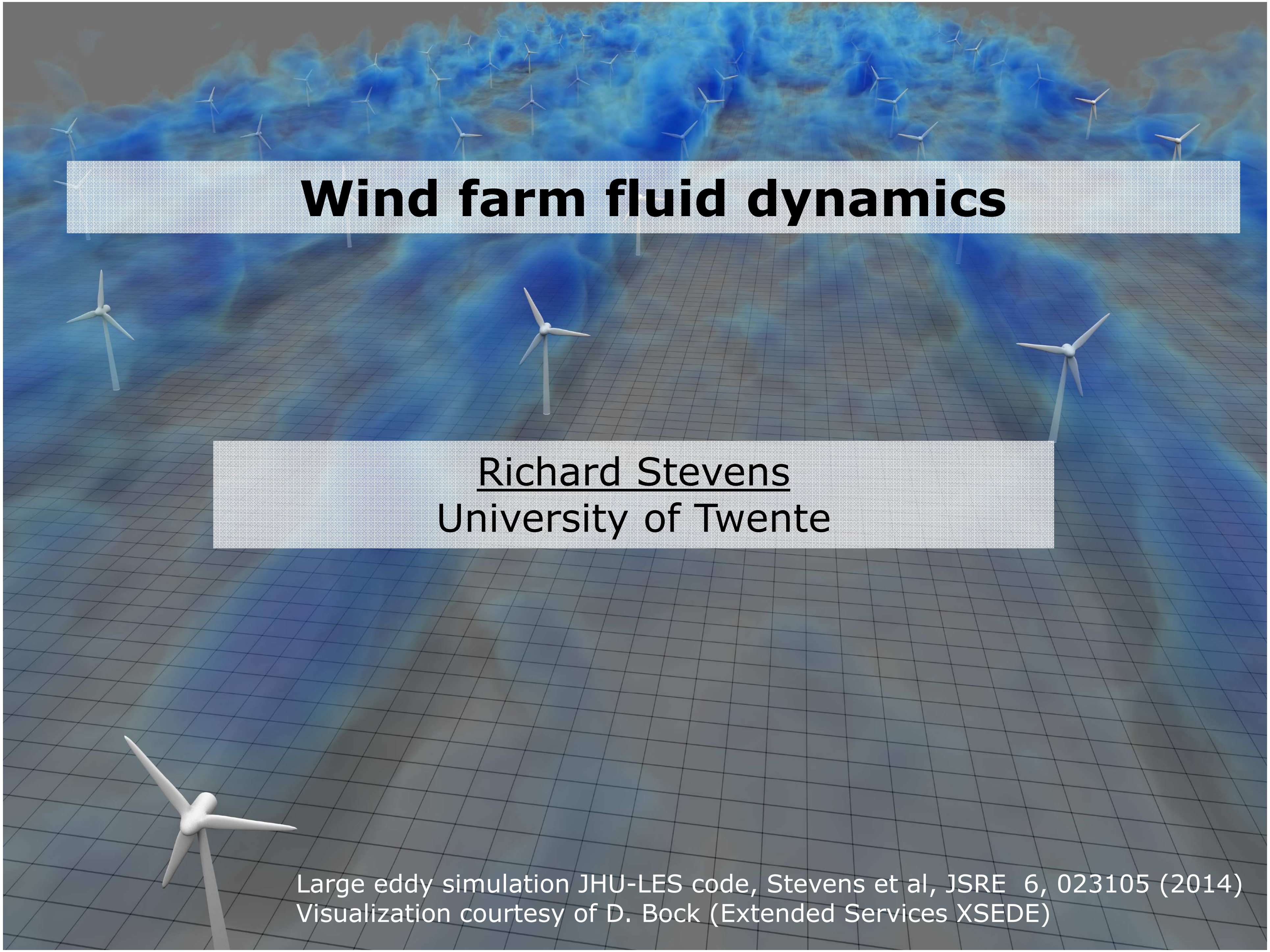
Wind farm fluid dynamics

Richard Stevens
University of Twente



Large eddy simulation JHU-LES code, Stevens et al, JSRE 6, 023105 (2014)
Visualization courtesy of D. Bock (Extended Services XSEDE)

Coworkers and funding

Mengqi Zhang (Now NUS, Singapore)

Srinidhi Nagarada

Jessica Strickland

Charles Meneveau (Johns Hopkins)

Denice Gayme (Johns Hopkins)

Michael Wilczek (Gottingen)

Laura Lukassen (Oldenburg)

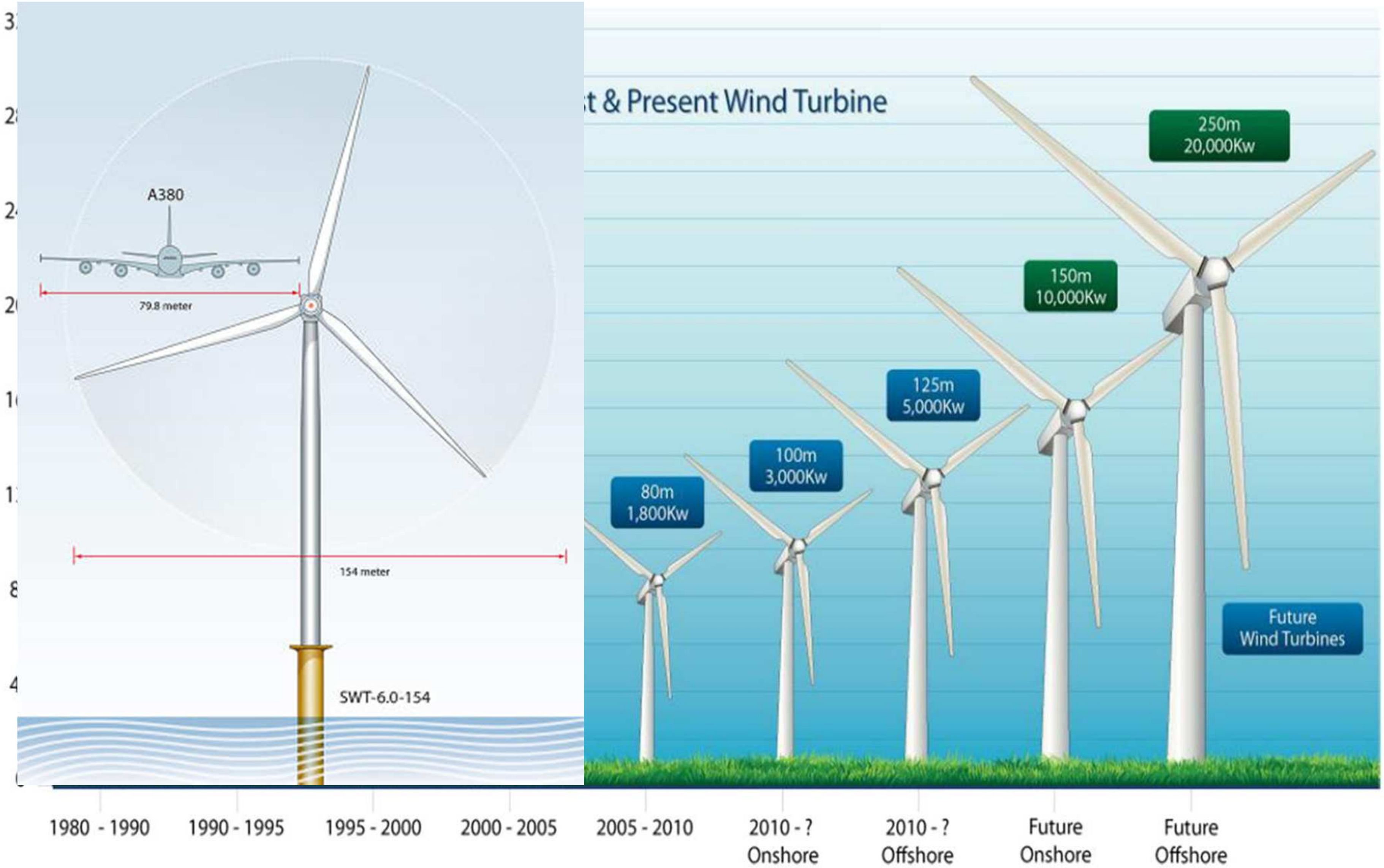
FOM

STW

NWO

Netherlands Organisation for Scientific Research

Development wind turbines



Global Wind Energy Council (GWEC), Global wind statistics 2014

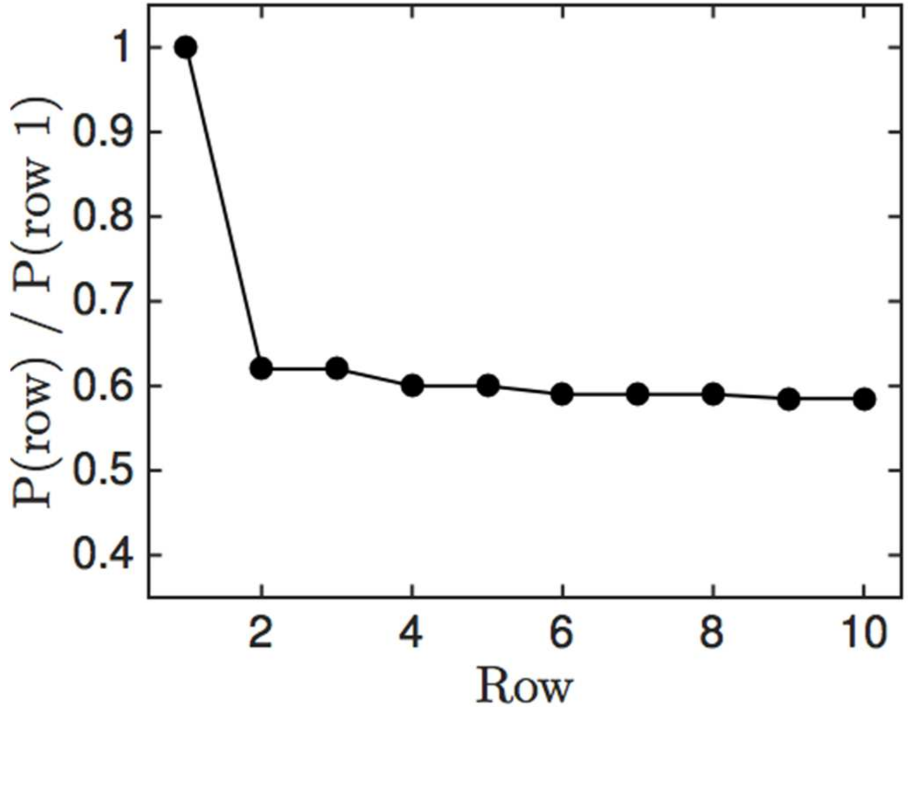
Wind turbine construction

Large wind-farms

What is the effect of the wake on the operation of downstream wind turbines?

