Wind speed reductions within and wake lengths behind wind parks, an analytical model

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Wind parks

what happens when turbines are close together? …

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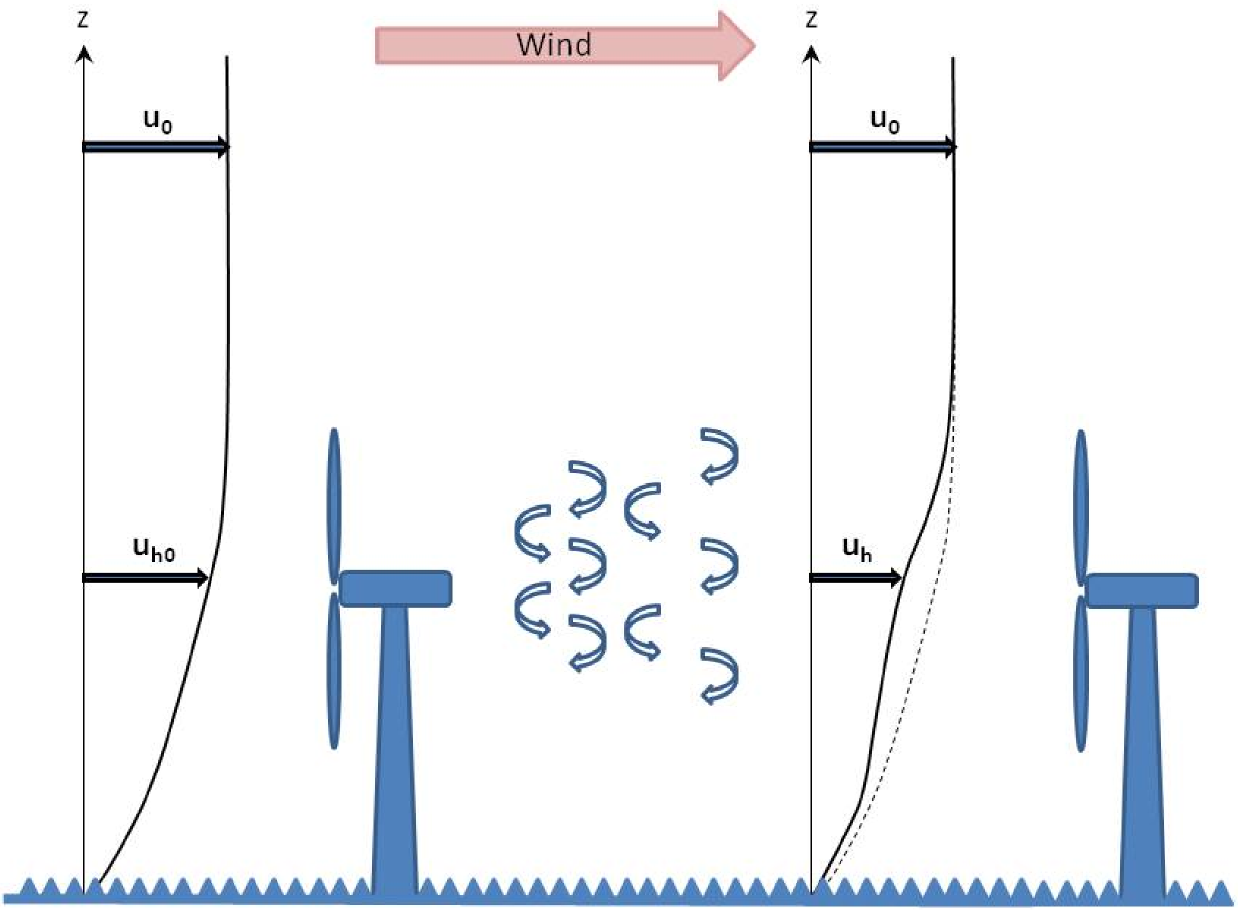
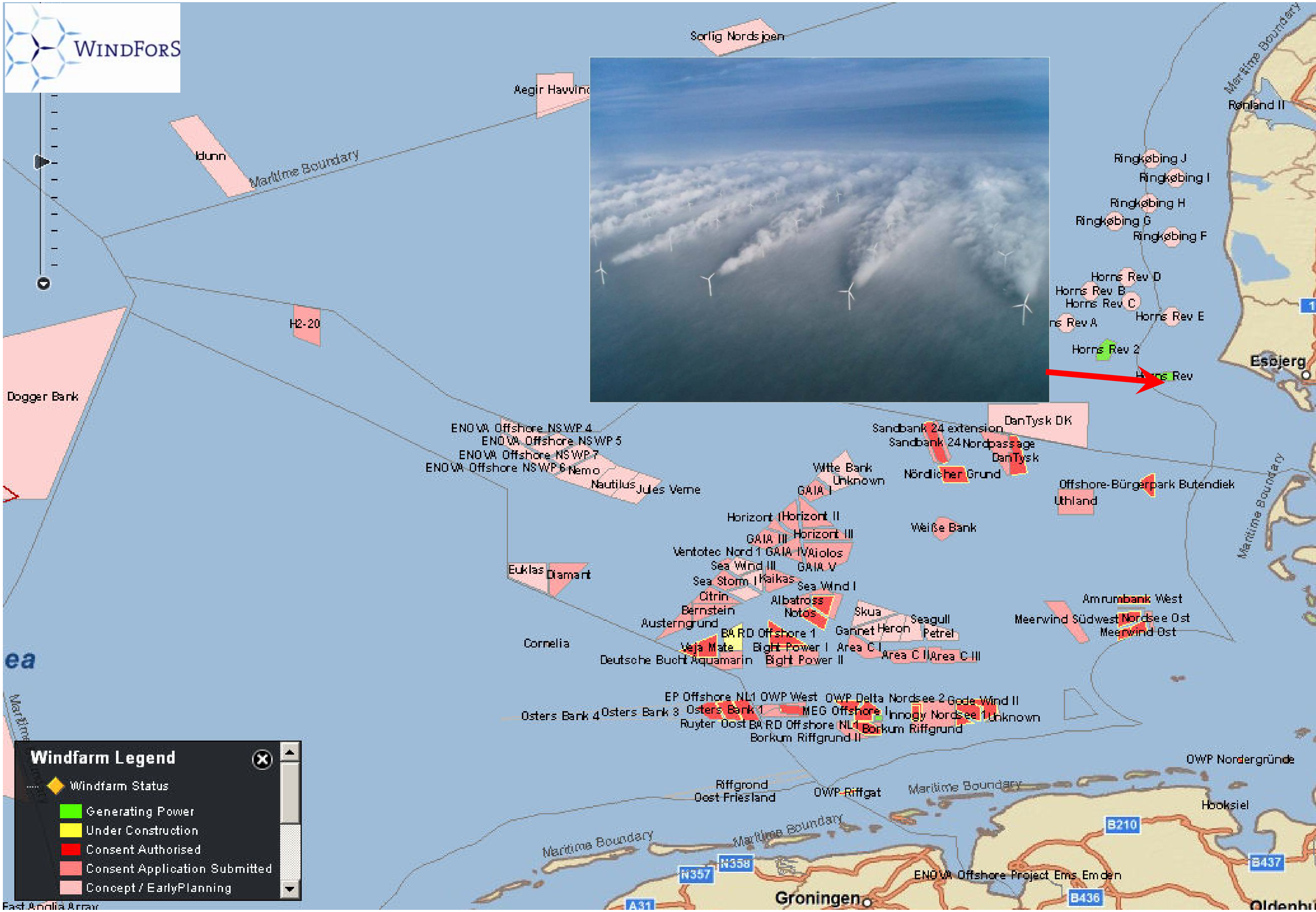
wake formation behind a wind turbine

