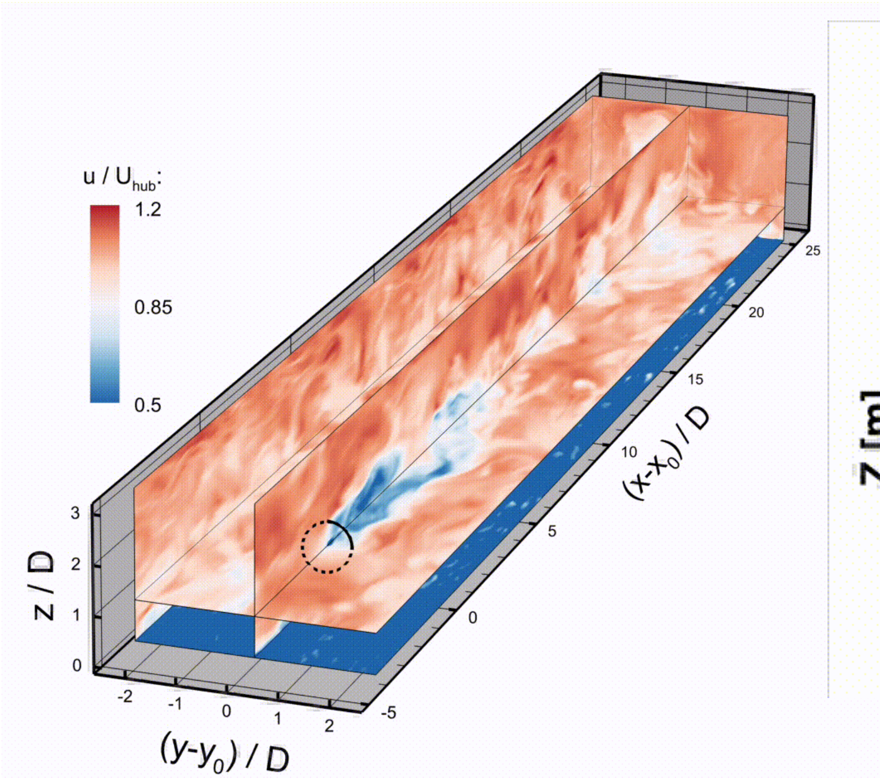



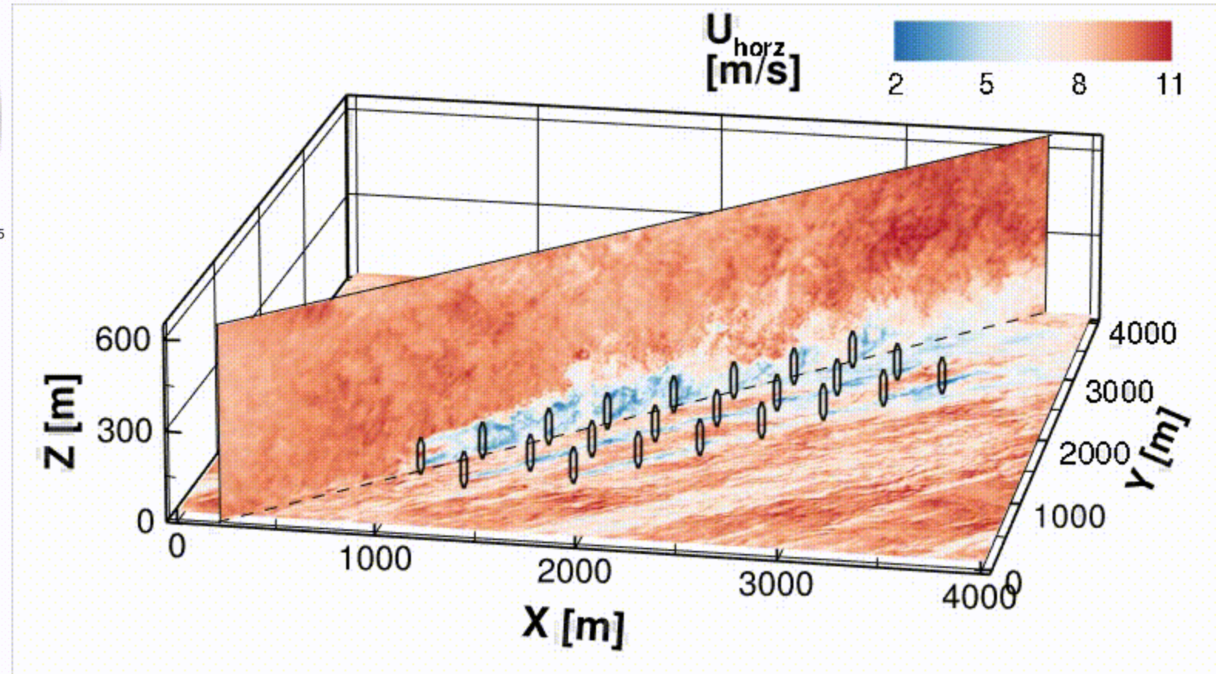




# Simulated single- and multi-turbine wakes



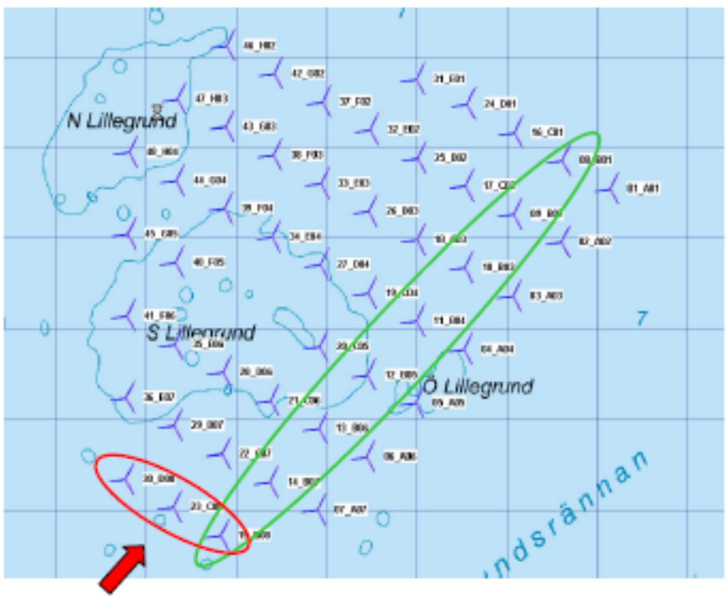




In-house code WiTTS (Wind Turbine and Turbulence Simulator)

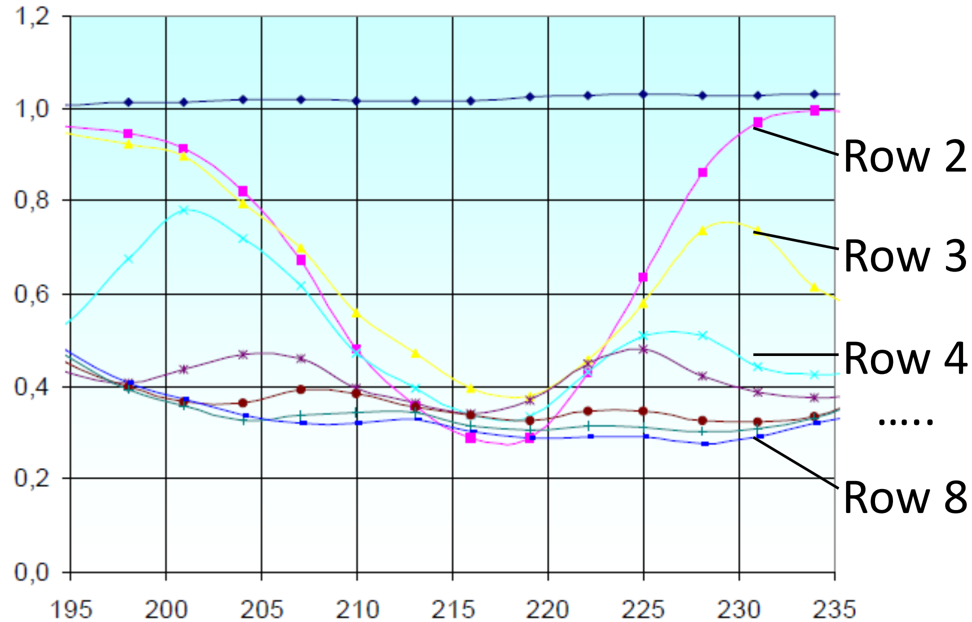
OpenFOAM-based SOWFA (Software for Offshore/onshore Wind Farm Applications)

Both are Large-Eddy Simulation (LES) codes

# Wind speed deficit = reduced power



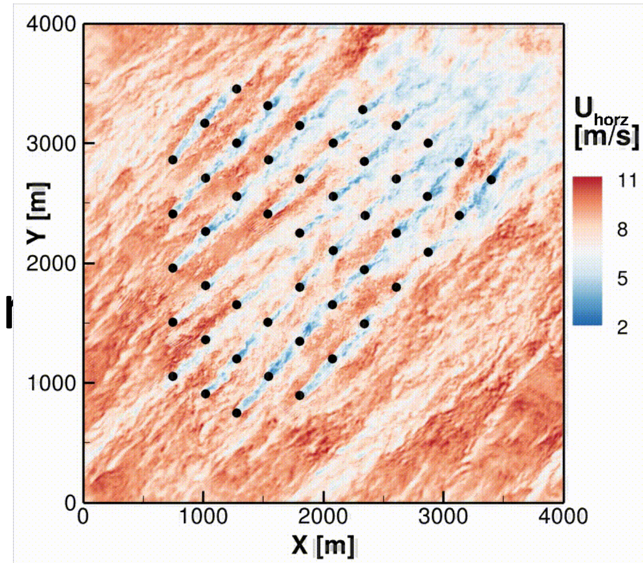
Layout of Lillgrund wind farm.
Both figures from Dahlberg (2009).



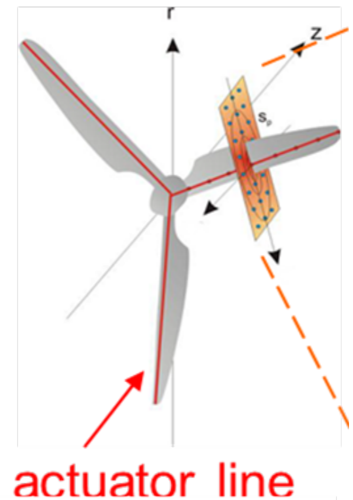

Relative power of turbines in highlighted row vs. wind direction.

