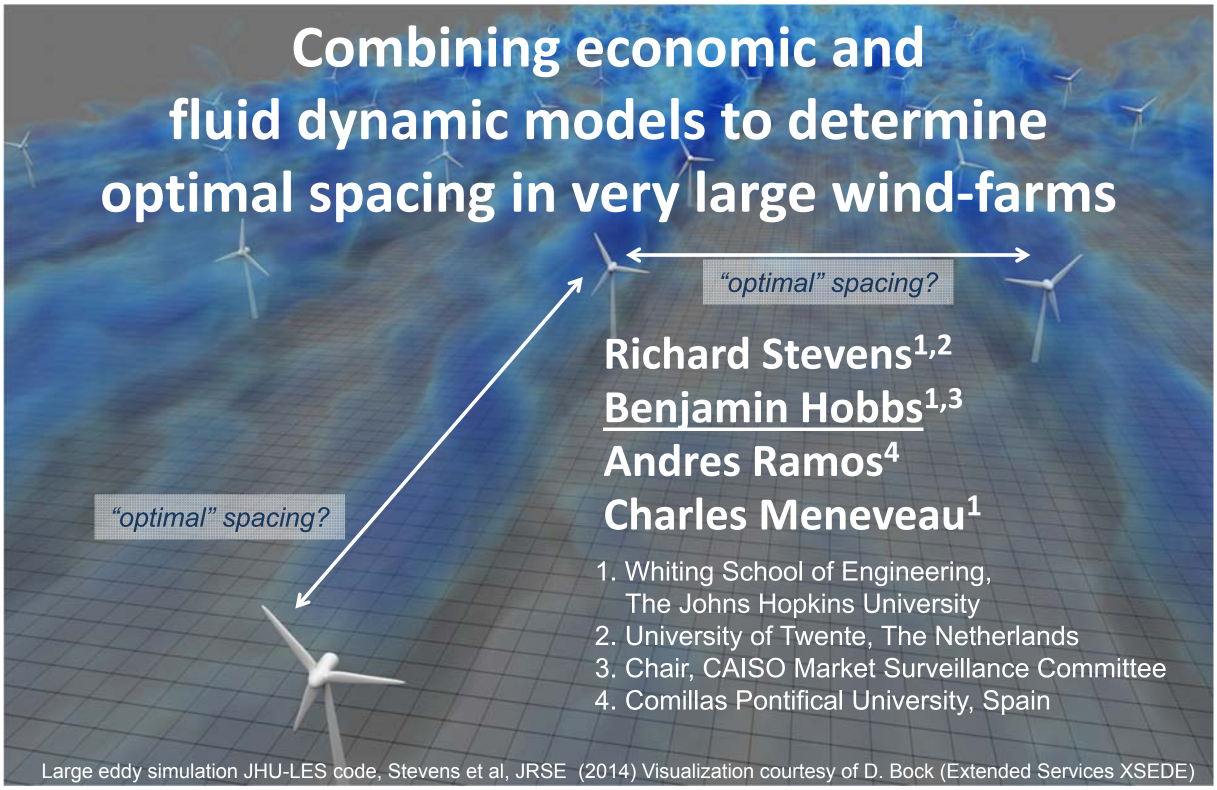
Combining economic and fluid dynamic models to determine optimal spacing in very large wind-farms



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Large eddy simulation JHU-LES code, Stevens et al, JRSE (2014) Visualization courtesy of D. Bock (Extended Services XSEDE)