- less wind speed

ahead of the next turbine in a wind park

- more turbulence





source: http://www.4coffshore.com/offshorewind/

Wind energy generation is based on momentum (energy) extraction from the air

momentum extraction decelerates the wind

➔ (1) wind park efficiency depends on the equilibrium wind speed in the interior of the park

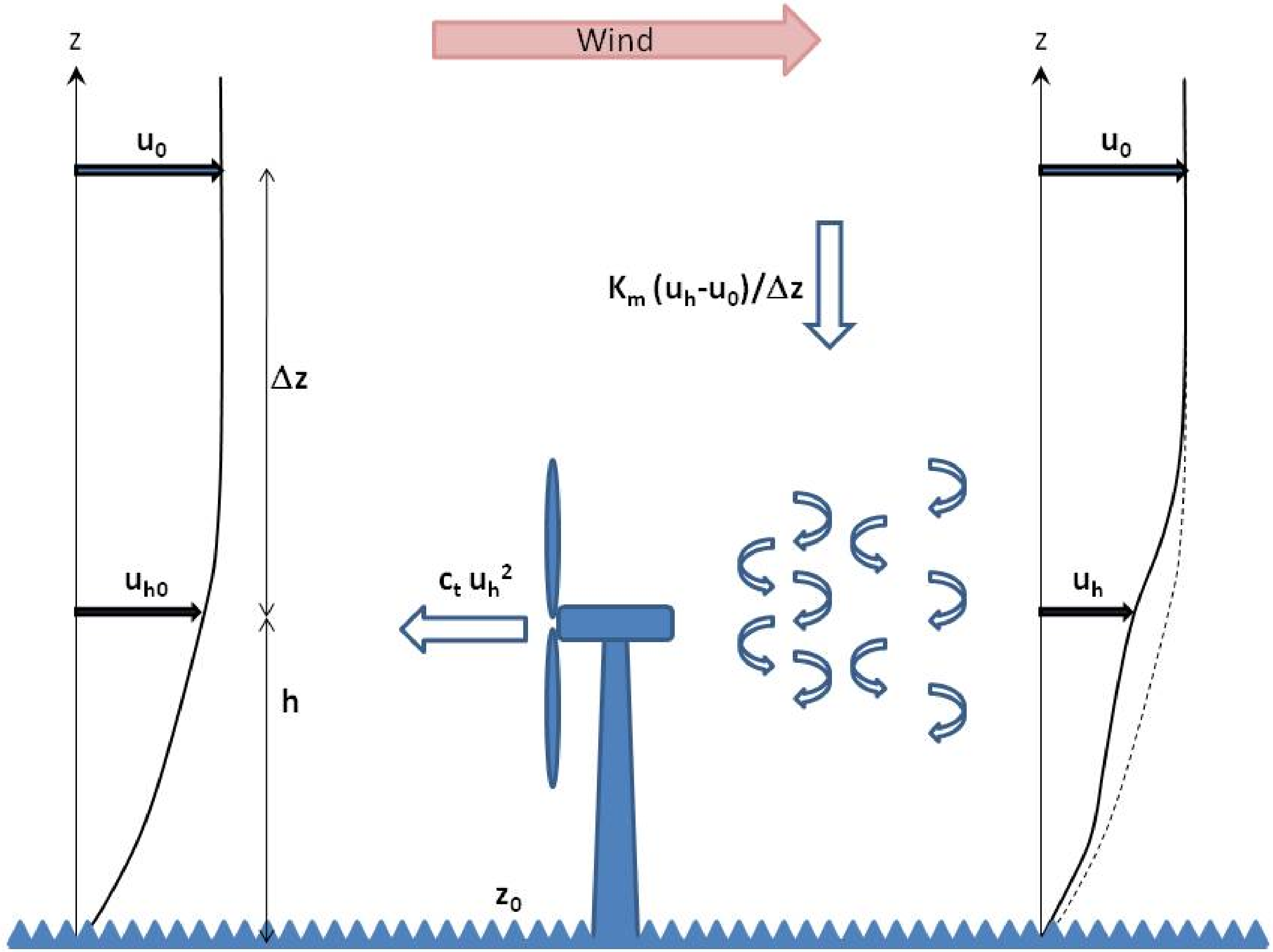
- equilibrium between extraction and re-supply of momentum