Sørensen, Annual Rev. Fluid Mech (2011); Emeis, DEWI Magazin 37, 52-55 (2010)

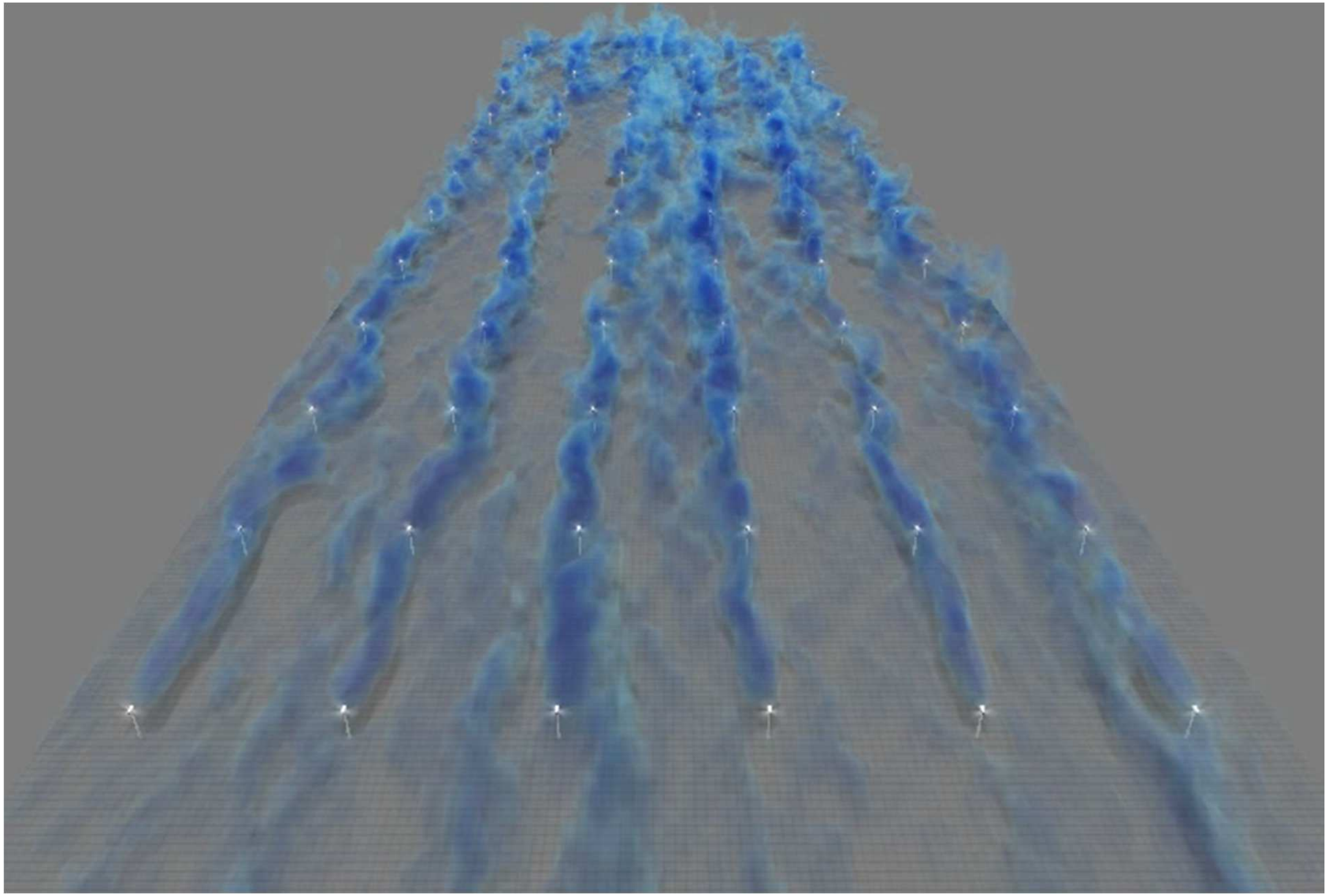
Wake effects in large wind-farms



Wake effects dramatically decrease performance of downstream turbines

Barthelmie, et al., Final report for UpWind WP8, Risø-R-1765(EN) (2011), 012049; Sanderse et al., Wind Energy 14, 799-819 (2011), Mehta et al., J. Wind Eng. Ind. Aerodyn. 133 (2014) 1–17

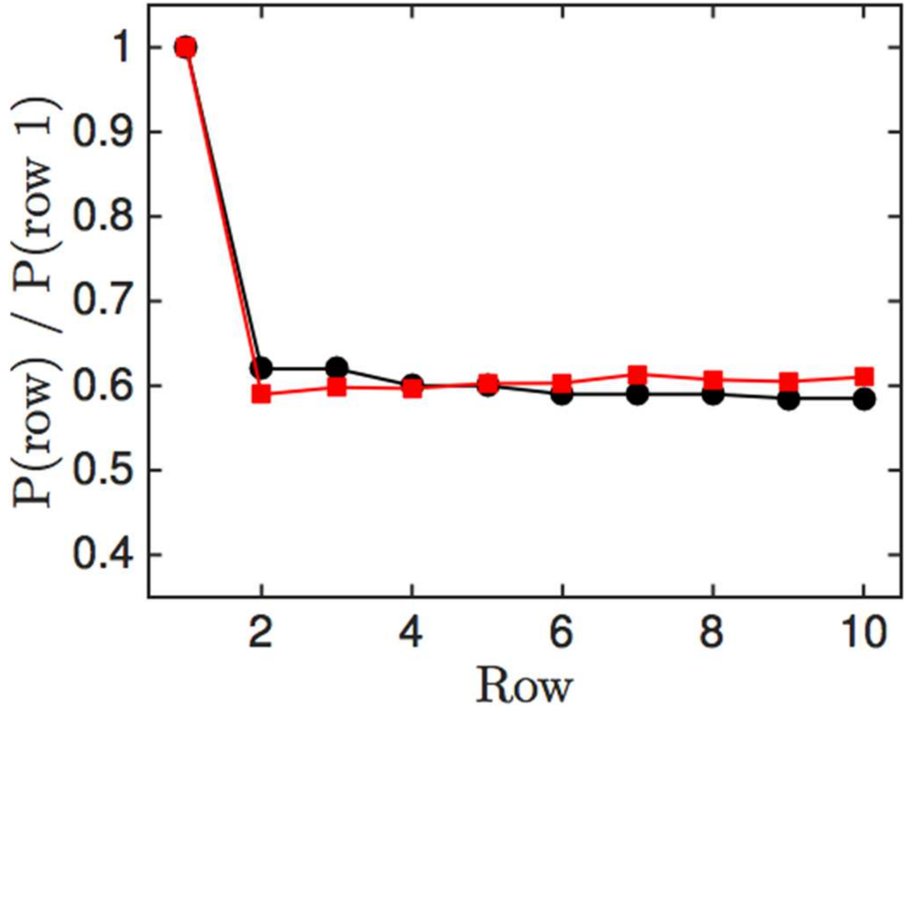
Simulation extended wind-farm



Large eddy simulation, Stevens et al. 2014

Visualization courtesy of D Bock (XSEDE)