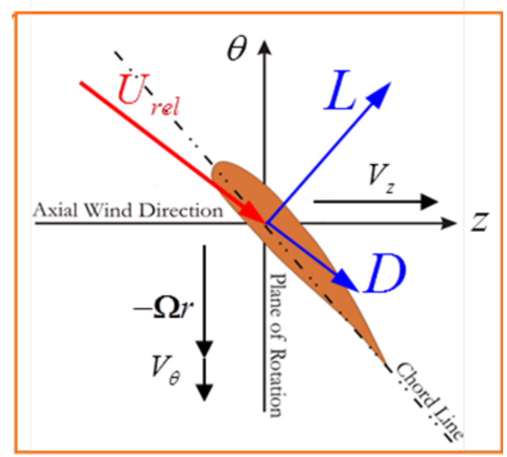
- Losses in generated power due to wakes of upstream turbines can be very large (>60%).
- Wake losses are affected significantly by farm layout, wind direction, and atmospheric stability.

# LES of a wind farm

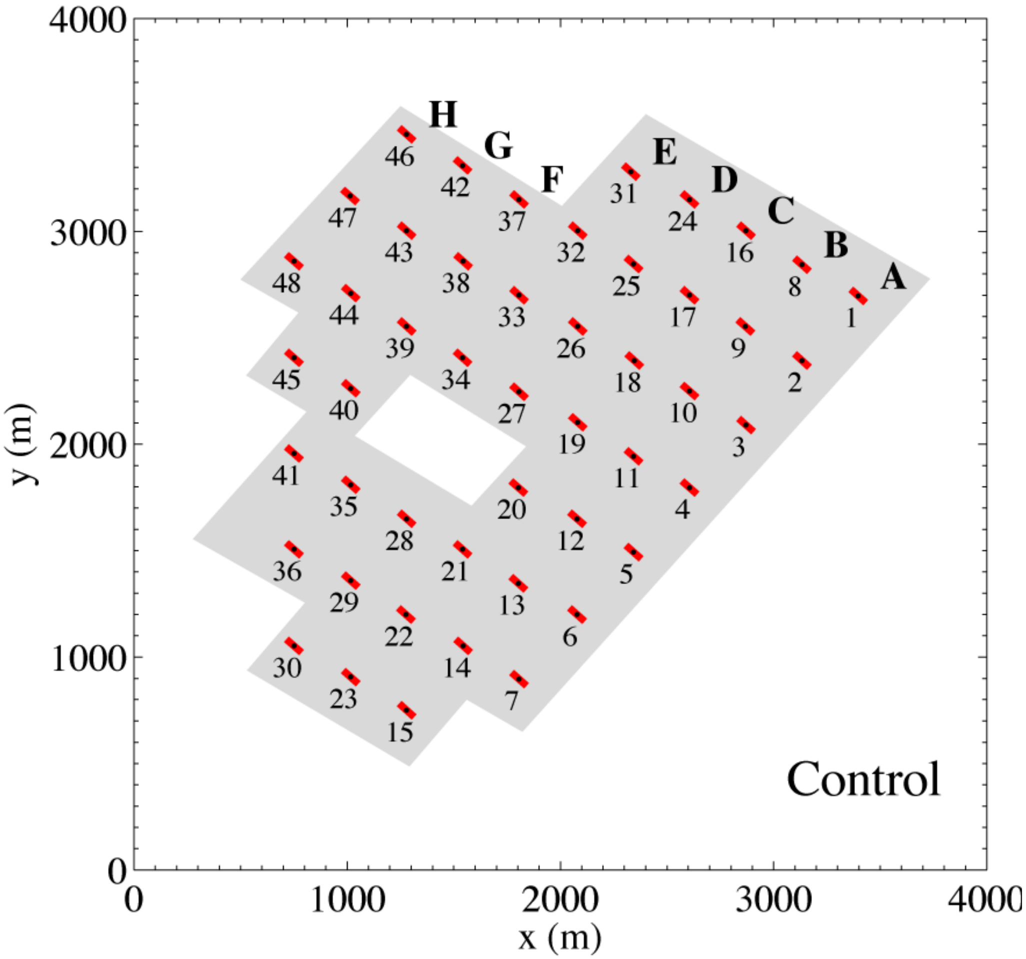


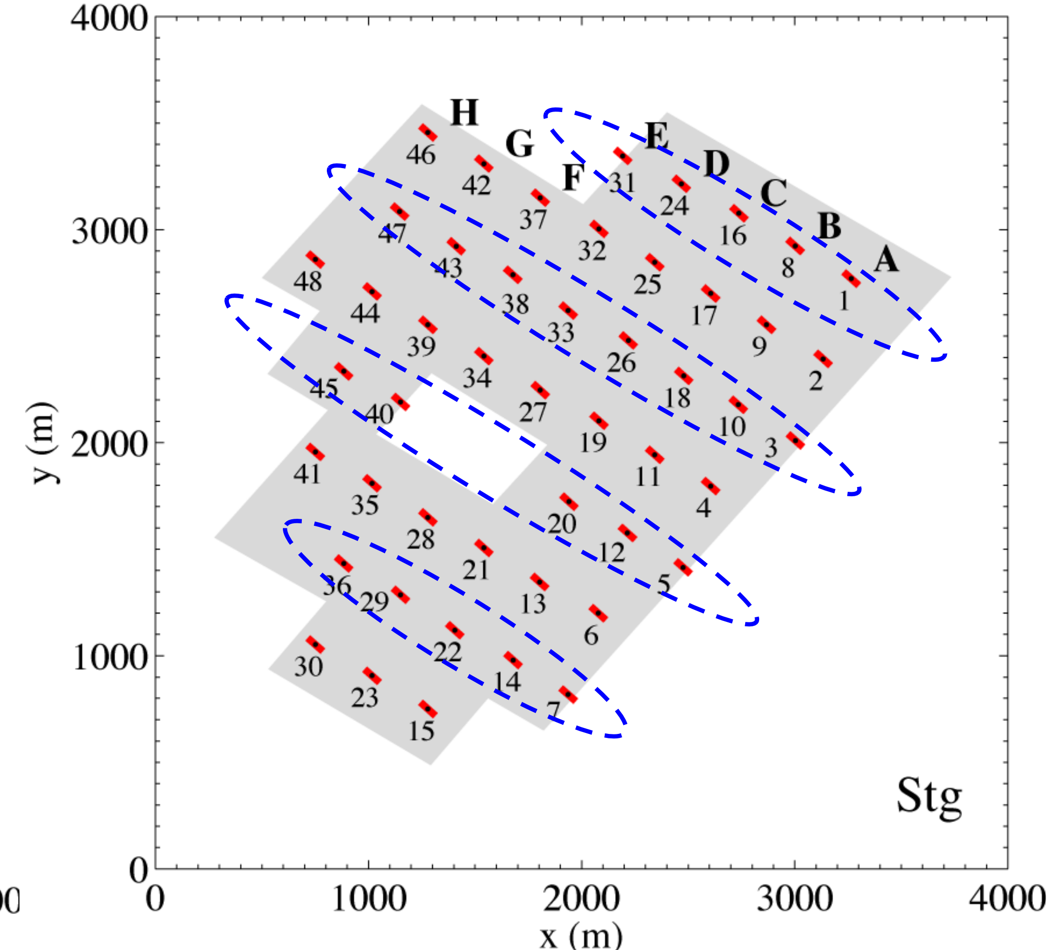

- Large-Eddy Simulations with **SOWFA** (Softwar
  Offshore/onshore Wind Farm Applications);
- SOWFA was developed at NREL;
- Actuator lines;
- Finite-volume, C++, OpenFOAM;
- SGS model: Lagrangian scale-invariant;
- Incompressible, Boussinesq, all stabilities;
- Lillgrund offshore wind farm;
- 48 Siemens 2.3 MW wind turbines;
- Spacing 3.3D x 4.3D;
- ~80 million grid cells;
- Resolution 3.5-7 m;
- Complex initialization method to provide non-periodic boundary conditions (precursor run).



# Layout effect: Original vs. staggered



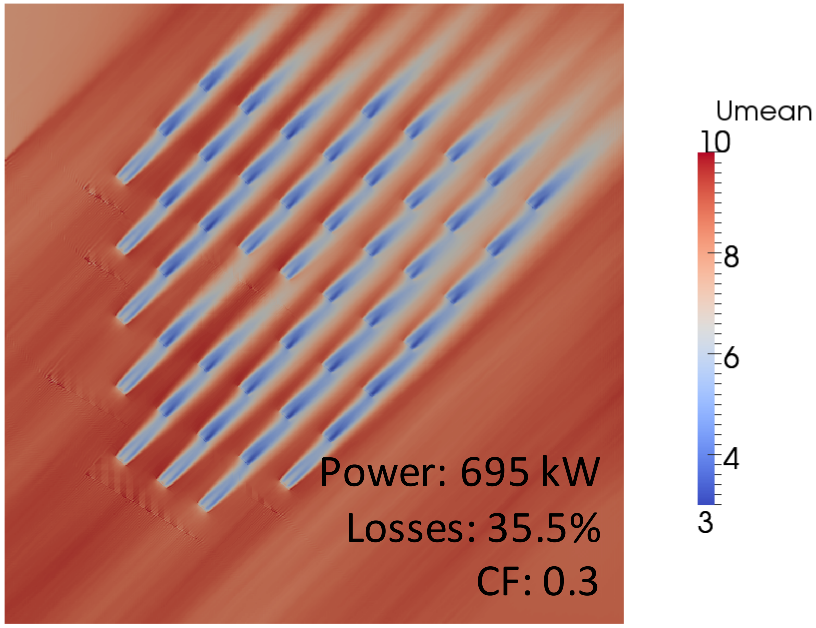




Archer et al. (GRL, 2013)