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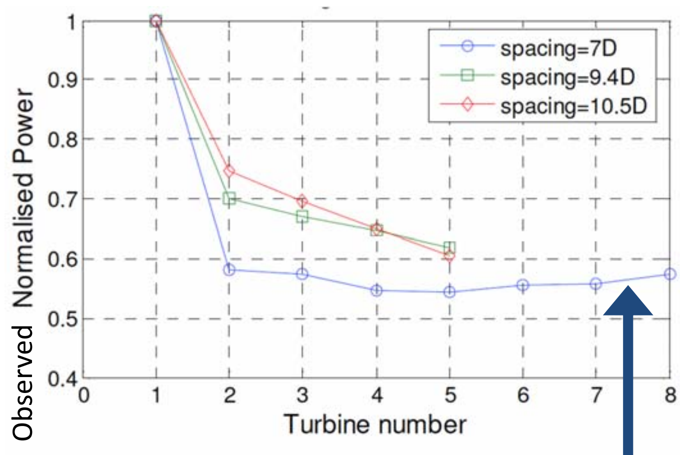
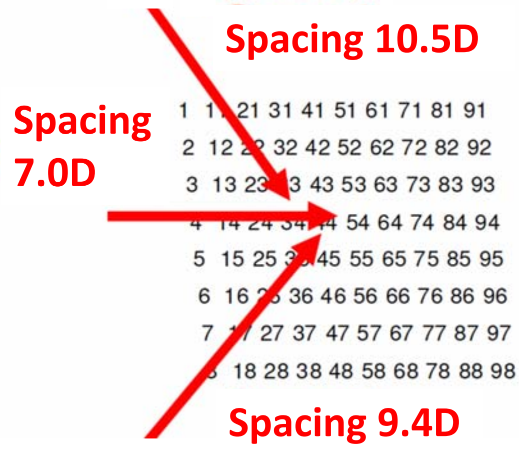
Outline

1. **Wake modeling**
2. **Modeling of tradeoffs:**
   Wake power loss *vs* Wind farm size costs
3. **Results**
   - **MIN Cost**
   - **MAX Profit, if limited land**
   - **Effect of turbulence-influenced O&M**
   - **Effect of alignment**

Wake effects in large wind-farms



Horns Rev layout



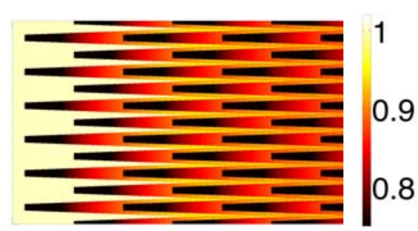
Depending on wind direction, loss of power ~50%!

Barthelmie, et al. J. Physics Conf. Series 75 (2007), 012049

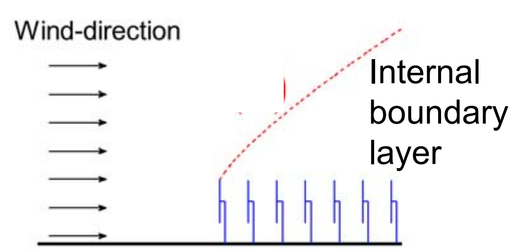
Coupled wake boundary layer model

Combines strength of two models:

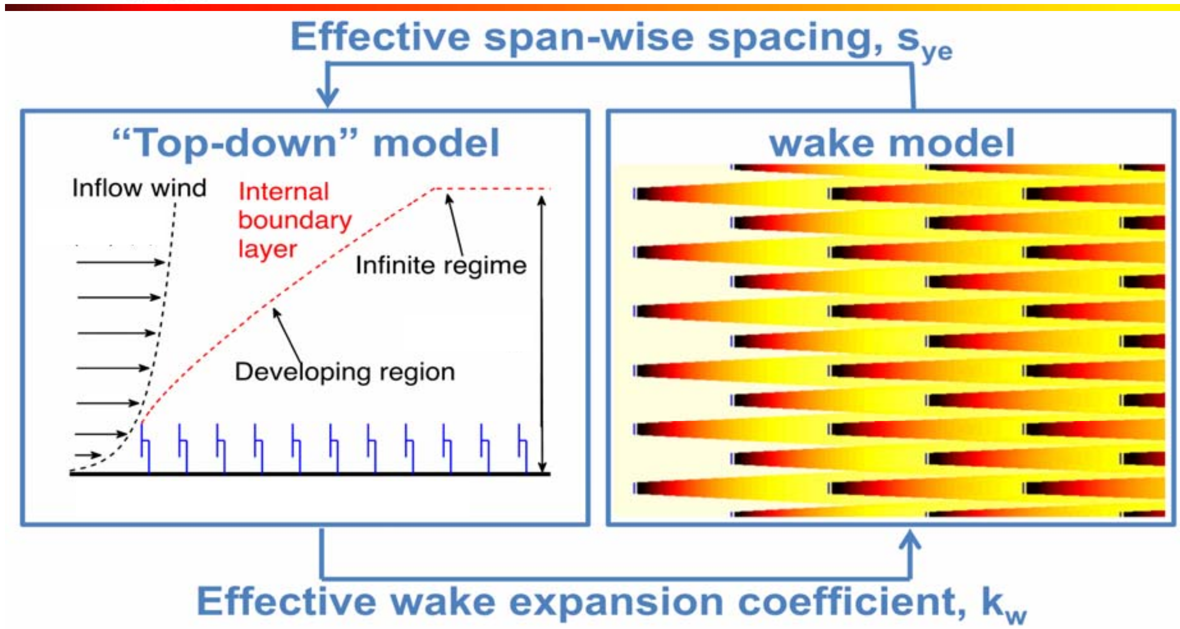
- **Wake model approach** (e.g., Jensen 1983)
  - \+ Works well in entrance regime
  - \- Doesn't in fully developed regime