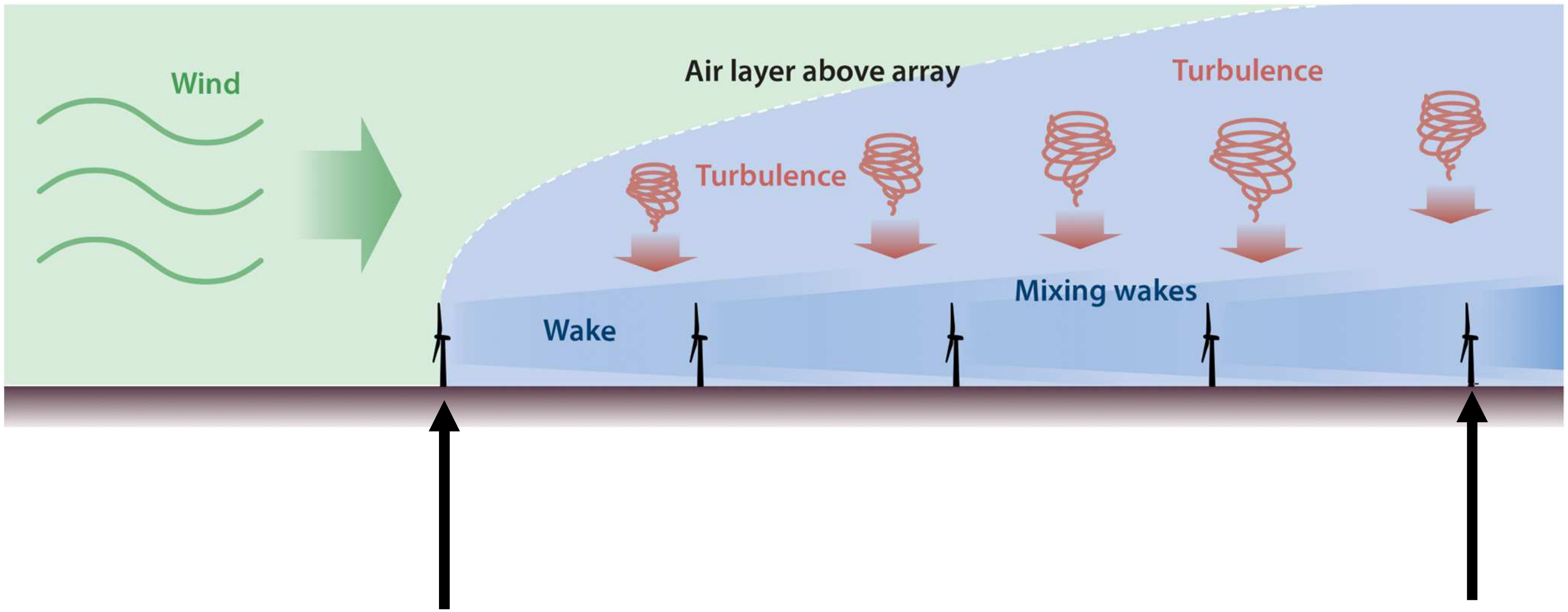
Wake effects in large wind-farms



State of the art simulations
capture performance trends

Barthelmie, et al., Final report for UpWind WP8, Risø-R-1765(EN) (2011)*, 012049; Sanderse et al., Wind Energy 14, 799-819 (2011), Mehta et al.,* J. Wind Eng. Ind. Aerodyn. 133 (2014) 1–17

Fluid dynamics phenomena in windfarms



First turbine row

Fully developed region

Stevens and Meneveau, Annual Rev. Fluid Mech 49, 311-339 (2017).

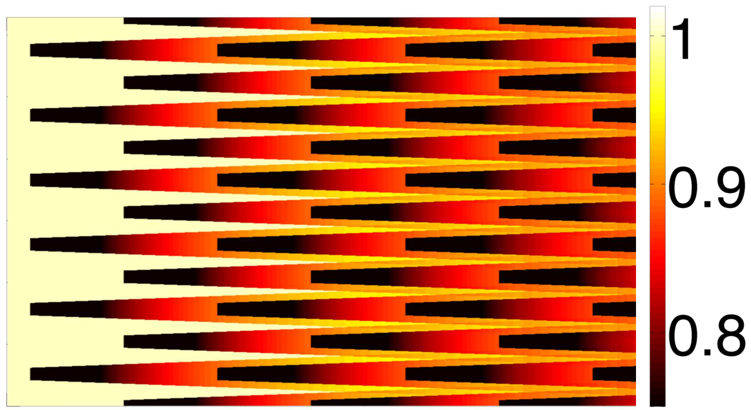
Coupled wake boundary layer model

Combines strength of two models

- **Wake model approach**

\+ Works well in entrance regime

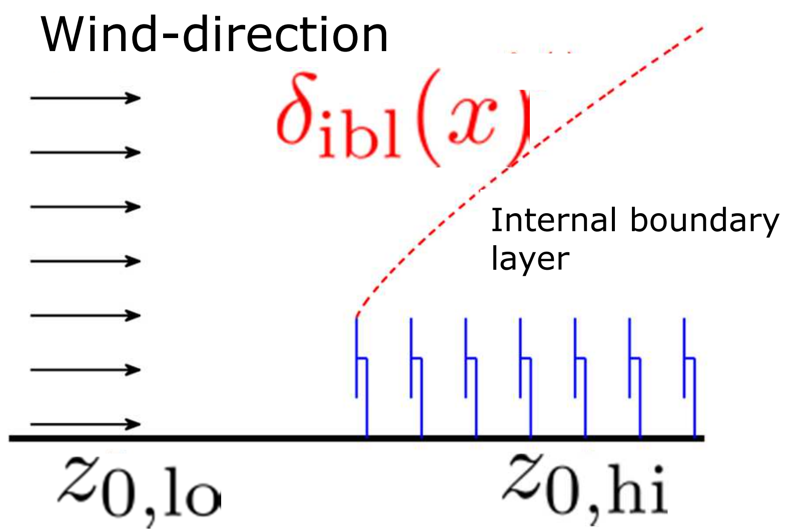
\- Does not work well in fully developed regime



- **'Top-down' approach**

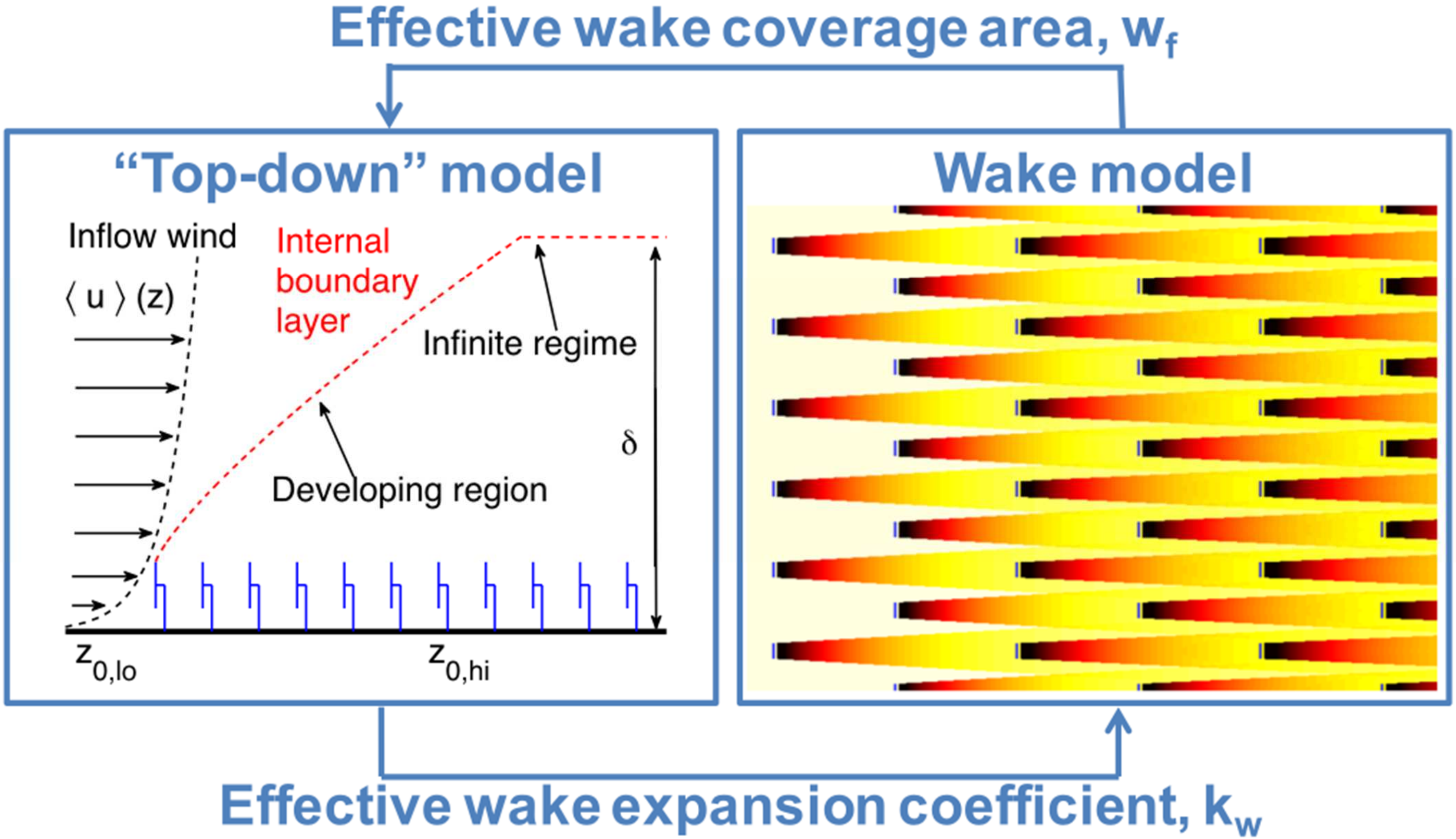
-No information about turbine positioning