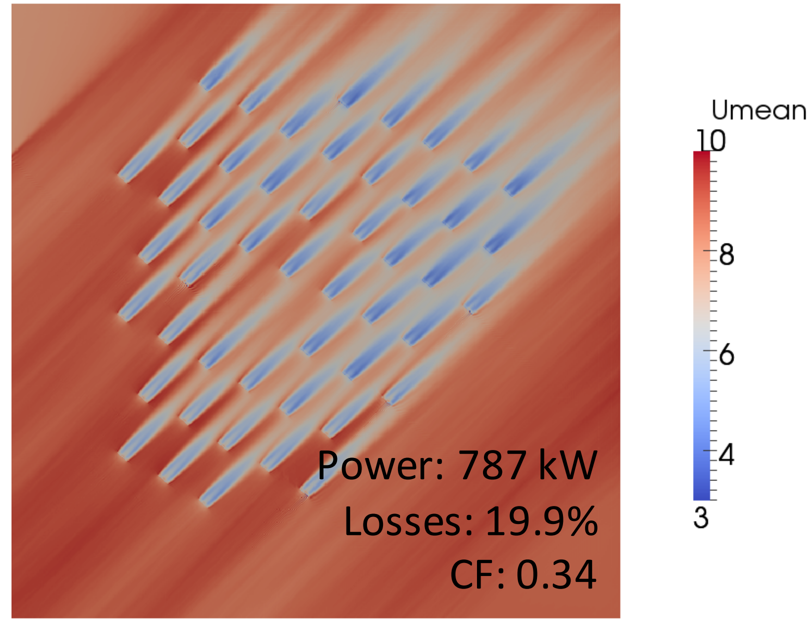
# Staggered layout better for wind from 225°

SOUTH-WEST (225°)

ORIGINAL



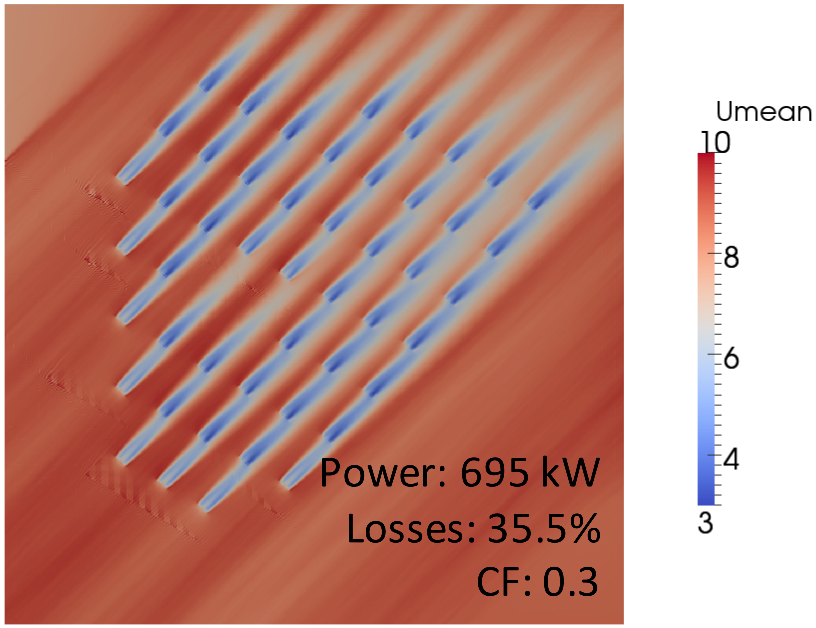

STAGGERED

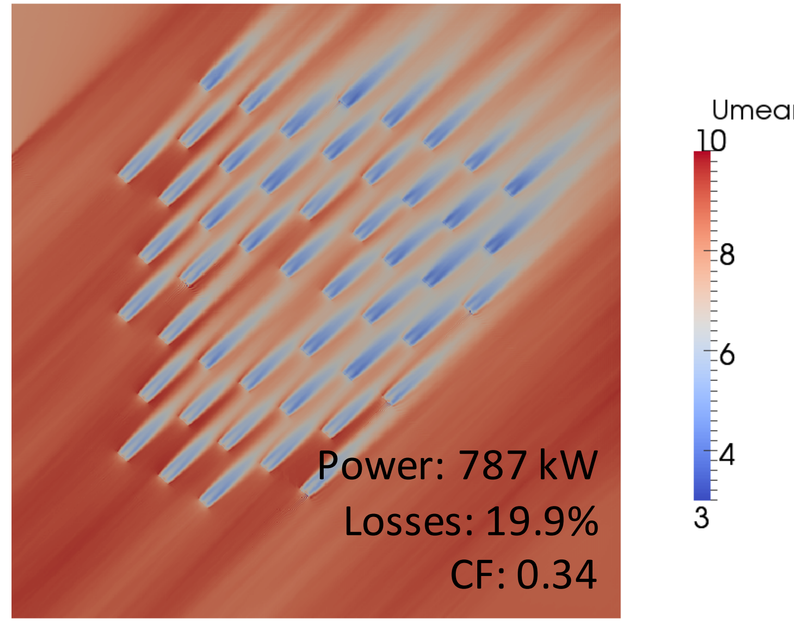


# Trade-offs exist for other wind directions

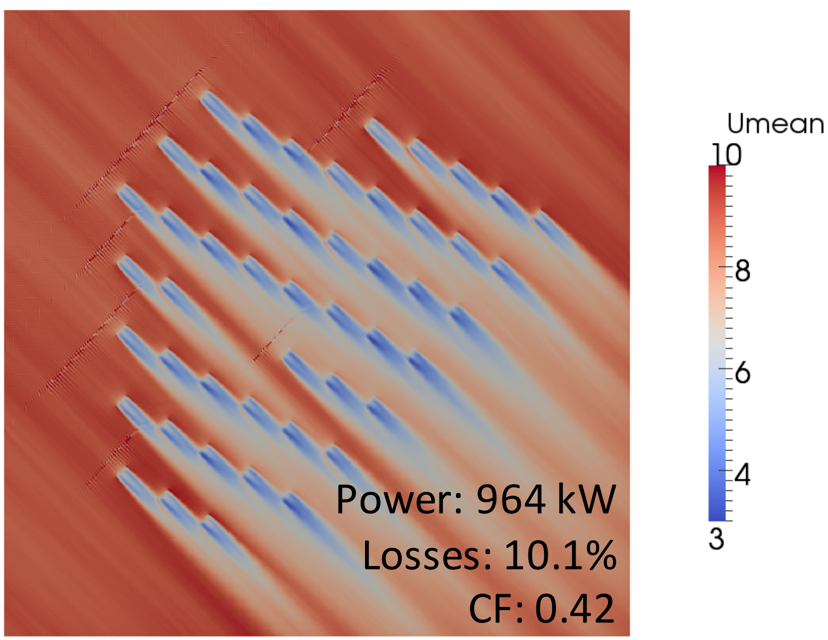
ORIGINAL | STAGGERED

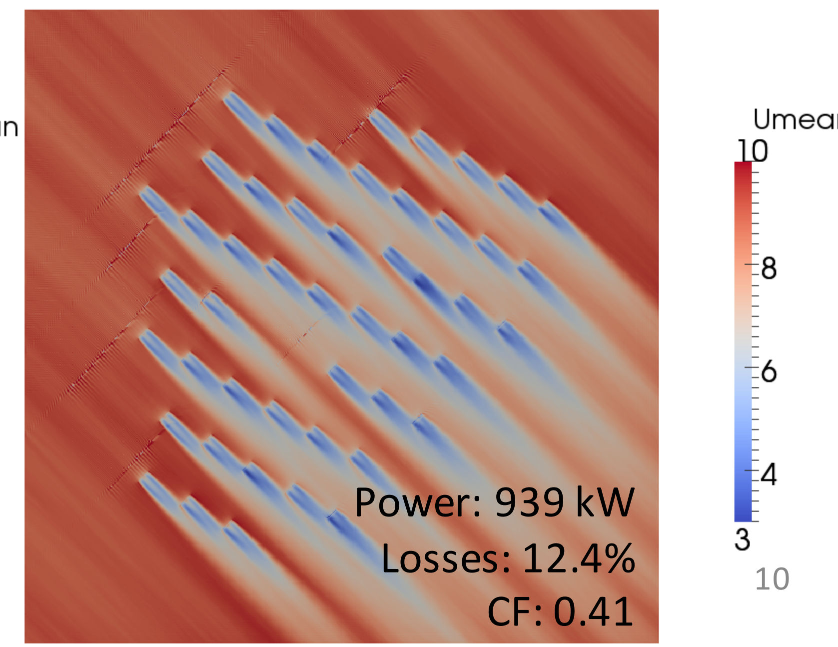
SOUTH-WEST (225°)



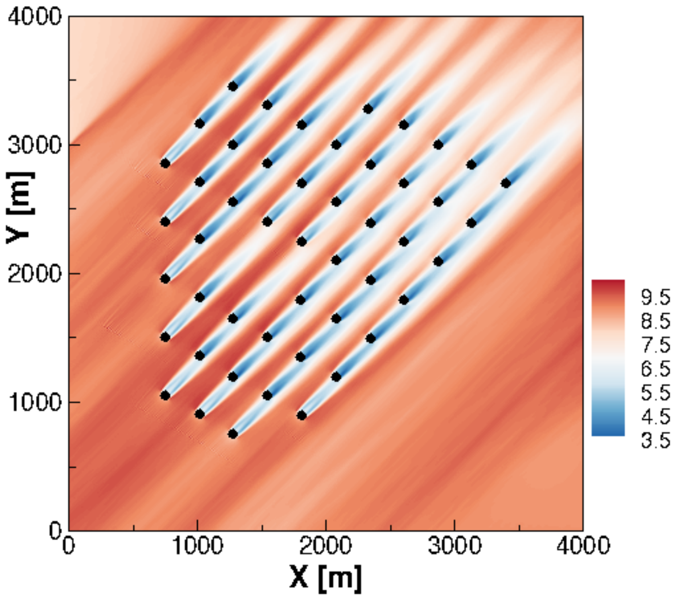




NORTH-WEST (315°)