- **'Top-down' approach** (Frandsen, 2006; Calaf, Meneveau, Meyers, 2010)
  - \- No info on turbine positions
  - \+ Captures interaction with atmospheric boundary layer



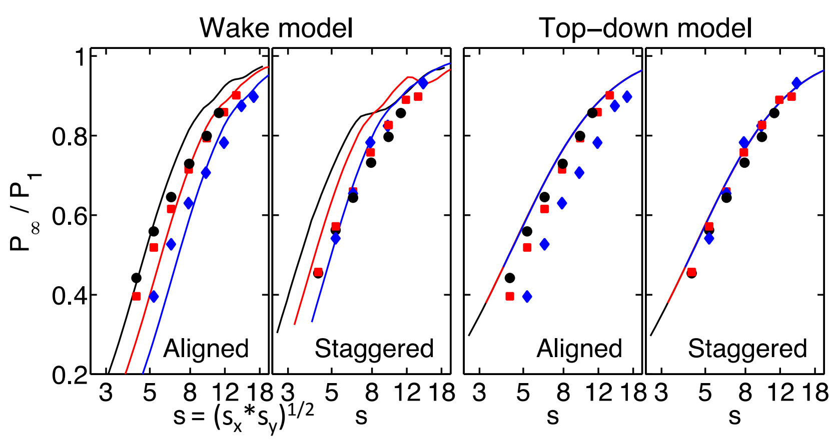
Coupled wake boundary layer model



- Turbine velocity (fully developed regime) depends on s_{ye} (top-down), k_w (wake); iterate until get same velocity in both models
- Two way coupling leads to improved results!

Stevens, Gayme, Meneveau, JRSE ***7****, 023115 (2015)*

Model comparison: Generic Farm (Neutral stability, Region II operation)



Symbols: *LES results;* Lines: *model results*

Colors: s_y=3.49
s_y=5.23
s_y=7.85

CWBL model captures effects in both aligned and staggered wind-farms; "Top-down" or wake models don't.

Stevens, Gayme, Meneveau, JRSE ***7****, 023115 (2015); Stevens et al. to be submitted*

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Objective:
Develop better understanding of *optimal* wind turbine spacing in large wind-farms

Industry approach:

Site-specific optimization for turbine placement with Jensen-type models.
Typical: S_{opt} *~6 - 10D*

Surprisingly "large" spacing from simple(st) model (Meyers & Meneveau, *Wind Energy*, 2012)**:**

Optimal spacing S_{opt} ***~12-15D*** for very large wind farms (top-down model)

- Accounted for land & turbine costs, but not cable/road costs

Questions:

1. What is the effect of including **linear costs** (cables, roads, losses)?
2. How robust are results to **optimization criteria**?
   i. Min cost/MWh (unlimited land)
   ii. Max profit/km^2 (limited land)
3. How do results depend on wind farm **layout** (staggered vs. aligned)?