\+ Captures interaction with atmospheric boundary layer



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

Coupled wake boundary layer model



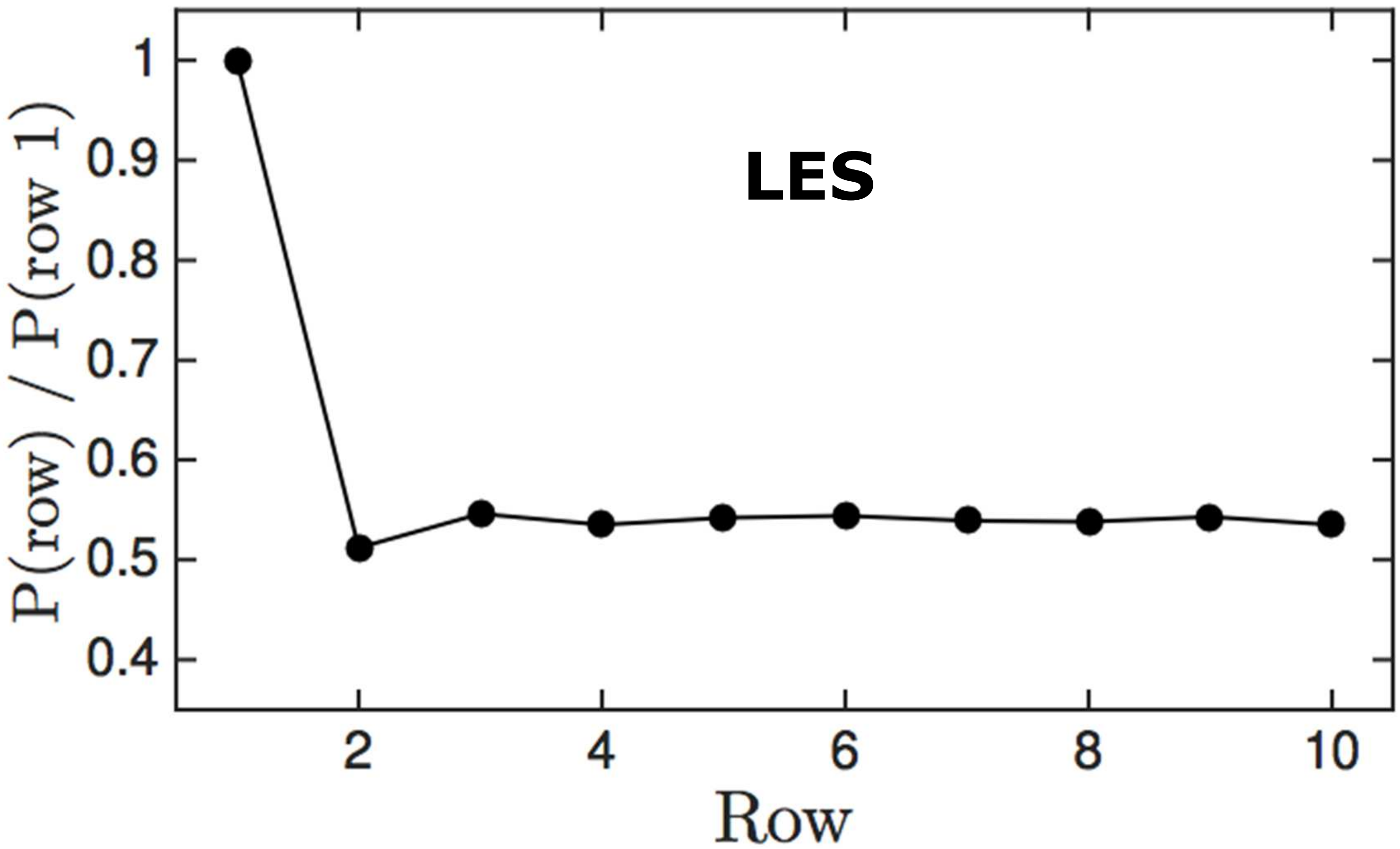
Two way coupling leads to improved results!

Stevens, Gayme, Meneveau, JRSE 7, 023115 (2015), Wind Energy 19 (11) (2016), 2023-2040

Analytical wind farm models

Requires **physical understanding**

Needed to improve wind farm design



Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016).

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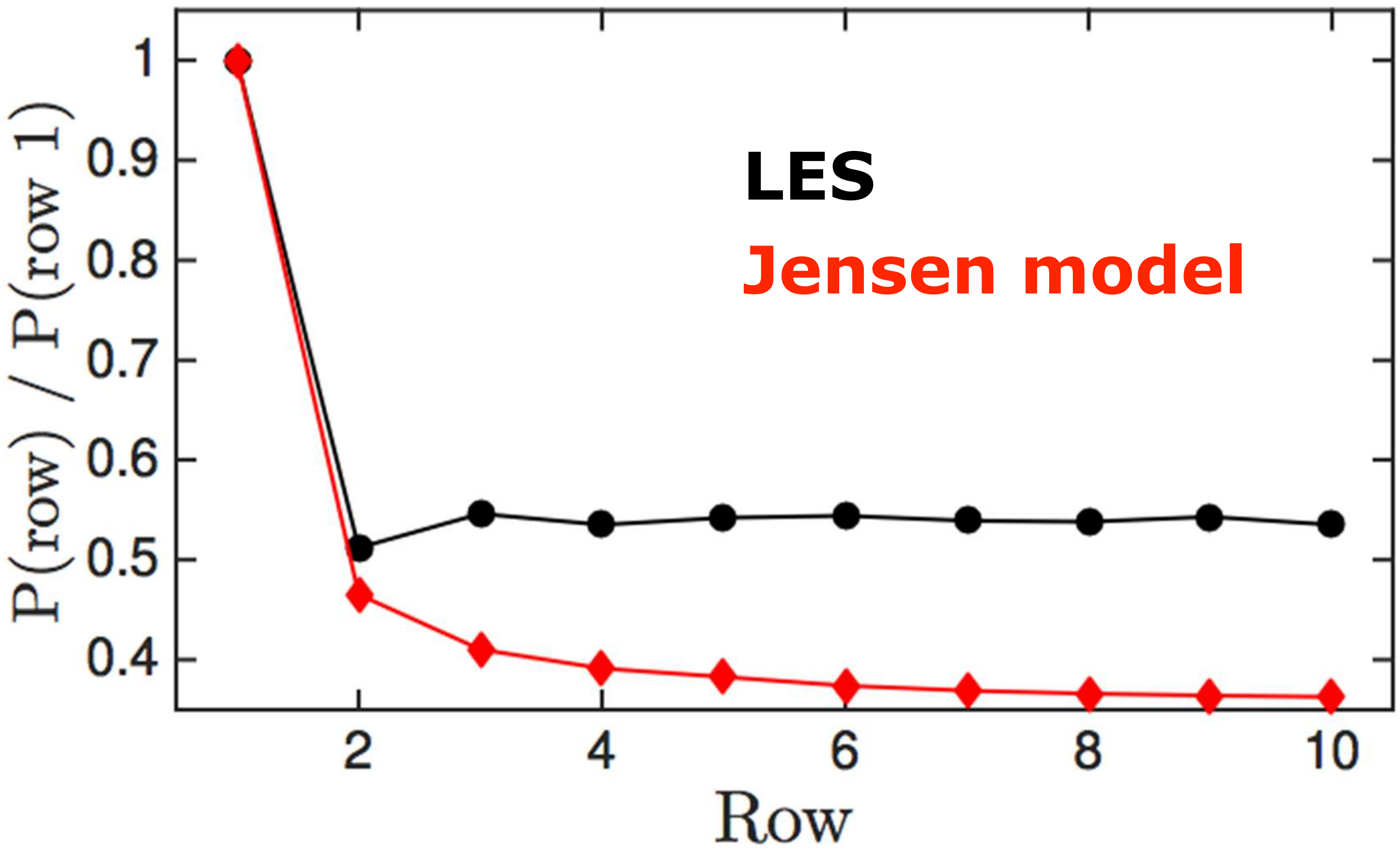