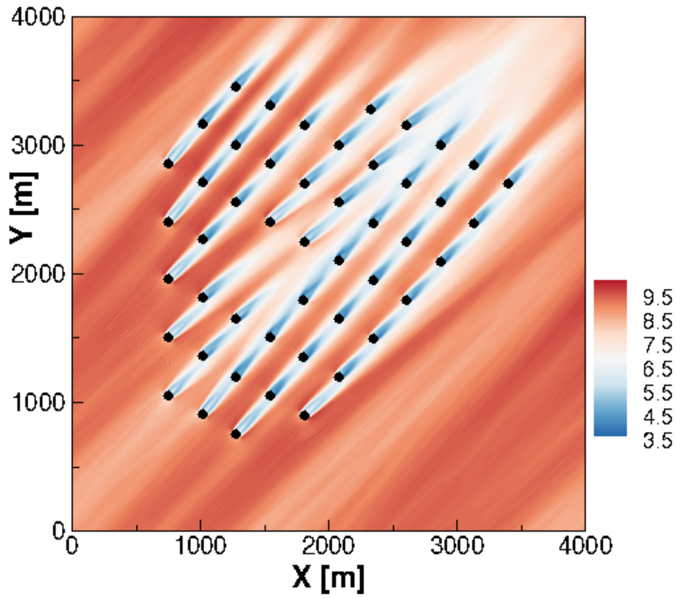


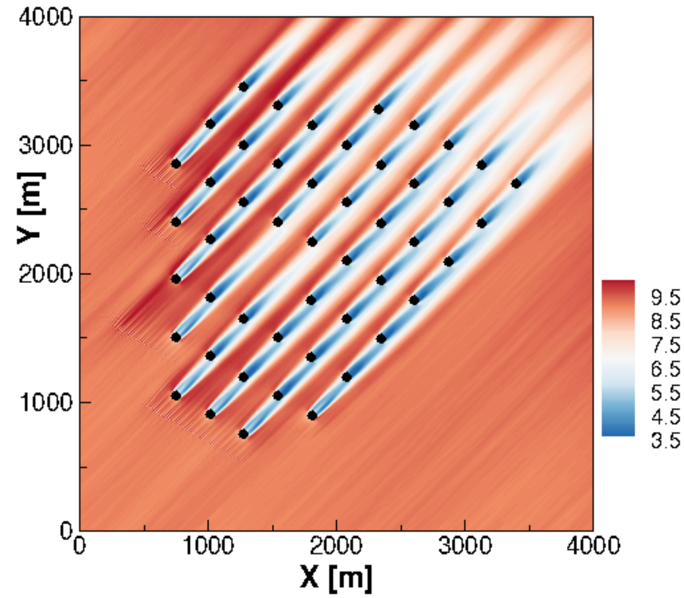
# Atmospheric stability effects




Neutral
$P_{TOT}$ = 33.4 MW




Unstable
$P_{TOT}$ = 35.1 MW

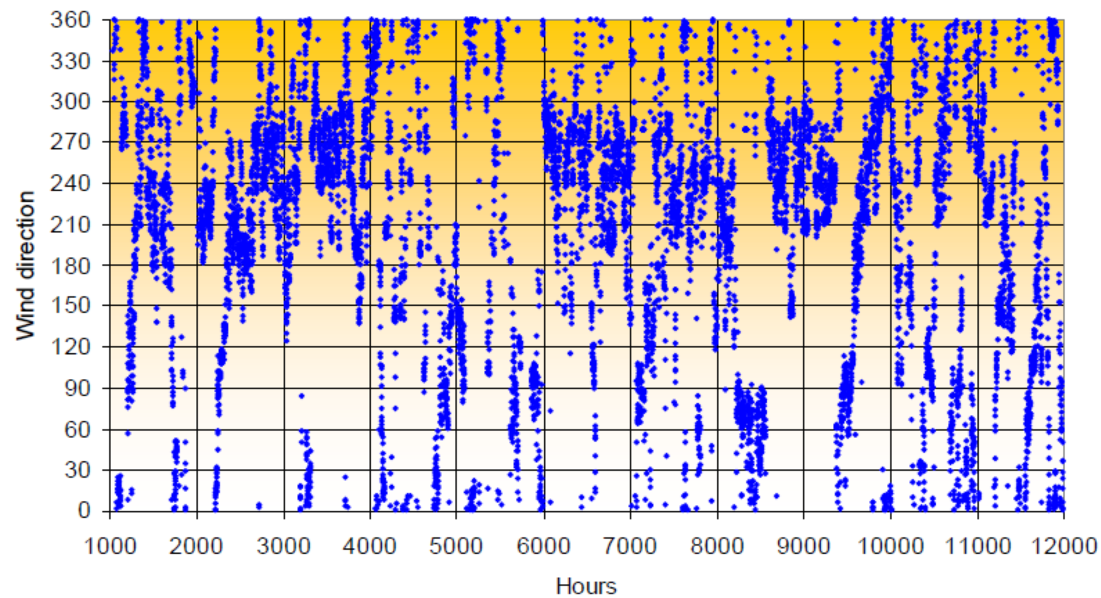



Stable
$P_{TOT}$ = 30.3 MW

- Initialized with same prescribed wind speed at 90 m (9 m/s);
- Neutral and stable case have reached equilibrium;
- Unstable case shows patterns of convergence and divergence;
- Wakes shorter in unstable, longer in stable, than neutral case.

# How to optimize layout?

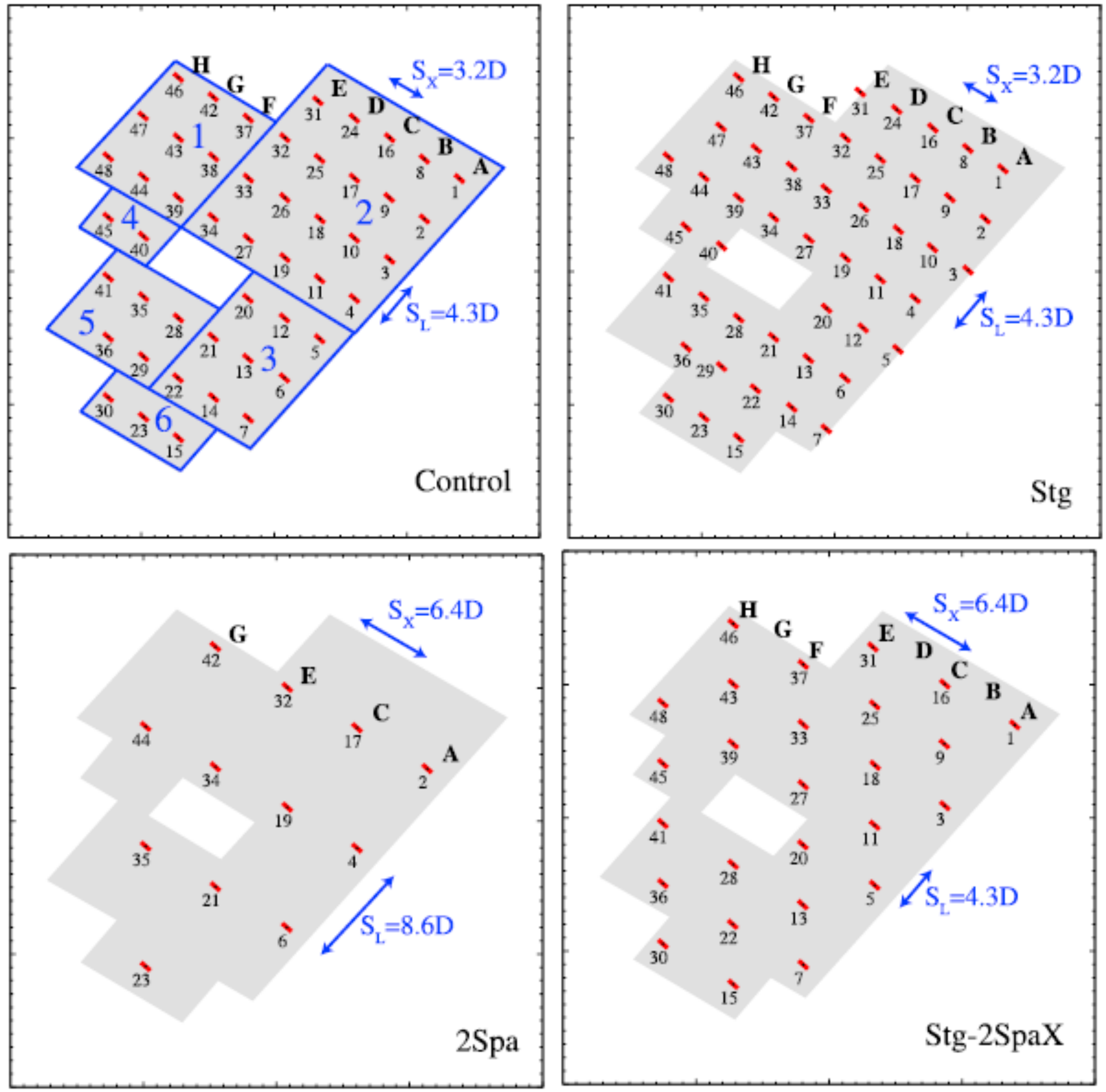
- Many attempts for fixed wind direction using LES:
  - Wu and Porté-Agel (2013);
  - Archer et al. (2013);
  - Stevens et al. (2014).
- Each LES takes ~45 days.
- Impossible to simulate all wind directions and all stabilities.
- *Aim: Develop simpler models based on LES.*




Observed wind direction vs. time at Lillgrund. Figure from Dahlberg (2009)