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Parameters considered

Normalized w.r.t. turbine costs

Area (land) cost

$$\theta = \frac{\text{Cost}_{\text{land}}}{\text{Cost}_{\text{turbine}}/D^2}$$

Linear (cable, road, loss) costs

$$\beta = \frac{\text{Cost}_{\text{cable}}}{\text{Cost}_{\text{turbine}}/D}$$

Revenue

$$\gamma = \frac{\text{Revenue over lifetime}}{\text{Cost}_{\text{turbine}}}$$

Maintenance cost

$$\epsilon = \frac{\text{Maintenance costs over lifetime}}{\text{Cost}_{\text{turbine}}}$$

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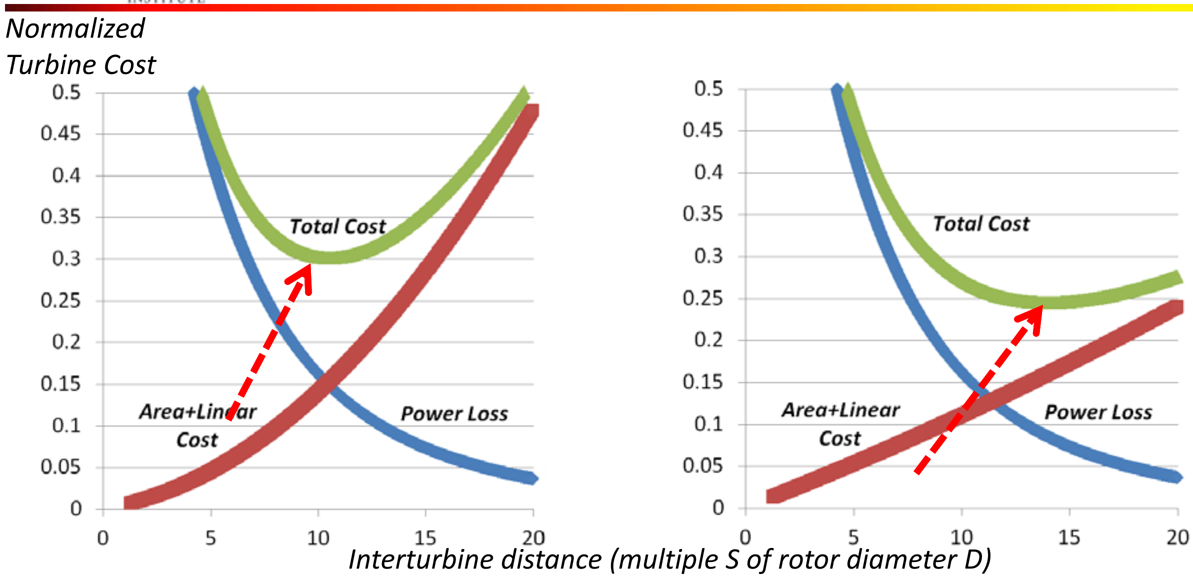
Power Loss—Distance Cost Tradeoffs



Land:

- Land cost θ = 0.001
  (Royalties ~$5000/ha)
- Length cost β = 0.004
  (Cables ~ $60/m; Roads ~$80/m; 60 W/m/turbine loss)

Off-Shore:

- Land cost θ < 0.0001
  (Lease cost ~$100/ha)
- Length cost β = 0.01
  (Cables ~$1000/m , 70 W/m/turbine loss)