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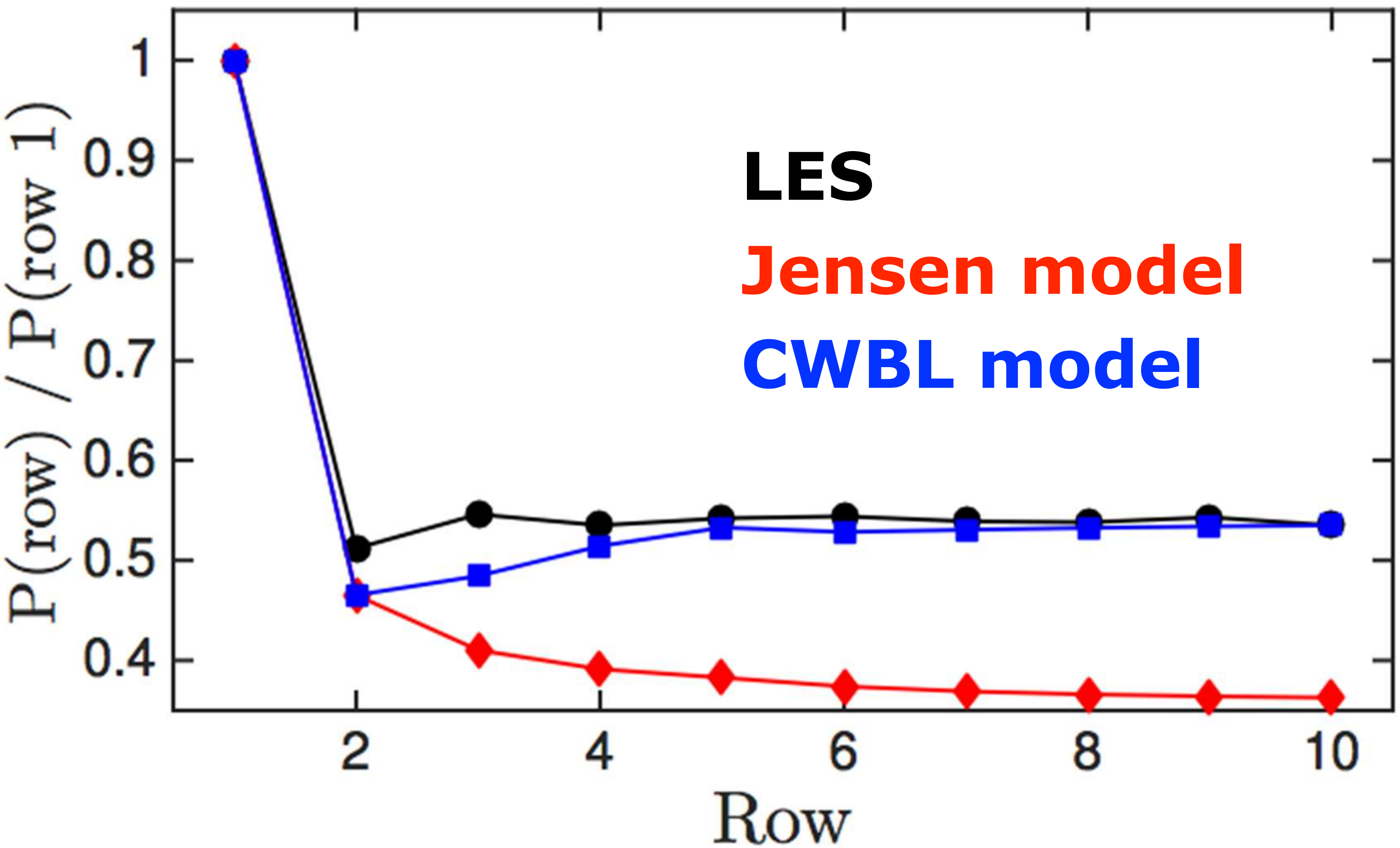
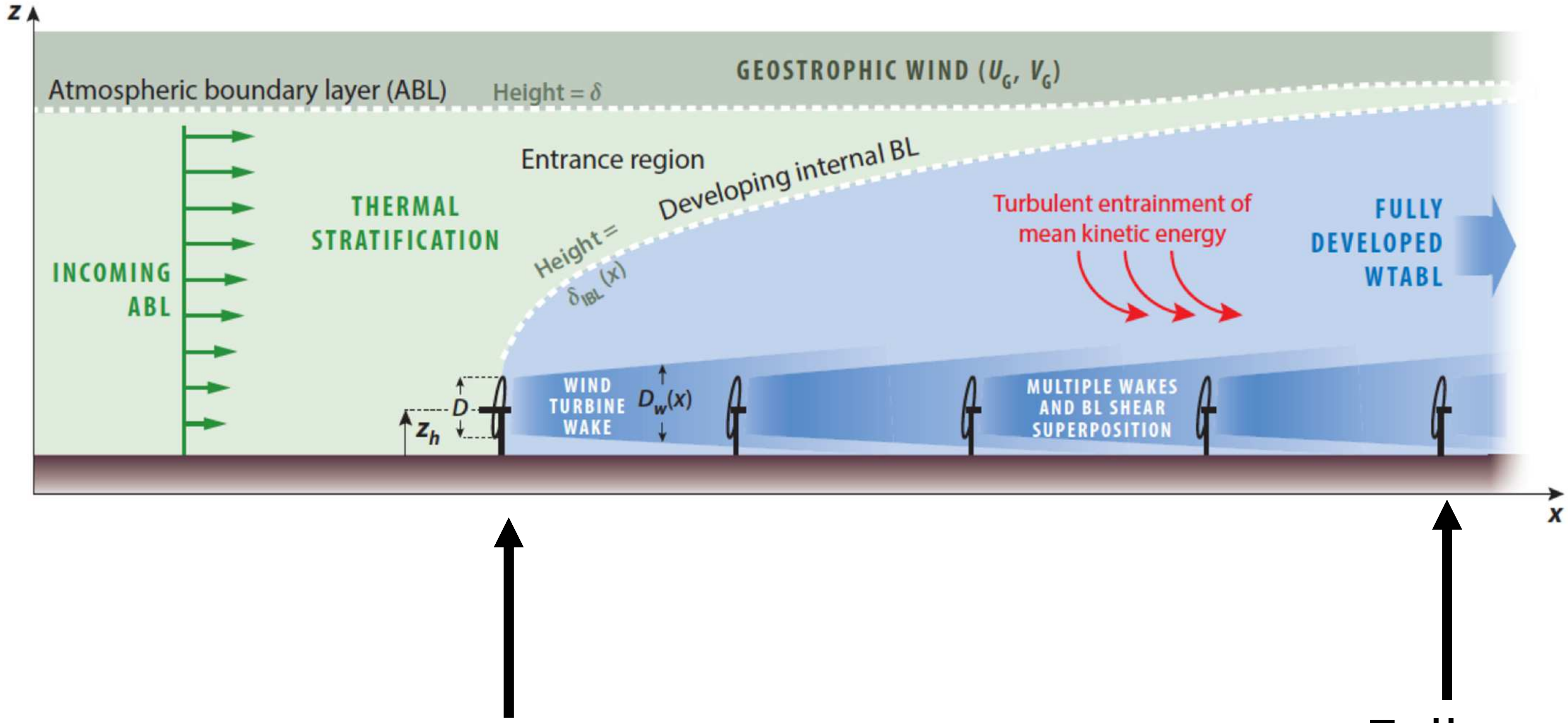


Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016).

Fluid dynamics phenomena in windfarms

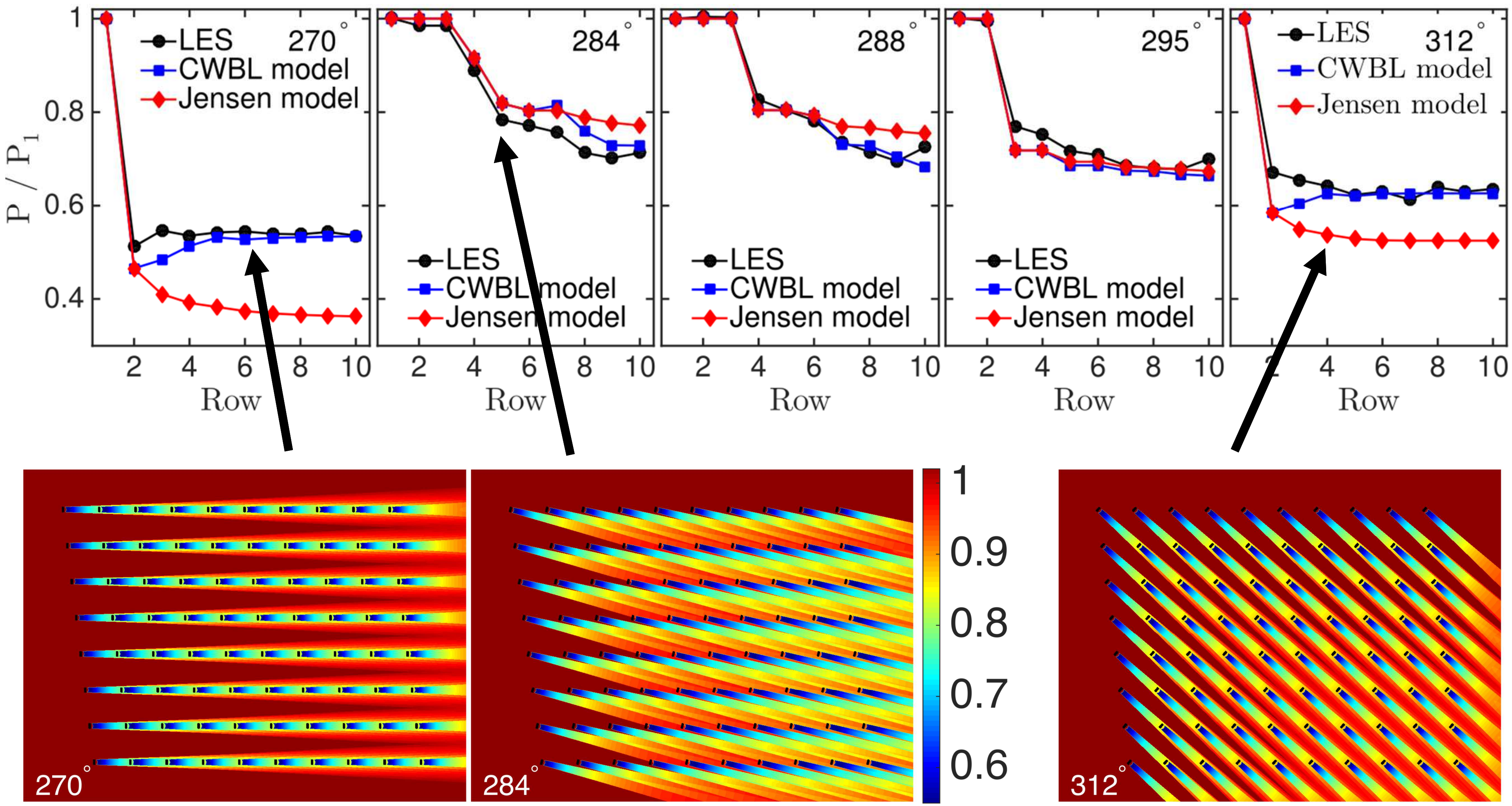


First turbine row

Fully developed region

Stevens and Meneveau, Annual Rev. Fluid Mech 49, 311-339 (2017).

Comparisons to the Horns Rev wind farm



Comparison with LES Porté-Agel, Wu, Chen, Energies 2013, 6, 5297-5313

Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016).