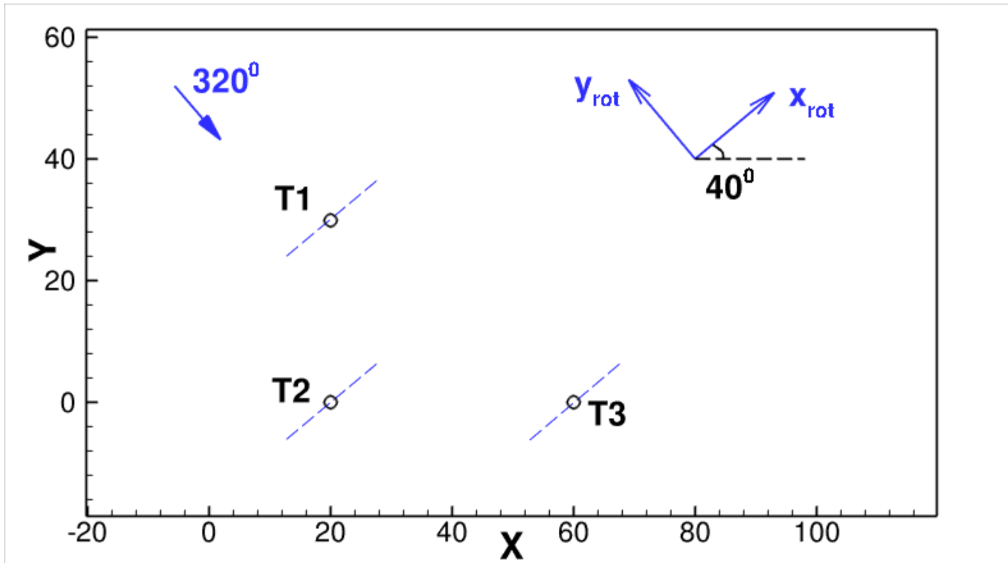
# Suite of “Lillgrund” LES

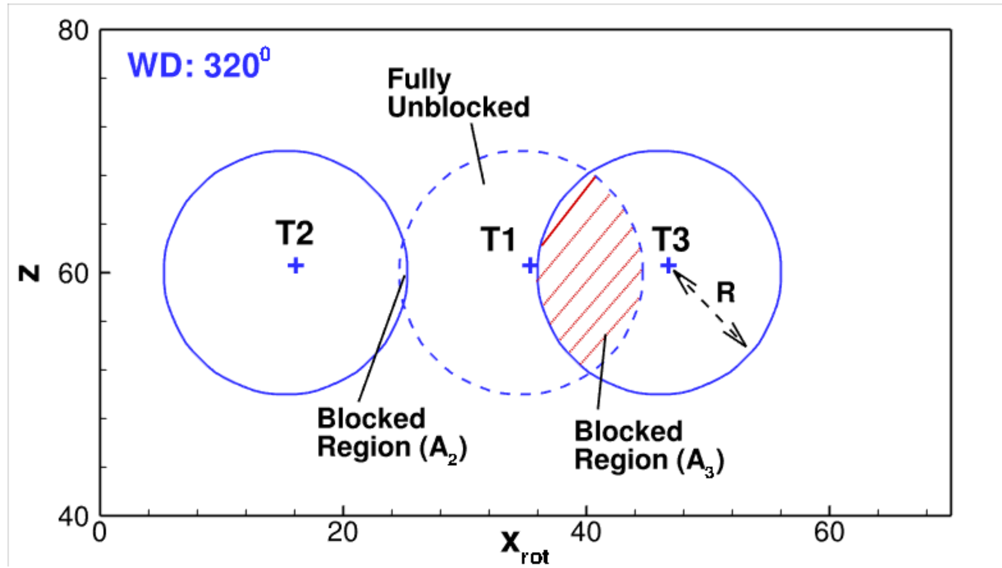
- Data from LES:
  - Several “Lillgrund” layouts
  - Wind Directions ($225^0$, $270^0$, $315^0$)
  - Stabilities: neutral, unstable, stable
- Final LES database:
  - 8 neutral,
  - 4 unstable,
  - 4 stable cases.




Archer et al. (GRL, 2013)

# Geometric quantities – Blockage Ratio



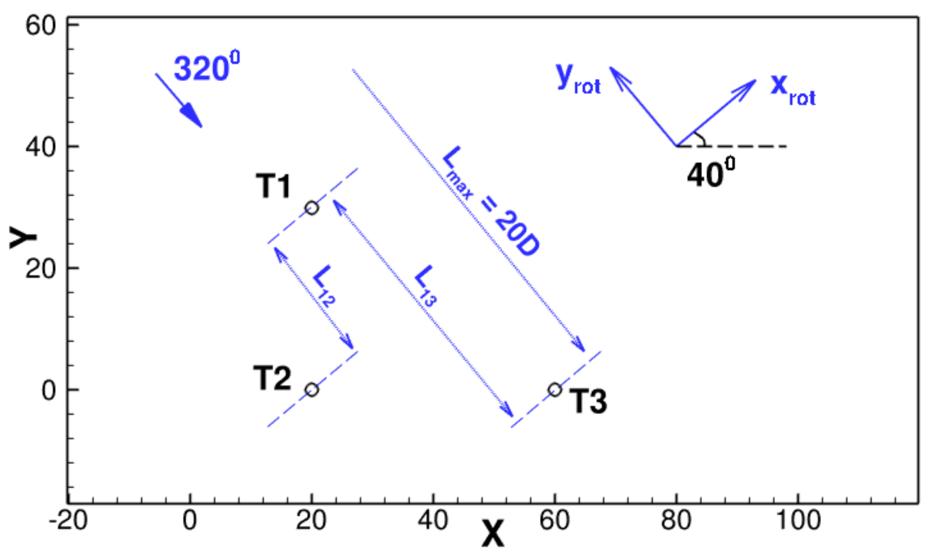



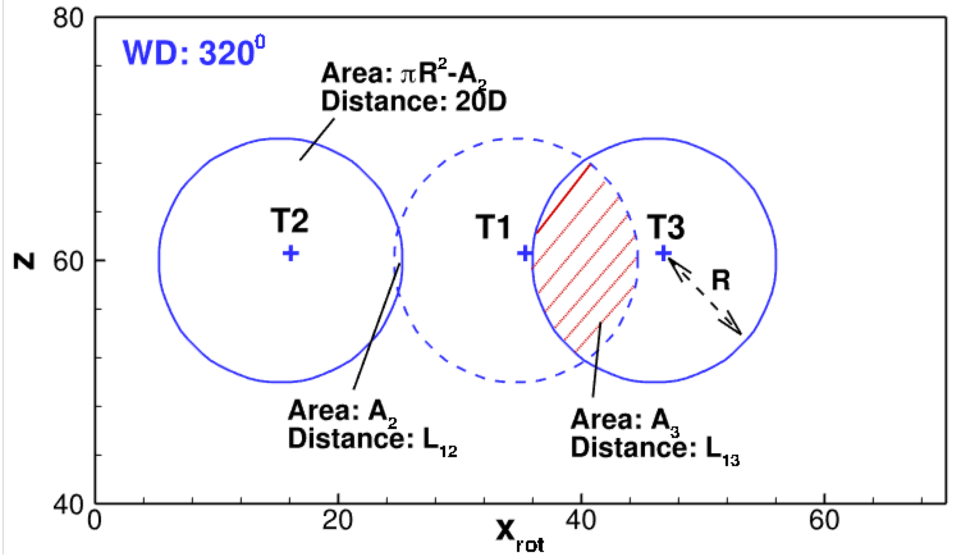

- Consider a 3-turbine wind farm;
- For each turbine i, define Blockage Ratio ($BR_i$):
  - Fraction of rotor area blocked by upstream turbines.

$$BR_1 = 0, \qquad BR_2 = \frac{A_2}{\pi R^2}, \qquad BR_3 = \frac{A_3}{\pi R^2}$$

Ghaisas and Archer (JAOT, 2015)

# Geometric quantities – Blockage Distance




Blockage Distance ($BD_i$):

- Distance to upstream blocking turbine weighted by fraction of area blocked;
- Limit to 20D wherever no blockage.

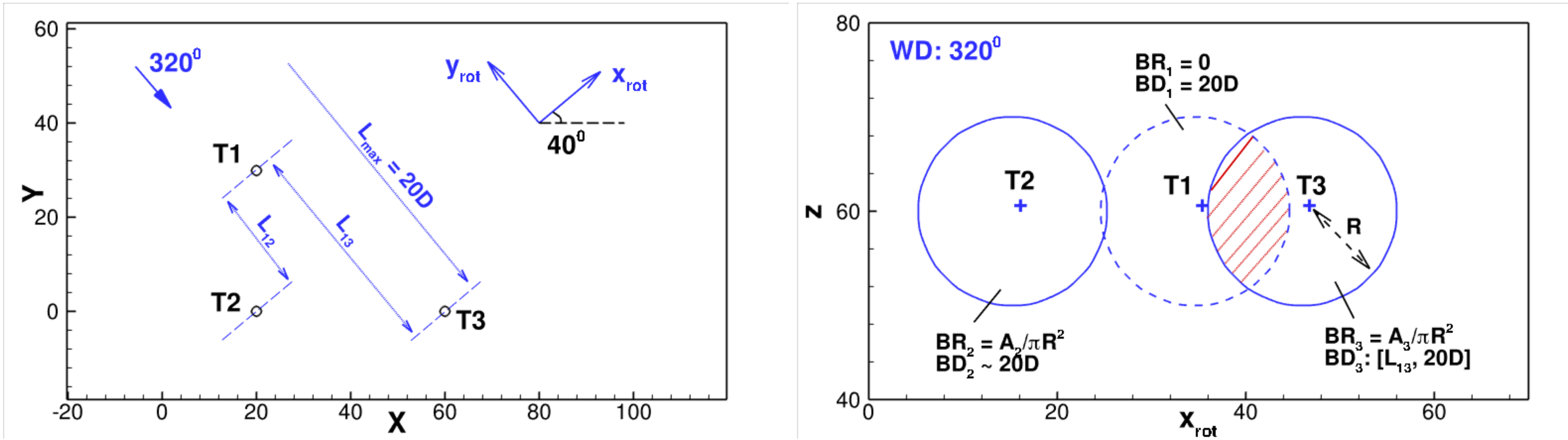
$$BD_1 = 20D,$$

$$BD_2 = L_{12}\left(\frac{A_2}{\pi R^2}\right) + 20D\left(1 - \frac{A_2}{\pi R^2}\right),$$

$$BD_3 = L_{13}\left(\frac{A_3}{\pi R^2}\right) + 20D\left(1 - \frac{A_3}{\pi R^2}\right)$$

Ghaisas and Archer (JAOT, 2015)

# Hypothesis



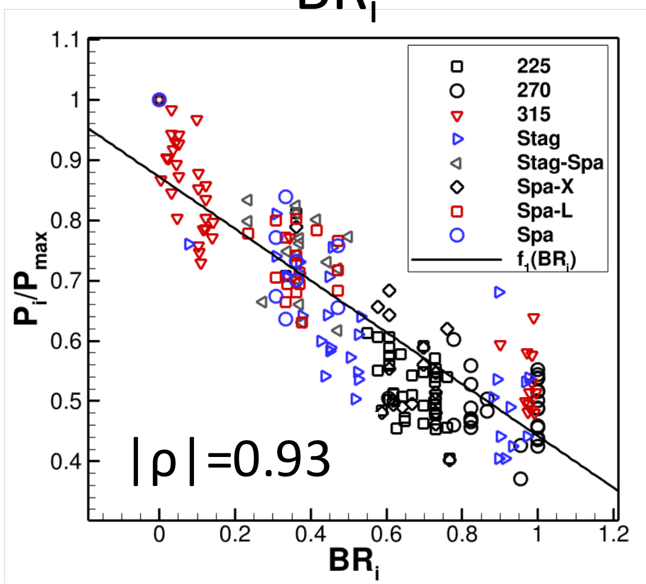

Ghaisas and Archer (JAOT, 2015)

- Turbines with $BR_i$ = 0 (unblocked) generate rated power ($P_{max}$);
- Relative power of other turbines is a function of $BR_i$, $BD_i$.