Optimize normalized costs

Define costs as

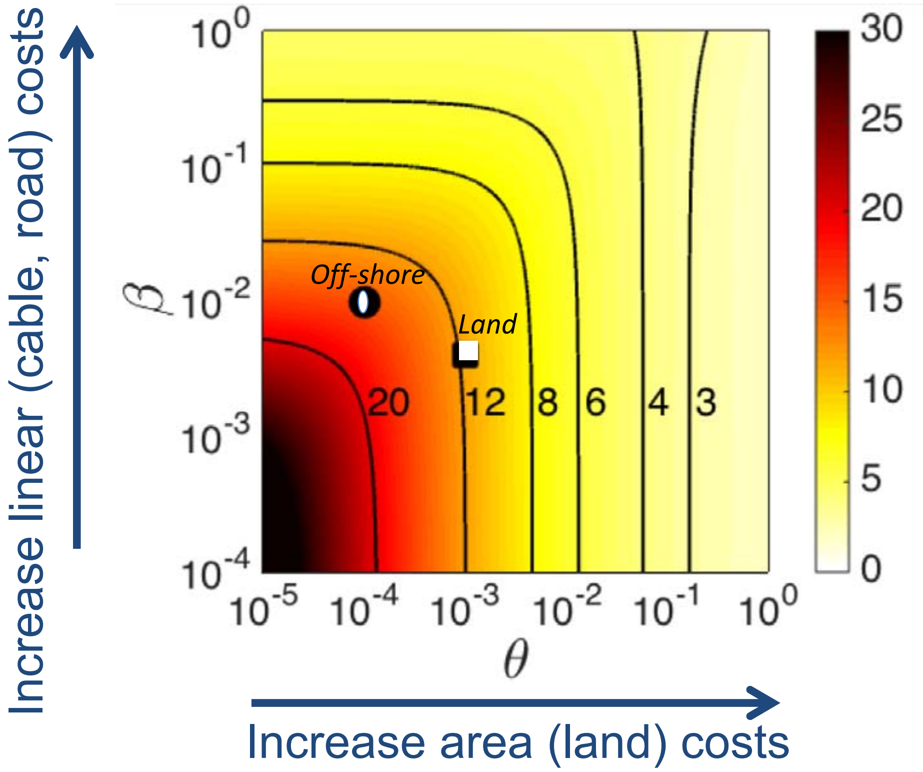
$$\mathrm{Cost} = \mathrm{Cost}_{\mathrm{turb}} + (\mathrm{sD})\mathrm{Cost}_{\mathrm{cable}} + (\mathrm{sD})^2\mathrm{Cost}_{\mathrm{land}}.$$

This gives the following normalized power per unit cost

$$P^* = \frac{P_\infty(s_{\mathrm{x}}, s_{\mathrm{y}}, \mathrm{layout}, ...)}{\mathrm{Cost}} = \frac{P_\infty(s_{\mathrm{x}}, s_{\mathrm{y}}, \mathrm{layout}, ...)}{\mathrm{Cost}_{\mathrm{turb}} + (\mathrm{sD})\mathrm{cost}_{\mathrm{cable}} + (\mathrm{sD})^2\mathrm{Cost}_{\mathrm{land}}}$$

$$= \frac{P_\infty(s_{\mathrm{x}}, s_{\mathrm{y}}, \mathrm{layout}, ...)}{\mathrm{Cost}_{\mathrm{turb}}} \frac{1}{1 + \beta s + \theta s^2}$$

Effect of linear & area costs



Optimize *profit* in fixed area

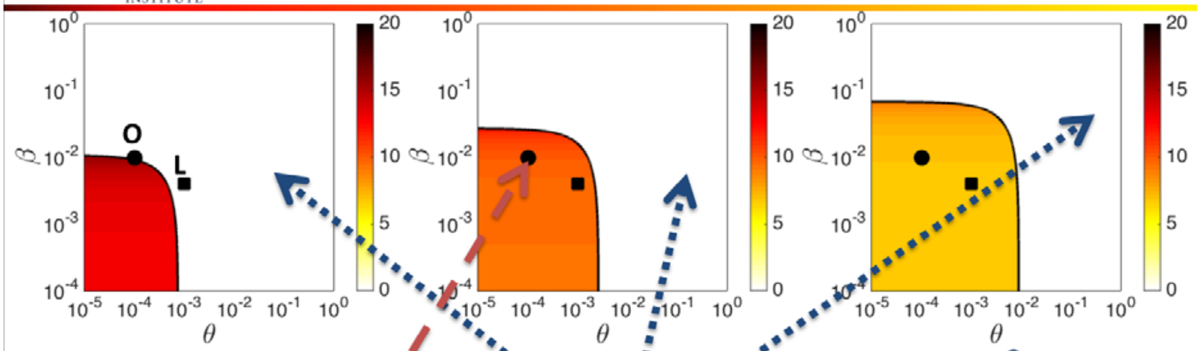
If (1) land limited and (2) wind highly profitable → want to squeeze in more turbines! Define *profit per unit area*:

$$\text{Profit} = \{P_\infty(s_x, s_y, \text{layout}, ...)\text{Revenue over lifetime} - \left[\text{Cost}_{\text{turb}} + \text{Cost}_{\text{cable}}(sD) + \text{Cost}_{\text{land}}(sD)^2\right]\} / (sD)^2$$

This gives the following normalized profit:

$$\text{Profit} = \{P_\infty(s_x, s_y, \text{layout}, ...)\gamma - \left[1 + \beta s + \theta s^2\right]\} / s^2$$

Optimize profit in fixed area



Revenue Ratio γ=1.25 γ=1.5 γ=2

- Wind *unprofitable* in white areas (unfavorable area & linear costs)
- Higher revenues (more profit per turbine) → *closer* spacing than MIN cost
  - ✓ E.g., S_{opt} ~10D (vs. 15D if MIN cost)
  - ✓ Why? Profit per turbine more than makes up for wake energy losses
- Higher linear costs can imply *greater* spacing
  - ✓ Effect of lower profit/turbine (→spread out) counteracts effect of higher costs (→ closer spacing)

Optimize profit, with O&M costs as function of turbulence

Define profit as

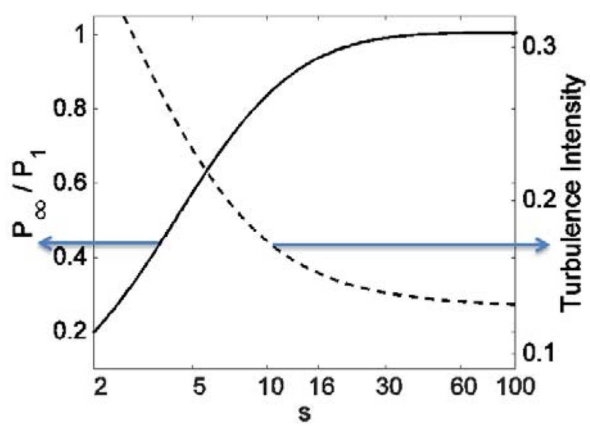
$$\text{Profit} = \{P_\infty(s_x, s_y, \text{layout}, ...)\text{Revenue over lifetime} - \left[\text{Cost}_{\text{turb}} + \epsilon' \text{TI}(\text{s}_\text{x}, \text{s}_\text{y}, \text{layout}, ...) + \text{Cost}_{\text{cable}} sD + \text{Cost}_{\text{land}}(sD)^2\right]\}/(sD)^2$$

This gives the following normalized expression for profit:

$$\text{Profit} = \{P_\infty(s_x, s_y, \text{layout}, ...)\gamma - \left[1 + \beta s + \theta s^2 + \epsilon \text{TI}(\text{s}_\text{x}, \text{s}_\text{y}, \text{layout}, ...)\right]\}/(sD)^2$$

Maintenance costs:

$$\epsilon = \frac{\text{Maintenance costs}}{\text{Cost}_{\text{turbine}}}$$



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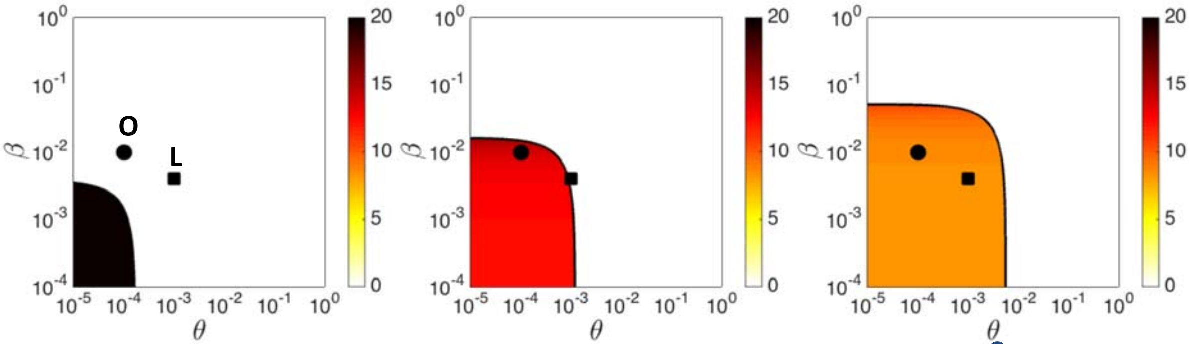
Optimize profit with O&M cost as function of turbulence (turbulence-influenced O&M ~10% of levelized capital cost)



γ=1.25 γ=1.5 γ=2

- Turbulence-sensitive O&M → wider optimal spacing
  - ✓ As reduced maintenance costs compensate in part for reduced revenues from having fewer turbines

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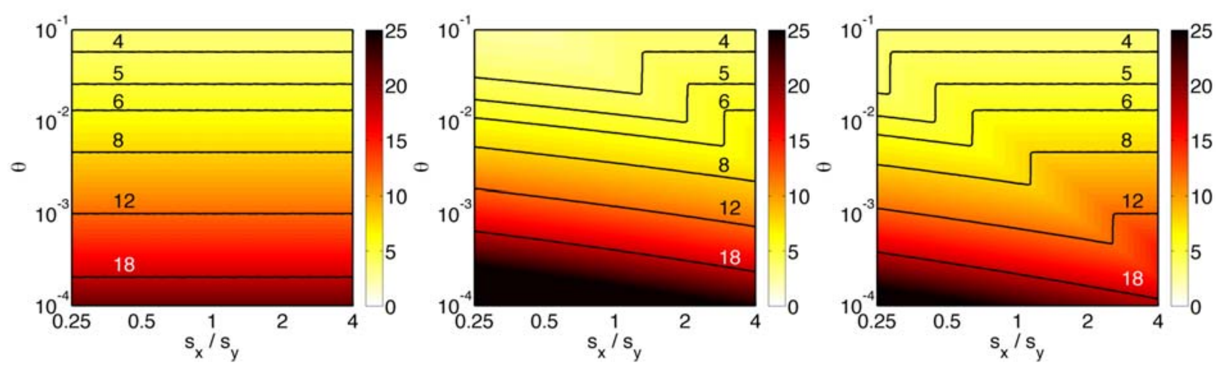
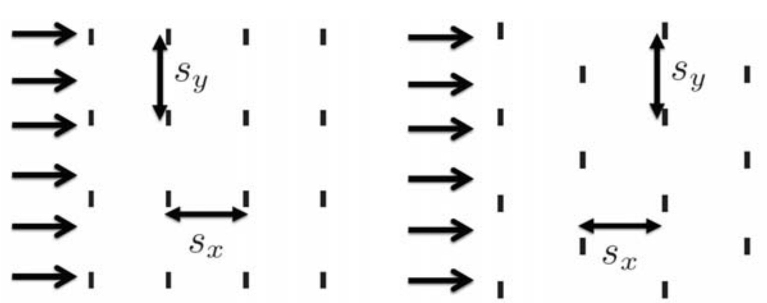
Effect of farm layout on optimal spacing (area costs only)



Best Aligned Staggered

Best: Minimize wake effects for given wind turbine density



Conclusions

Contribution: Optimum spacing for large farm with:

- CWBL model
- Area & linear costs

Under our parameters:

- *Min* cost in infinite farm → S_{opt} ~ 10-15D
- *Max* profit in limited area → *closer* (depending on profit/turbine)
- Considering turbulence-sensitive O&M → *spread out*

S_{opt} sensitive to:

- Length costs (especially off-shore farms)
- Area costs (especially on-shore)

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