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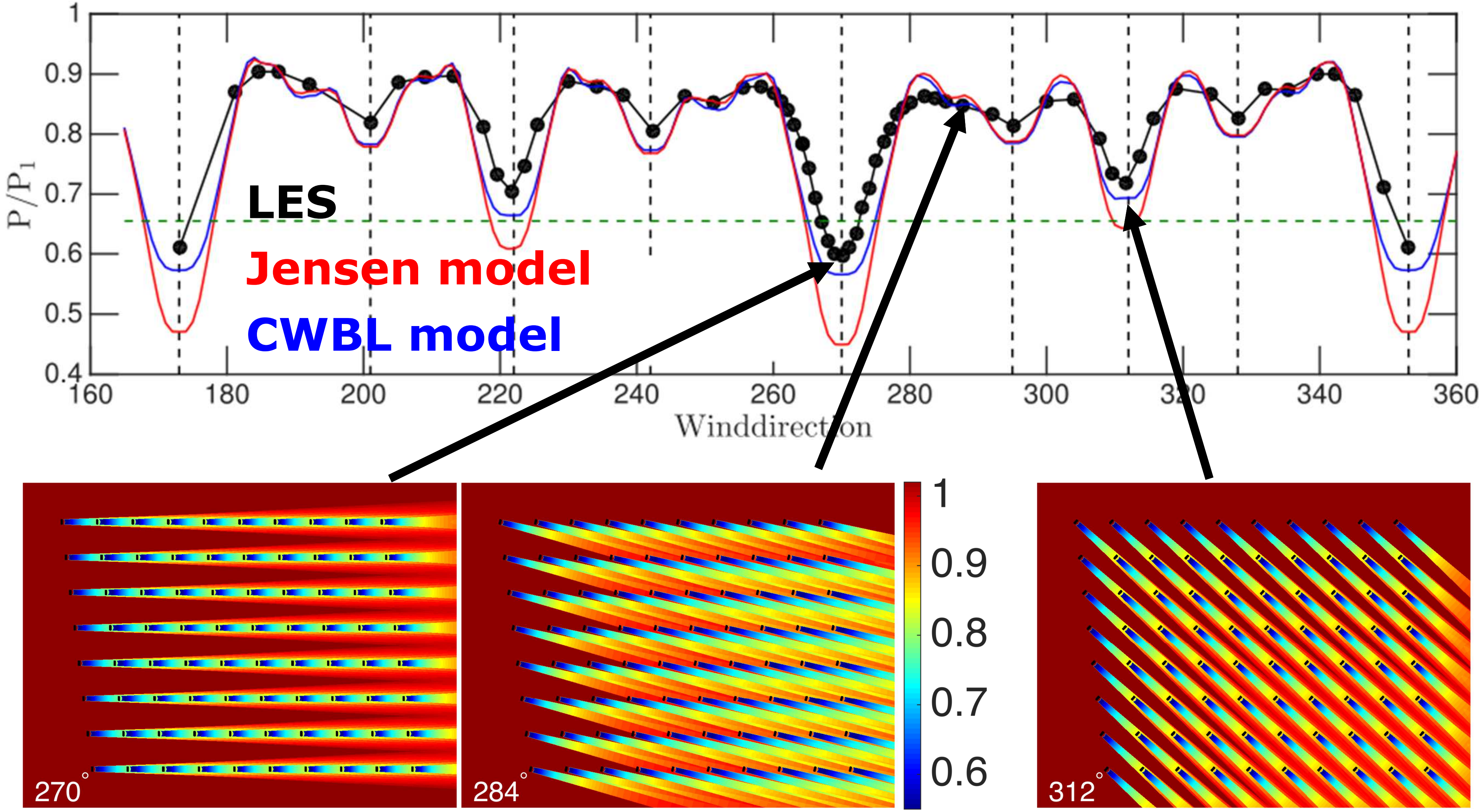
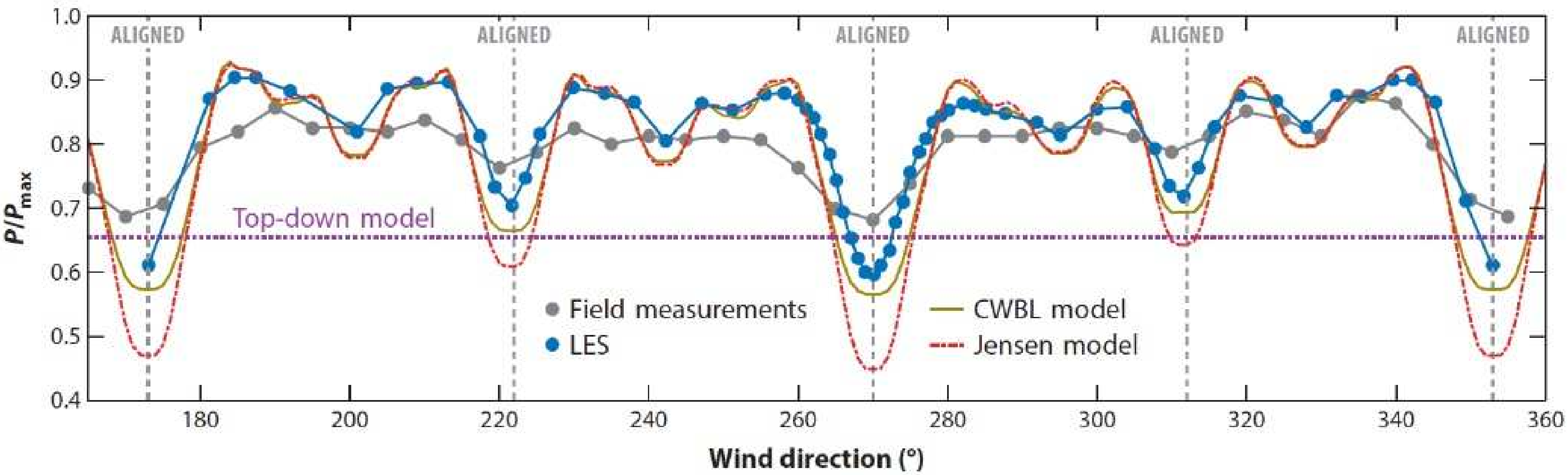


Comparison with LES Porté-Agel, Wu, Chen, Energies 2013, 6, 5297-5313

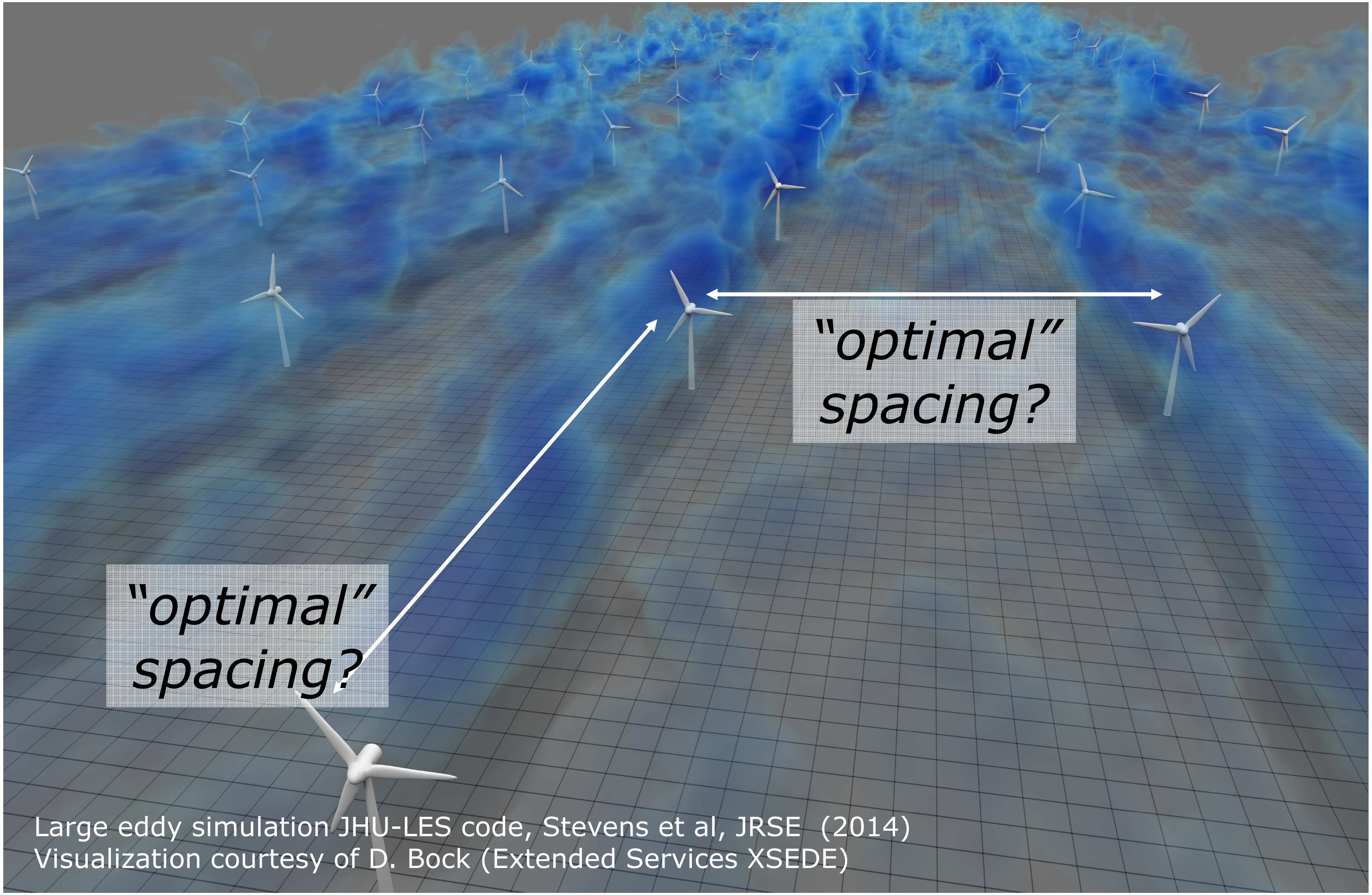
Stevens, Gayme, Meneveau, Wind Energy 19 (11), 2023-2040 (2016).

Modeling Horns Rev performance



Stevens, Meneveau, Annual Review of Fluid Mechanics, 49, 311-339 (2017).