➔ (2) wind park wakes influence other wind parks downstream

- wake length is inversely proportional to the momentum re-supply

➔ for wind park design it is important to know:
1) the magnitude of wind speed reduction in the park interior
2) the length of wakes

1) the magnitude of wind speed reduction in the park interior



Wind
z
z
u0
u0
Δz
Km (uh-u0)/Δz
uh0
ct uh2
uh
h
z0

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basic idea of the analytical model

reduction of wind speed in the park interior (calculation of the equilibrium condition for the momentum fluxes)

$$c_{teff} u_h^2 = \frac{\kappa u_* z (u_0 - u_h)}{\Delta z \phi_m}$$

extraction = re-supply from above

turbine and surface drag

flux-gradient-relationship

Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, 13, 459-469.

solution of the analytical model

reduction of wind speed in the park interior (calculation of the equilibrium condition for the momentum fluxes):

momentum extraction by the turbines

surface roughness

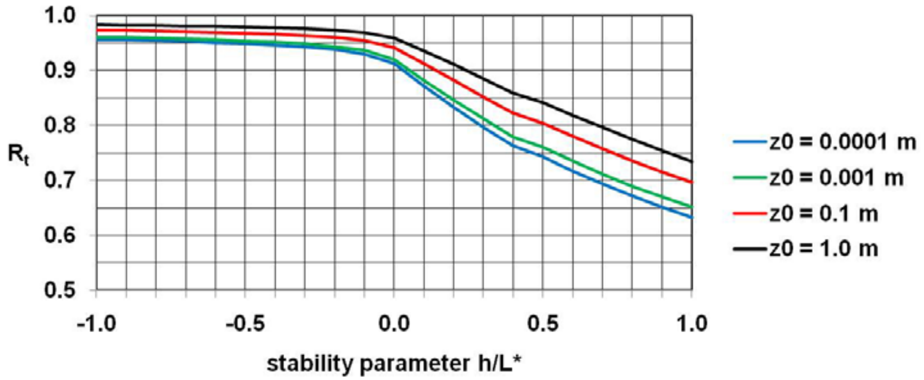
thermal layering of the PBL

turbine-induced turbulence

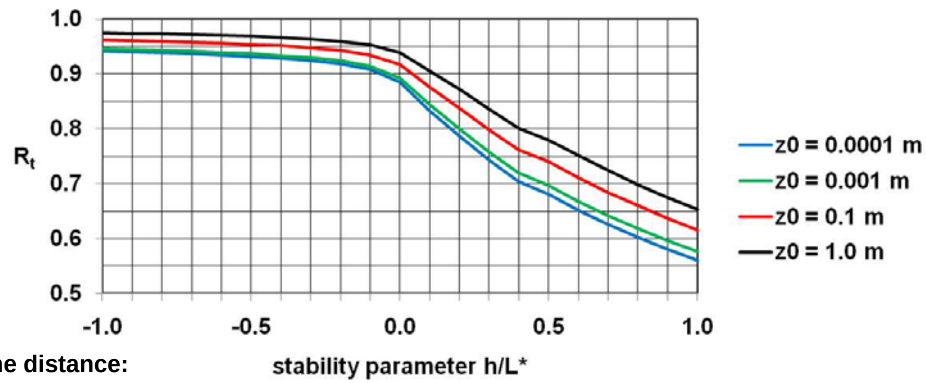
$$R_t = \frac{\left(f_{h,\Delta z} T_i + \frac{\phi_m}{\kappa^2} c_{s,h} \right)}{\left(f_{h,\Delta z} T_i + \frac{\phi_m}{\kappa^2} c_{teff} \right)}$$

Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, 13, 459-469.