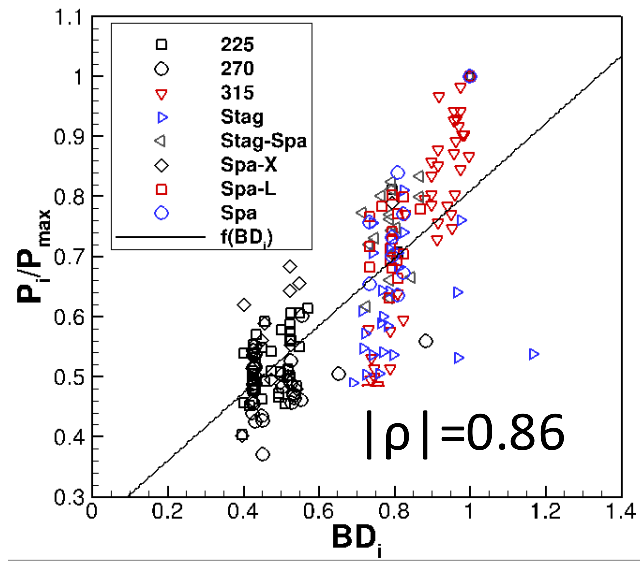
$$\Rightarrow \frac{P}{P_{\max}} = \begin{cases} 1, & BR_i = 0 \\ f(BR_i, BD_i), & BR_i \neq 0 \end{cases}$$

# Correlations: Neutral

$BR_i$




$BD_i$

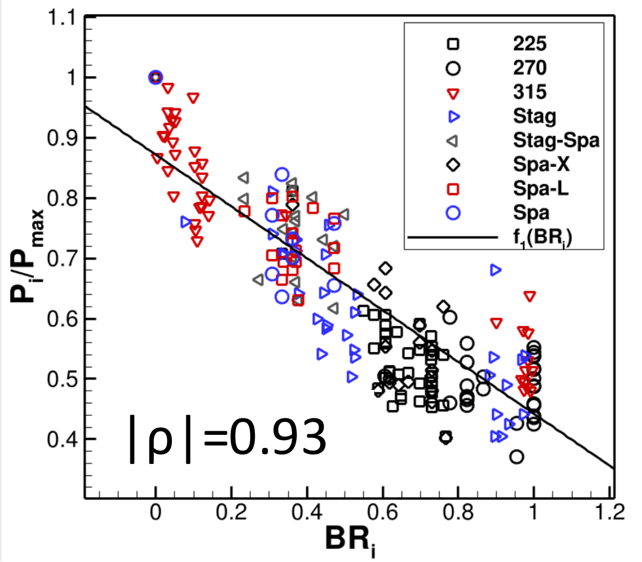



- Individual correlations of $BR_i$ and $BD_i$ are high;

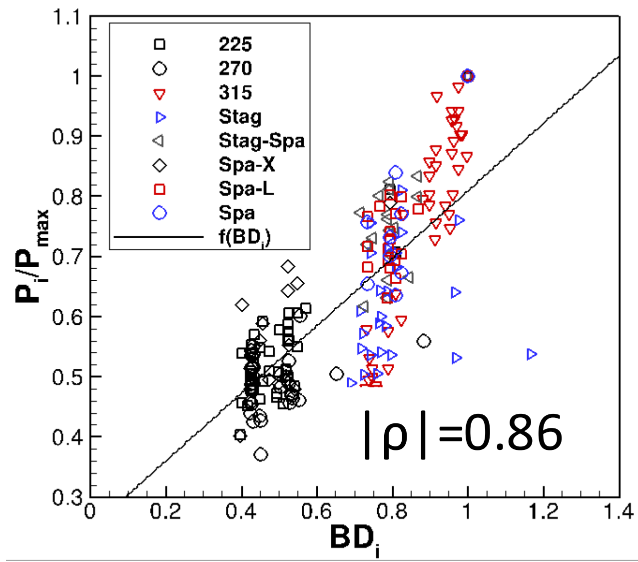
Ghaisas and Archer (JAOT, 2015)

# Correlations: Neutral

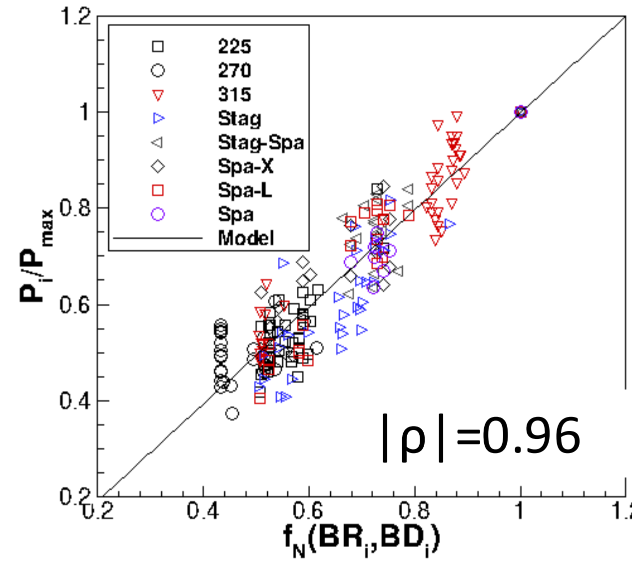
$BR_i$




$BD_i$




MLR



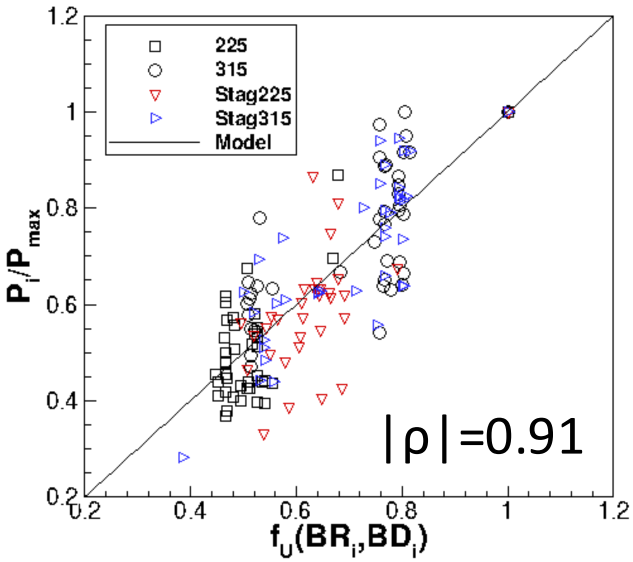

- Individual correlations of $BR_i$ and $BD_i$ are high;
- Multiple Linear Regression (MLR) gives even higher correlation;
- Geometric Model (GM): use MLR with coefficients calibrated from the LES.

$$P_i / P_{\max} = f_N(BR_i, BD_i)$$

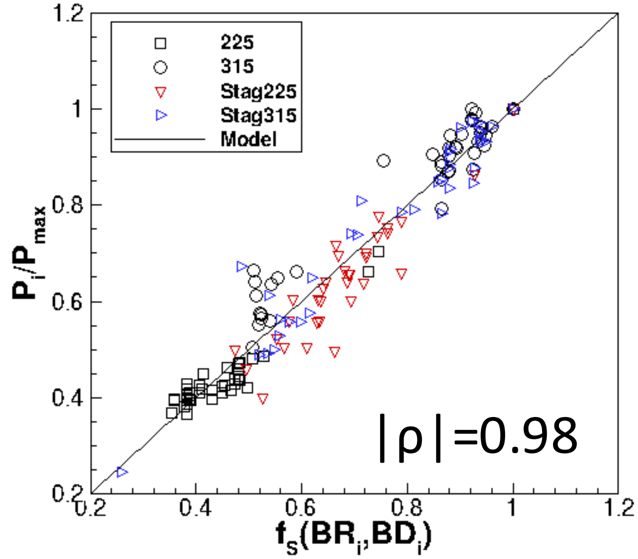
Ghaisas and Archer (JAOT, 2015)