Optimal spacing in wind-farms



Optimal spacing in large wind-farms

- Actual turbine spacing in wind-farms is around 6-10D in stream-wise and span-wise direction
- Meyers and Meneveau predicted optimal distance in square fully developed (infinite) wind farms is 15D, using a physics based modeling approach
- Spacing effect is hugely important to make sure we understand how to "scale up” wind farms
- We reveal that optimal spacing depends on wind-farm length

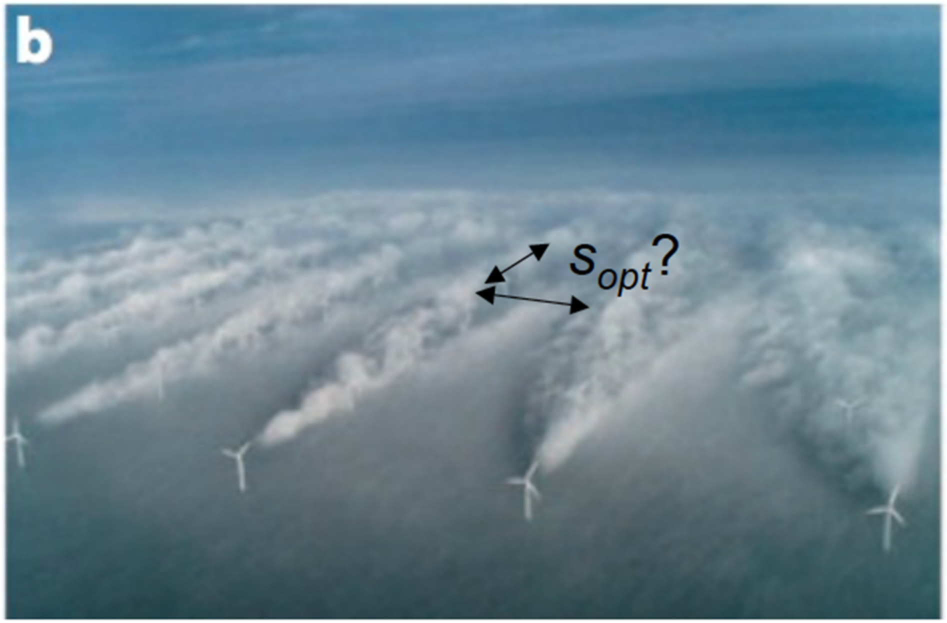


Photo by Uni-Fly A/S (Wind turbine maintenance company)

Meyers, Meneveau, Wind Energy 15, 305–317 (2012); Sørensen, Annual Rev. Fluid Mech (2011)

Cost optimization (simplest approach)

Consider total

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

Define dimensionless cost ratio:

Turbines: $$\alpha = \frac{\mathrm{Cost}_{\mathrm{turb}}/(\frac{1}{4}\pi D^2)}{\mathrm{Cost}_{\mathrm{land}}}$$

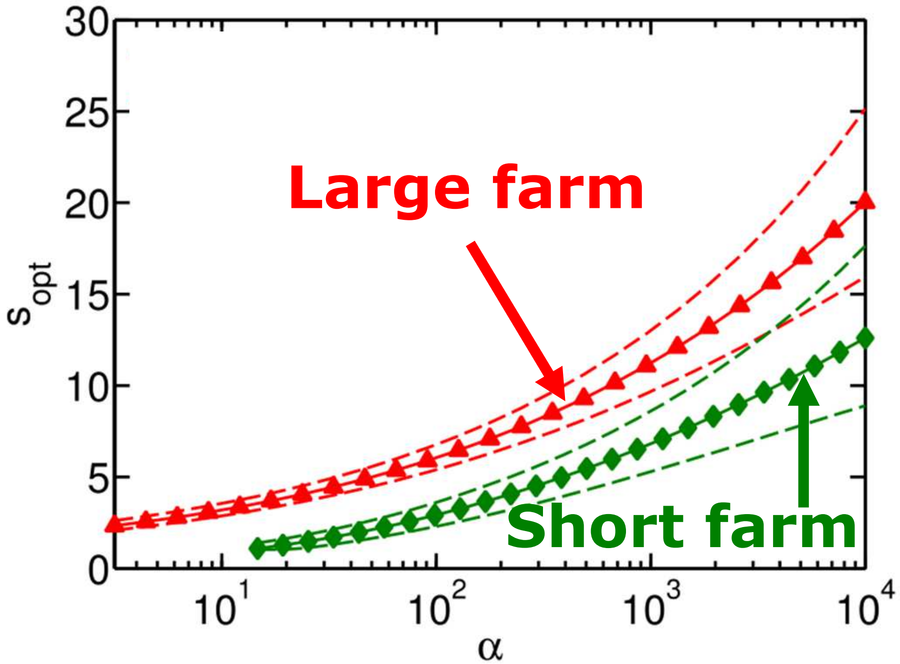
Power per unit cost

$$P^* = \frac{P_\infty(s_x, s_y, \mathrm{layout}, ...)}{s} \frac{4s^2/\pi}{\alpha + 4s^2/\pi}$$

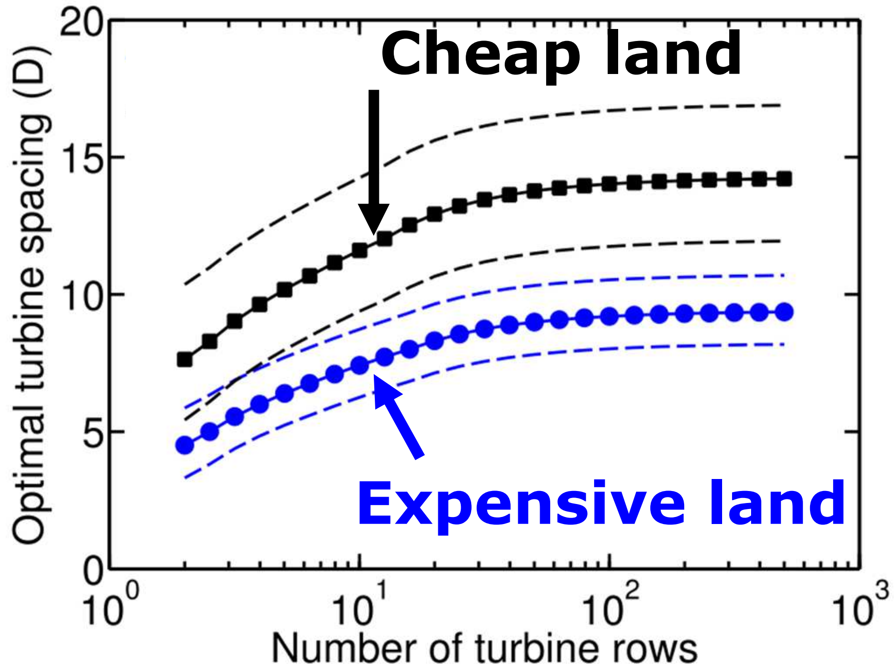
Where P_{avg} is the average turbine power output normalized with the power output of the first row

Meyers, Meneveau, Wind Energy 15, 305–317 (2012); Stevens, Wind Energy 19, 651-663 (2016)

Optimal spacing in large wind-farms



Optimal spacing as function of cost ratio



Optimal spacing as function of wind-farm length

Spacing in simple model similar to what is observed in real wind farms

Meyers, Meneveau, Wind Energy 15, 305–317 (2012); Stevens, Wind Energy 19, 651-663 (2016)

Taking cable costs into account

Area (land) cost

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

$$\frac{\$/m^2}{\$/m^2}$$

Linear (cable, road, loss) costs

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

$$\frac{\$/m}{\$/m}$$

Revenue

Minimize cost (or MAX power/cost)

Define costs as

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

Power per unit cost for a turbine deep into a large farm:

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

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

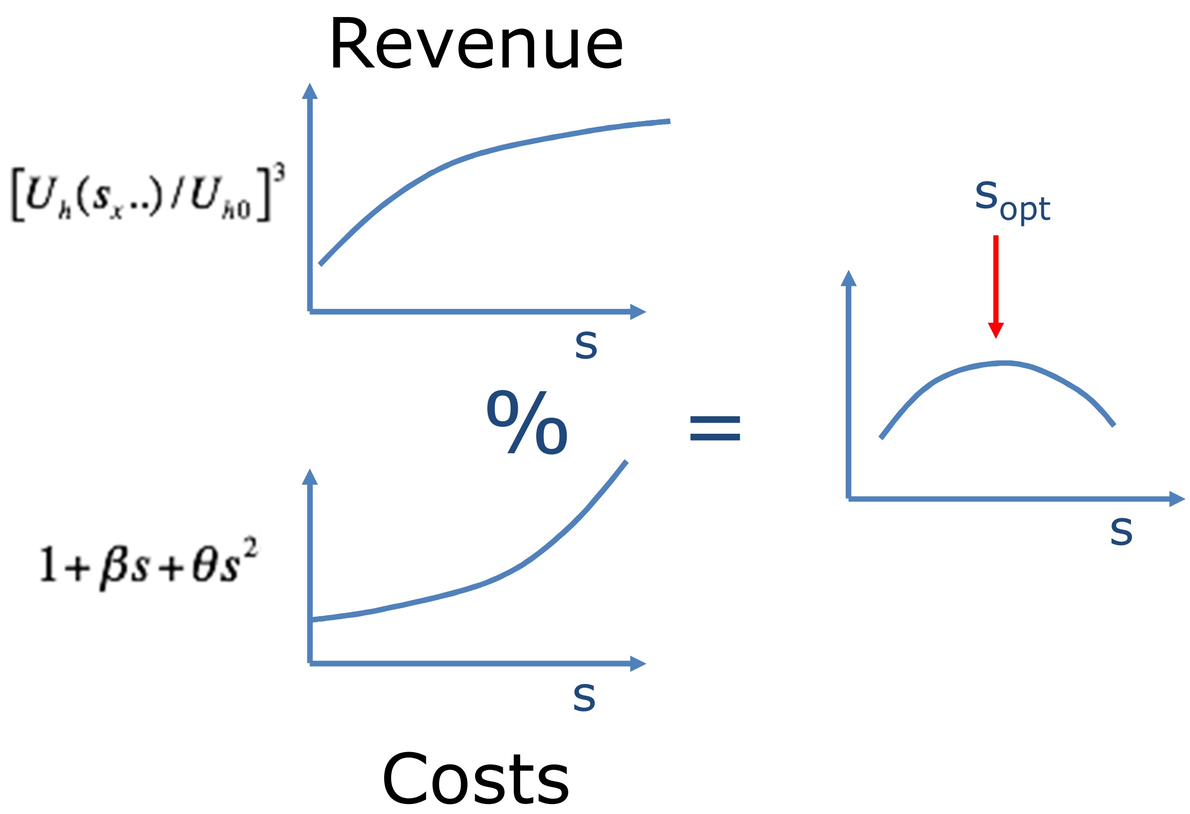
$$P^* = \left(\frac{\frac{1}{2} C_p \rho A U_{h0}^3}{Cost_{turb}} \right) \frac{\left[U_h(s_x, s_y, layout, C_T ..) / U_{h0} \right]^3}{1 + \beta s + \theta s^2}$$

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

Minimize cost (or MAX power/cost)