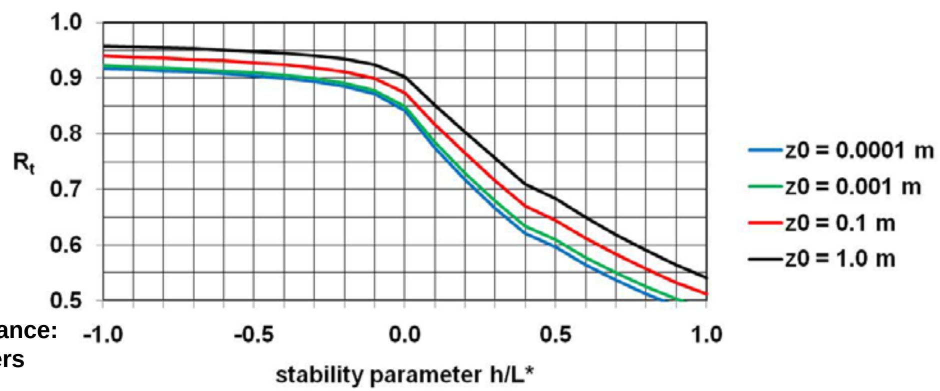
reduction of wind speed in the park interior



mean turbine distance: 10 rotor diameters

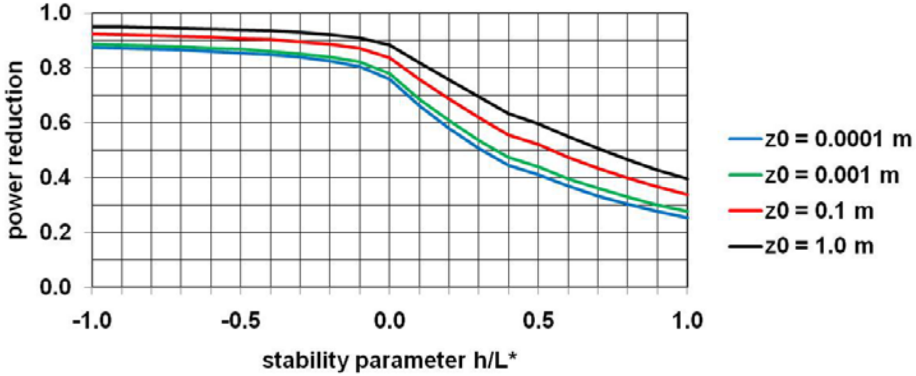


mean turbine distance: 8 rotor diameters

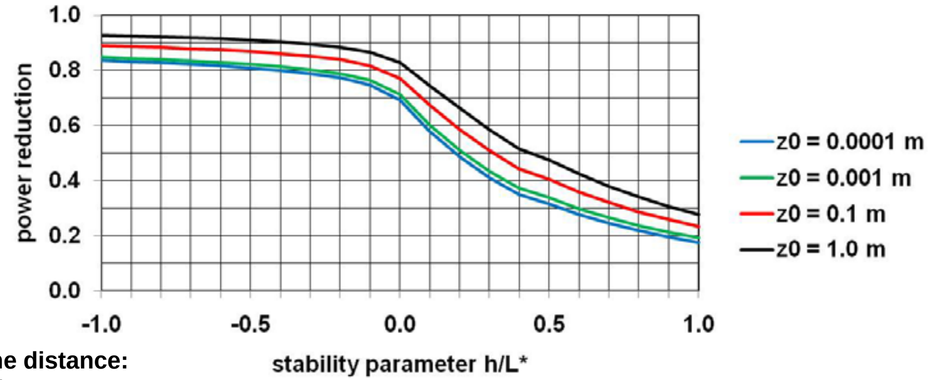


mean turbine distance: 6 rotor diameters

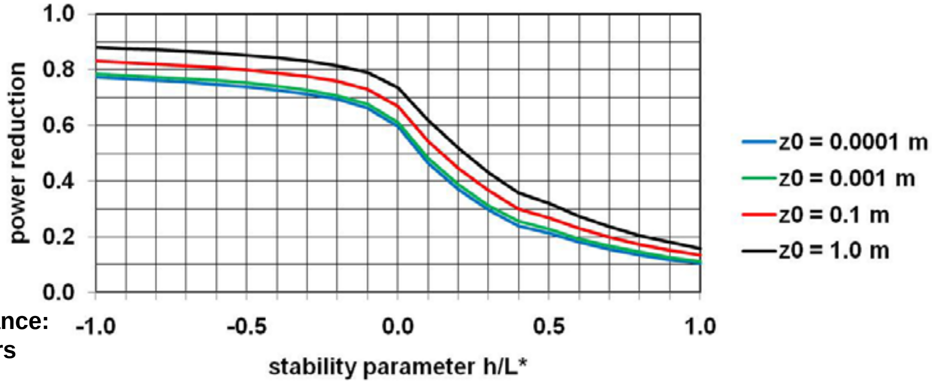
reduction of wind power in the park interior