# Correlations: All stabilities

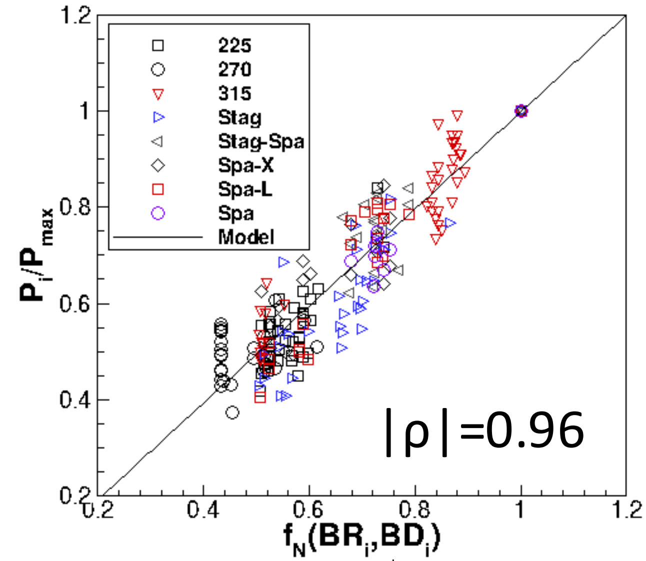
Unstable




Stable




Neutral



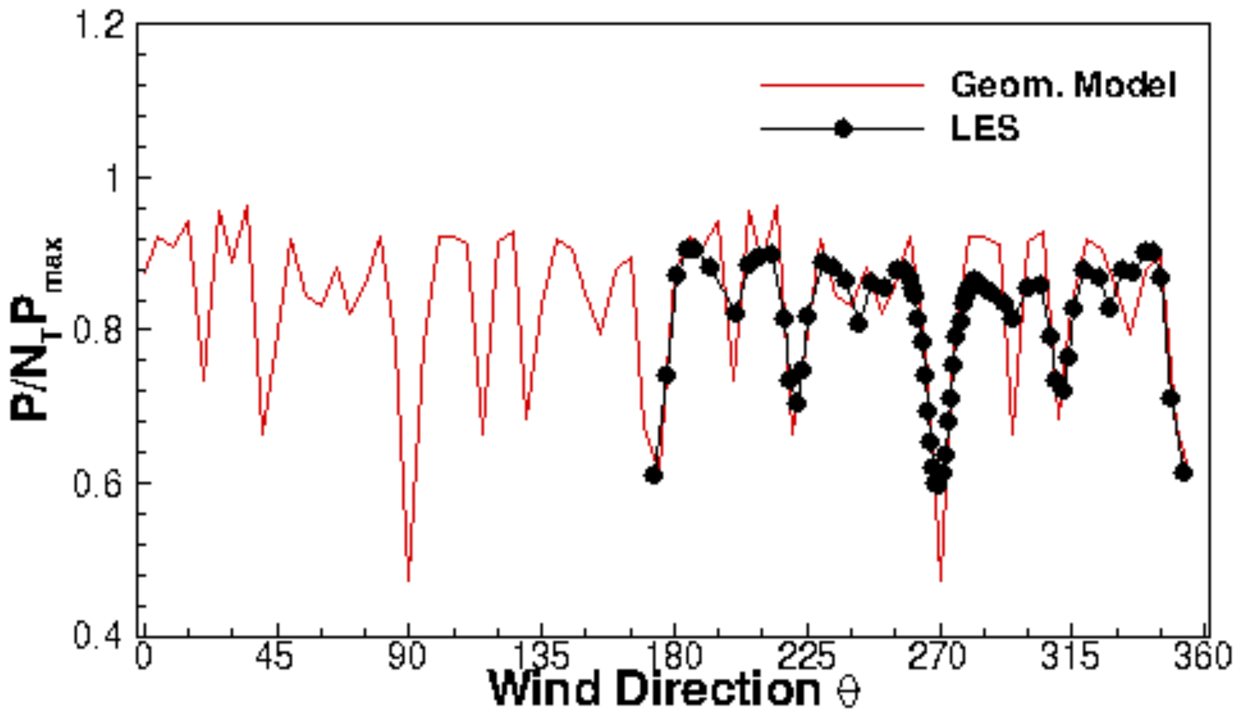

$$P_i/P_{max} = f_U(BR_i, BD_i)$$

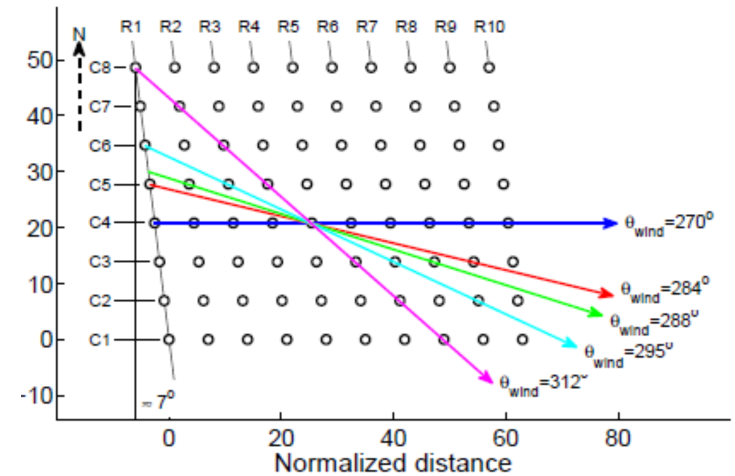
$$P_i/P_{max} = f_S(BR_i, BD_i)$$

$$P_i/P_{max} = f_N(BR_i, BD_i)$$

- Similarly high correlations for unstable and stable cases.

# GM validation – LES of Horns Rev



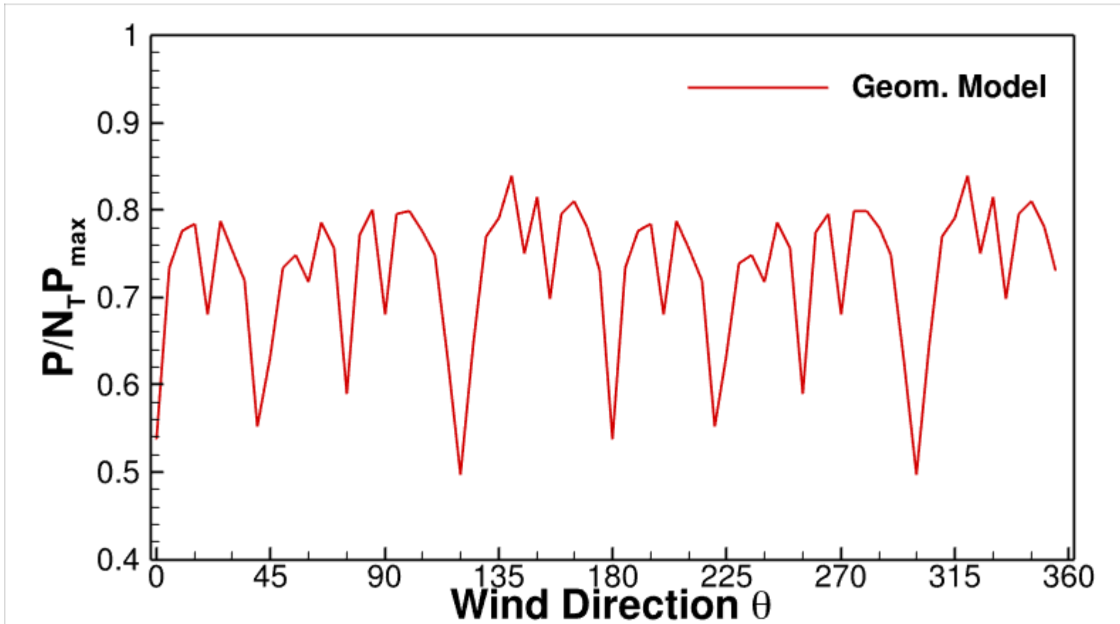



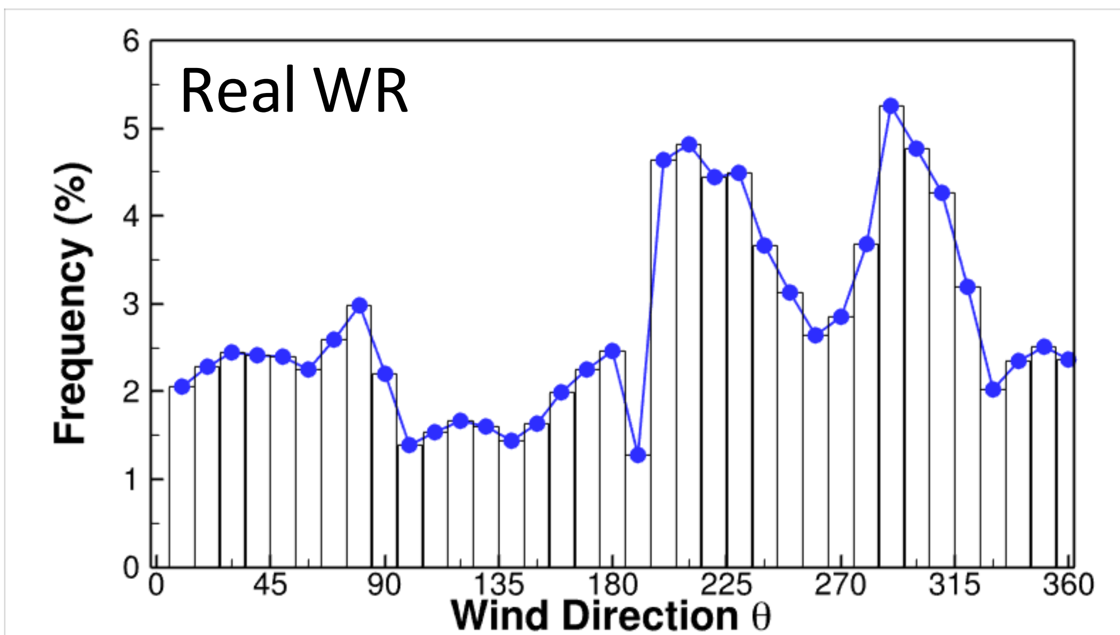

- Comparisons to neutral LES of Horns Rev (Porté-Agel et al., 2013);
- Geometric Model (GM) trained on Lillgrund translates very well to other farms, like Horns Rev.

# Application of Geometry-based Model

- Geometry-based Model is very inexpensive (~1 minute for a 100-turbine layout for each wind direction);
- Multiple wind directions can be evaluated efficiently;
- Used in a search-based optimization procedure.