Power per unit cost for a turbine deep into a large farm:

$$P^* = \left(\frac{\frac{1}{2} C_p \rho A U_{h0}^3}{Cost_{turb}} \right) \frac{\left[U_h(s_x, s_y, layout, C_T ..) / U_{h0} \right]^3}{1 + \beta s + \theta s^2}$$



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

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$$\theta = \frac{\mathrm{Cost}_{\mathrm{land}}}{\mathrm{Cost}_{\mathrm{turbine}}/D^2} \qquad \beta = \frac{\mathrm{Cost}_{\mathrm{cable}}}{\mathrm{Cost}_{\mathrm{turbine}}/D}$$

Sample (levelized) cost ratios:

Land:
- Land cost θ ~ 0.53/550 ~ 0.001
- Length cost β ~240/5.8x10^4 ~ 0.004

Royalties for 20 yrs ~\$5300/ha = 0.53 \$/m^2

Cables ~ \$60/m + Roads ~\$80/m,
+ Resistance losses~\$100/m = \$240/m
1 Turbine = 6.2 \$Million
(3.6 MW turbine, D=106 m, NREL 2013 all-in value: \$1728/kW x 3,600 = 6.2 \$M
550 \$/m^2 and 5.8 x 10^4 \$/m

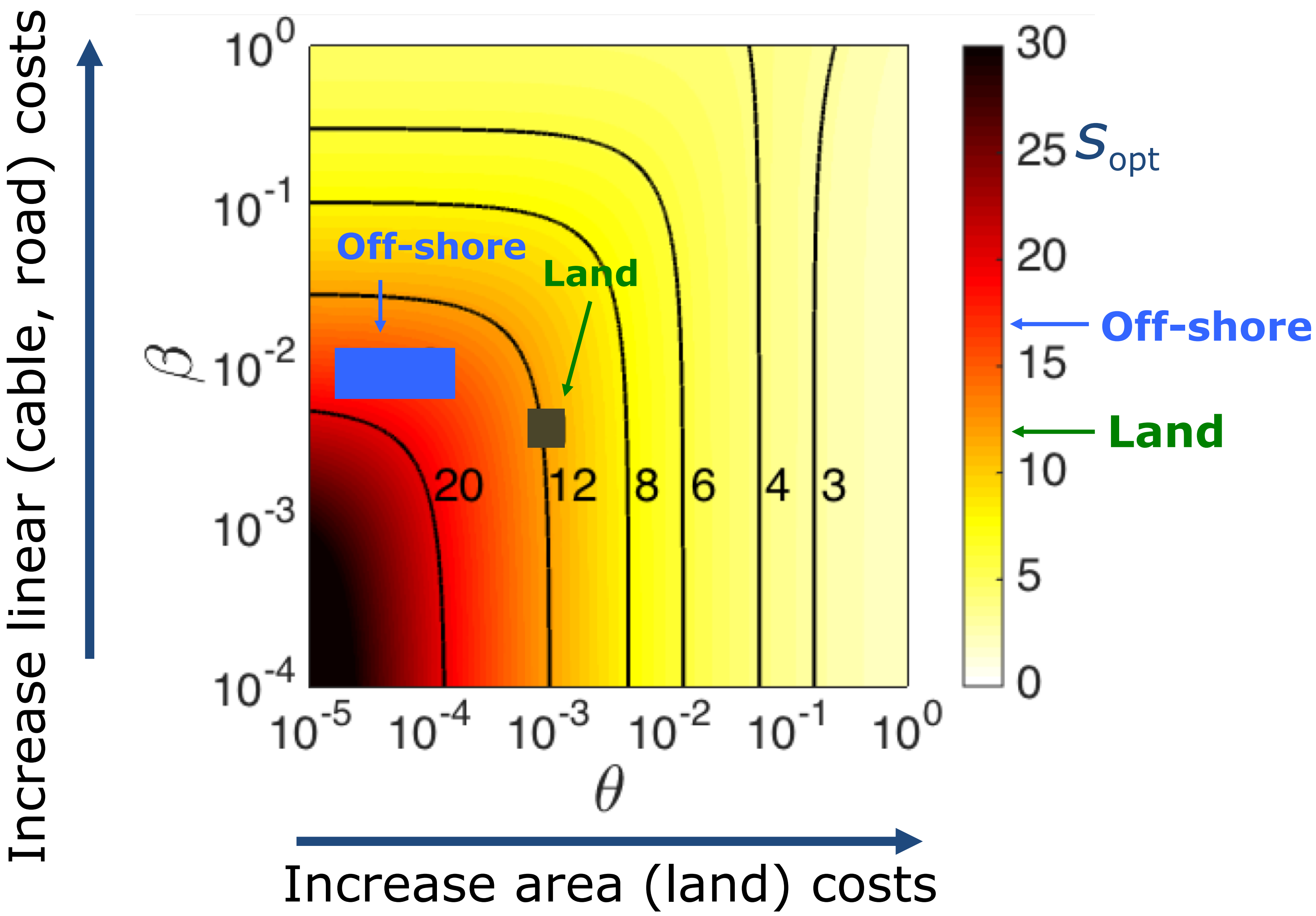
Off-Shore:
- θ ~ 0.01/1,664 < 0.00001
- β ~1,370/1.76x10^5 ~ 0.008

Lease cost for 20 yrs ~ 0.01 \$/m^2
Cables ~ \$1000/m, Resistance~370 \$/m
1 Turbine = 18.7 \$Million
(3.6 MW turbine, D=106 m, NREL 2013 all-in value:
\$5187/kW x 3,600 = 18,700 \$M

1,664 \$/m^2 and 1.76 x 10^5 \$/m

NREL: C. Mone et al., 2013 Cost of Wind Energy Review, NREL/TP-5000-63267, Feb. 2015
IRENA, Renewable Energy Technologies: Cost Analysis Series, Wind Power, Volume 1, Power Sector, Issue 5/5, June 2012.

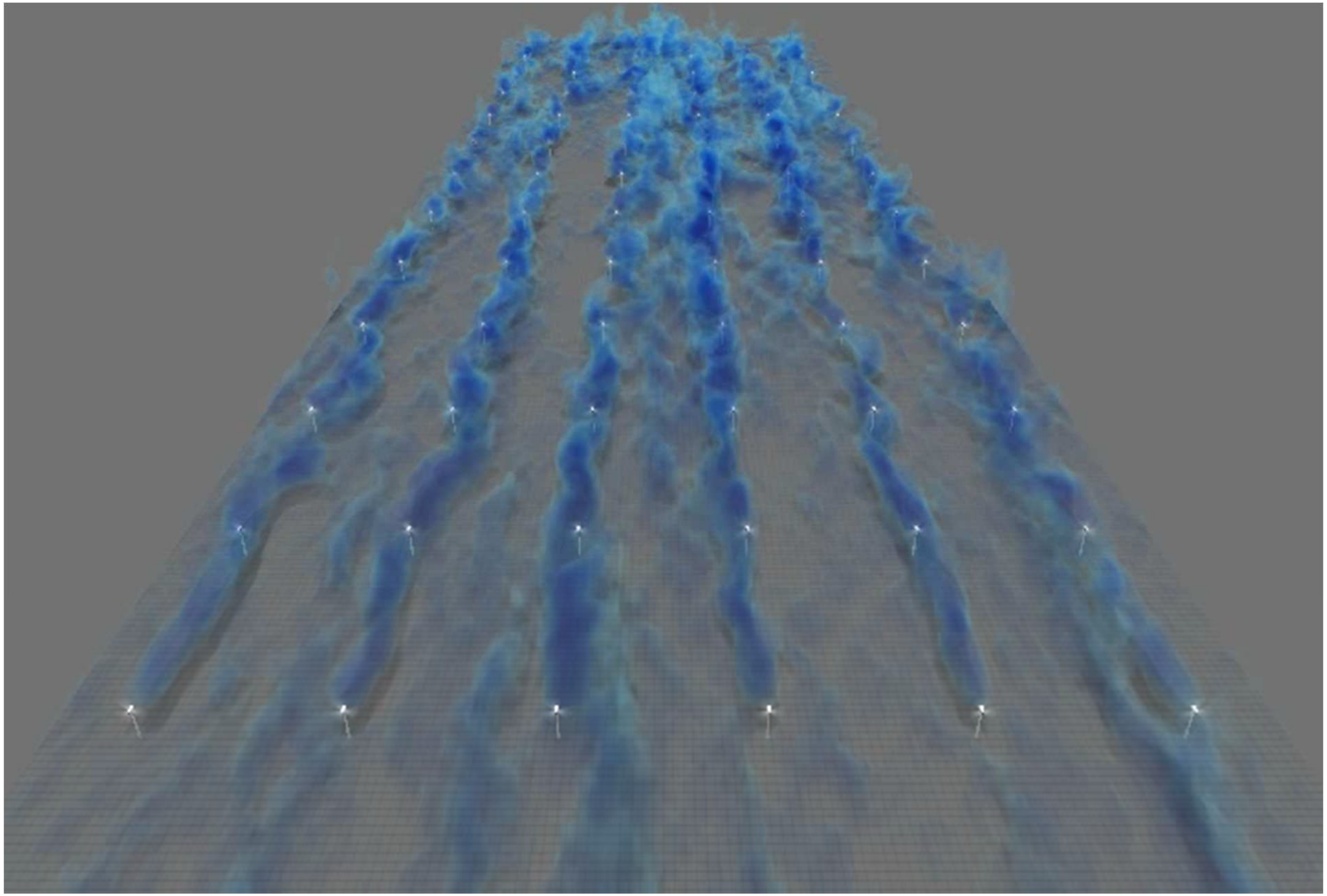
Effect of linear and area costs



Conclusions

- State of the art large eddy simulations can be used to get reliable performance estimates of wind-farms
- Large simulations can be used to further develop simplified wind farm models that can be used to optimize wind farm design

Questions?



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Visualization courtesy of D. Bock (Extended Services XSEDE)