# Wind Rose



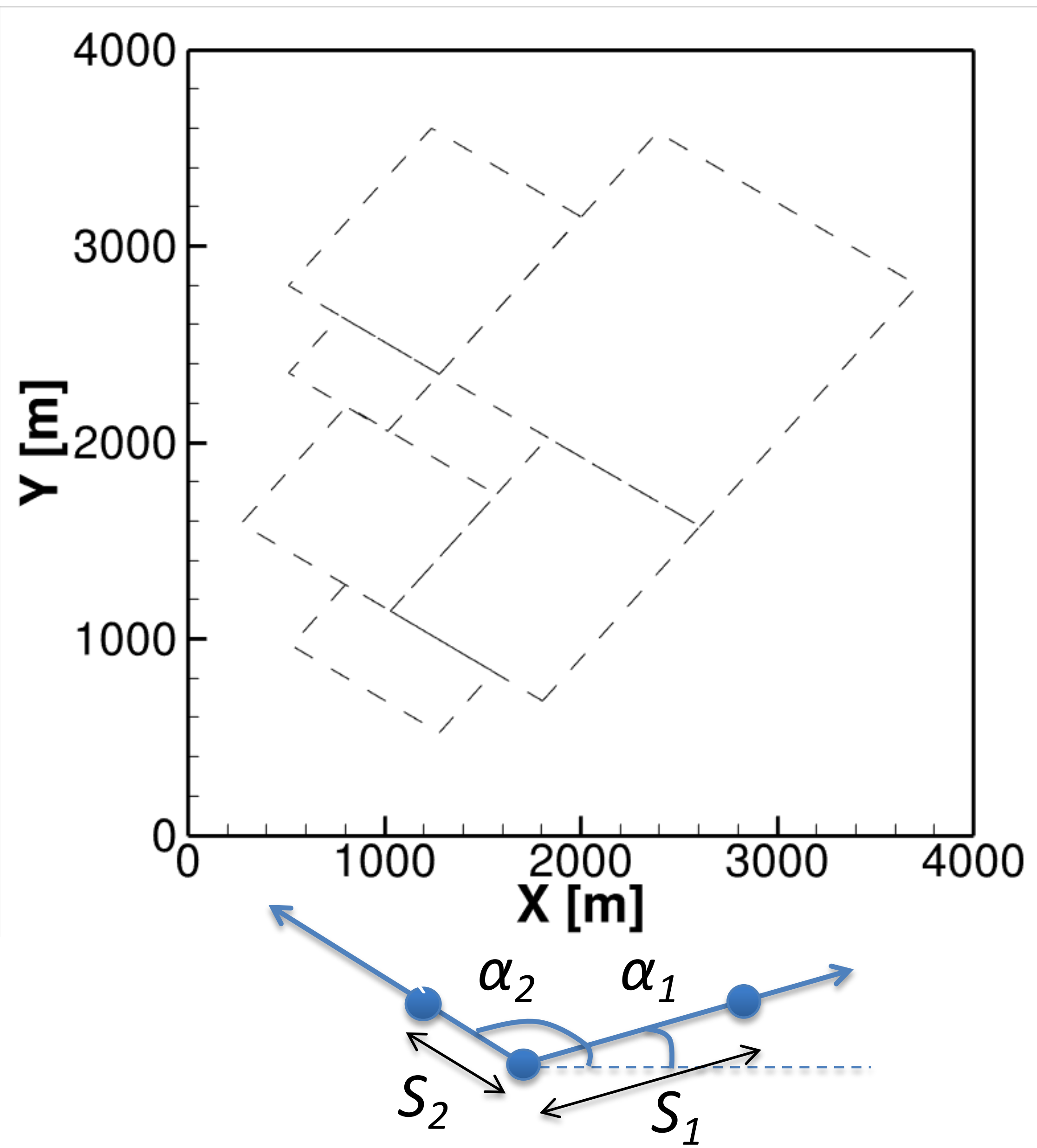




- Use the Wind Rose (WR) to compute weighted-average power in a year:

$$\frac{P_{WR}}{N_T P_{\max}} = \sum_k F_k \frac{P_k}{N_T P_{\max}}$$
$$= 0.723$$

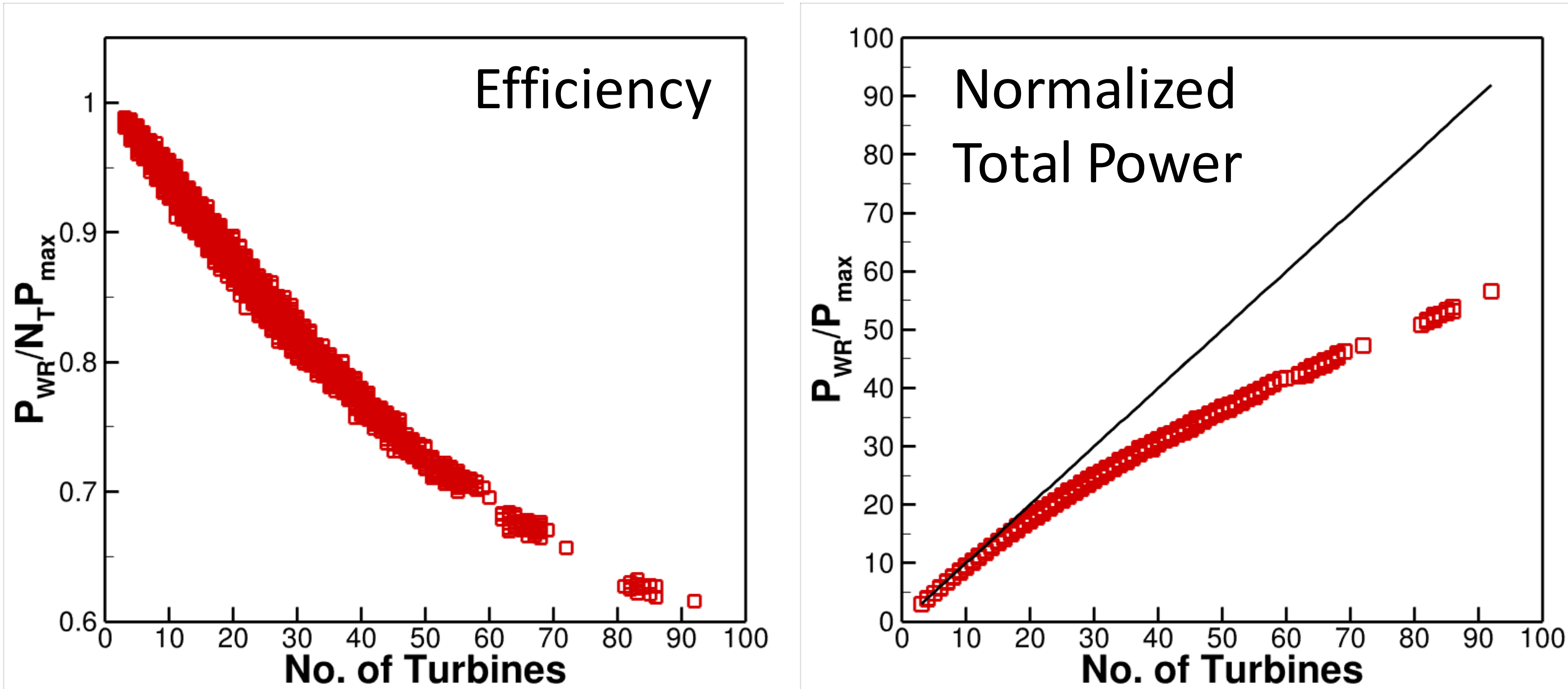
- Total power generated is a function of Wind Rose.

# Layout optimization



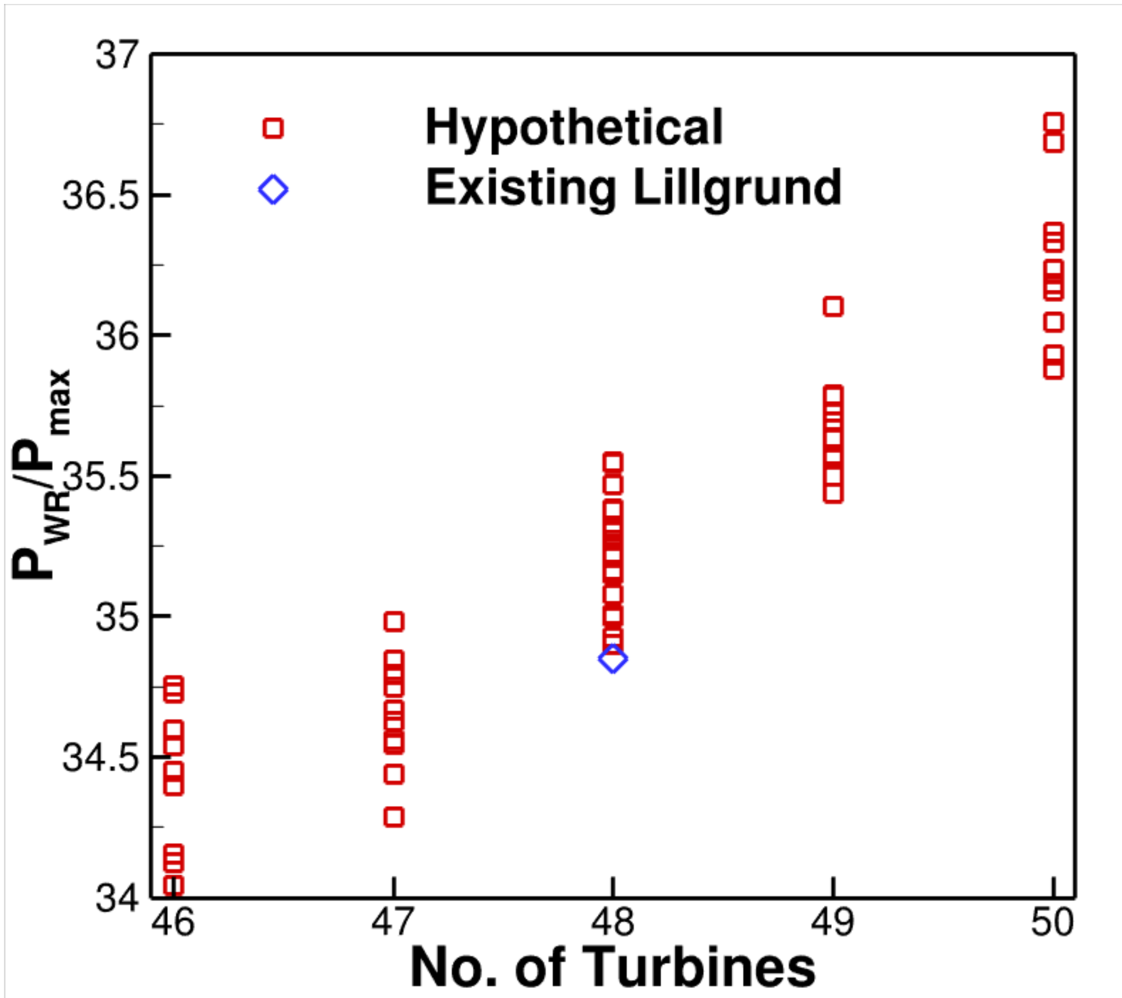

- Layout design variables:
  - $\alpha_1, \alpha_2$: [0: $10^0$: $180^0$]
  - $S_1, S_2$: [4D: 1D: 12D]
  - $N_T$ varies; max: 2 x 48.
  - Total n. of layouts: 9477
- Compute $P_{WR}/N_T P_{max}$ for each layout, with neutral stability and real WR.

# Evaluation of layouts




- Efficiency decreases as $N_T$ increases;
- Total power increases as $N_T$ increases, but with diminishing returns.

# Evaluation of layouts – Zoom in




- Close-up view around $N_T$ = 48.
- Several layouts more efficient than Lillgrund.
- Some layouts with 47 turbines produce more power than existing Lillgrund.

# Conclusions

- Wind farm power can be modeled in terms of geometric parameters.
- Linear regression model has been calibrated based on data from LES.
- Neutral, unstable, stable conditions treated separately.
- Effect of multiple wind directions can be considered efficiently.
- Search-based optimization methodology applied to Lillgrund identifies several better layouts.

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