mean turbine distance:
10 rotor diameters

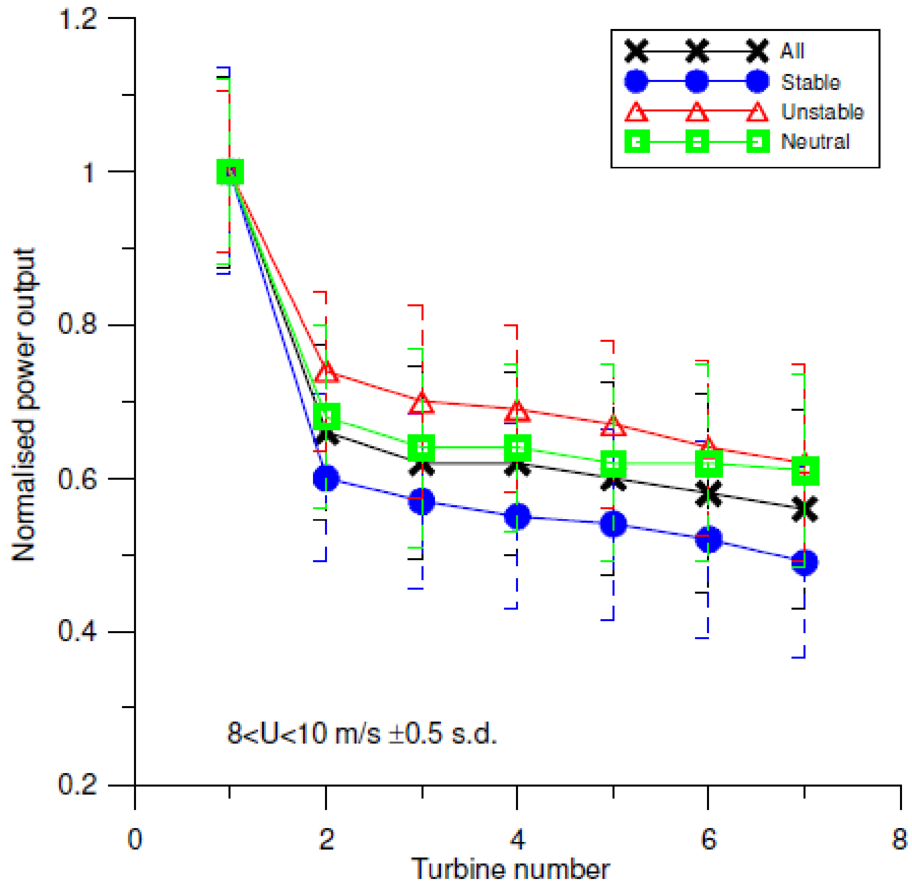


mean turbine distance:
8 rotor diameters



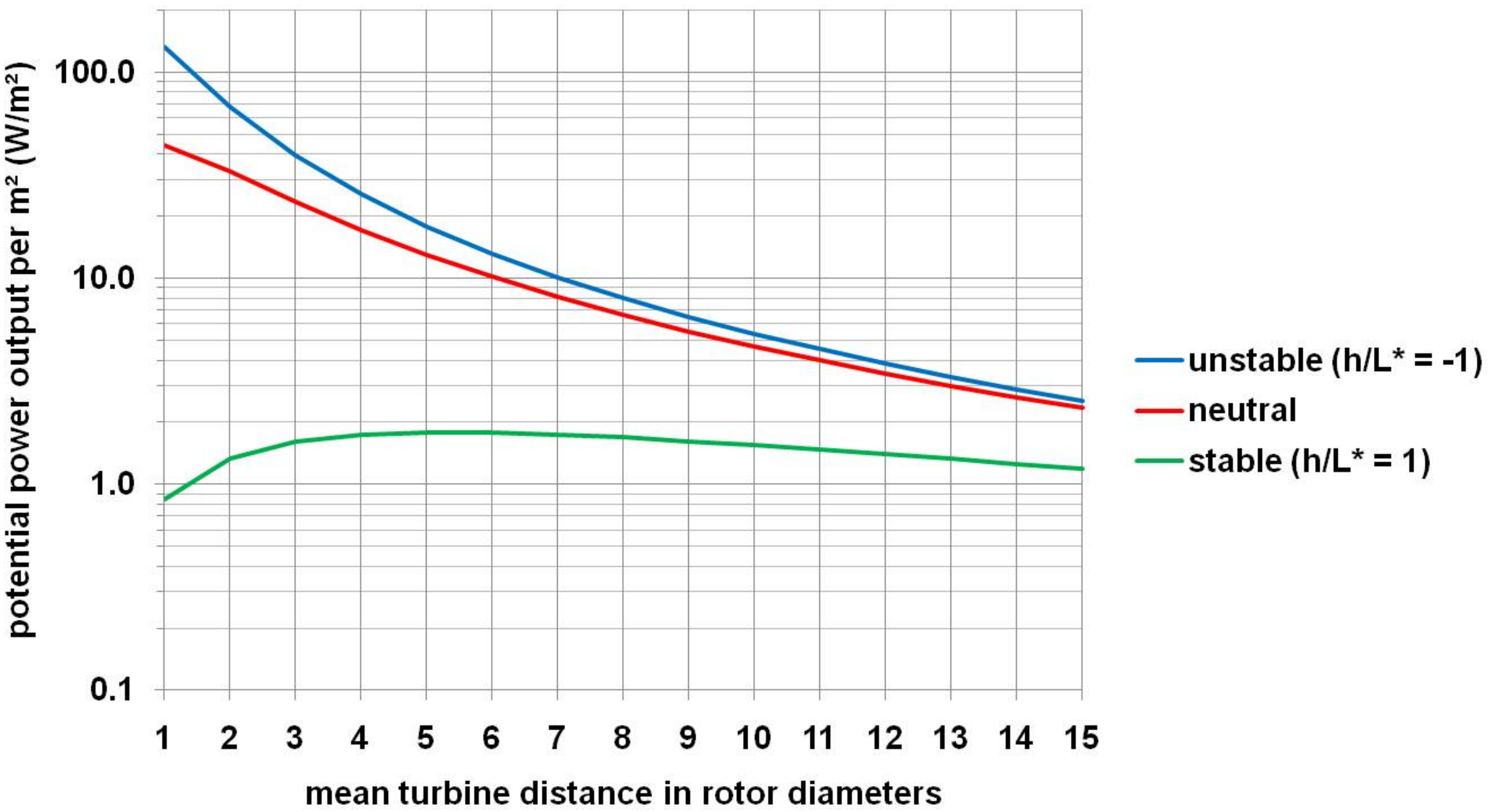
mean turbine distance:
6 rotor diameters

reduction of wind power in the park interior measurements at Nysted wind park (Baltic sea)

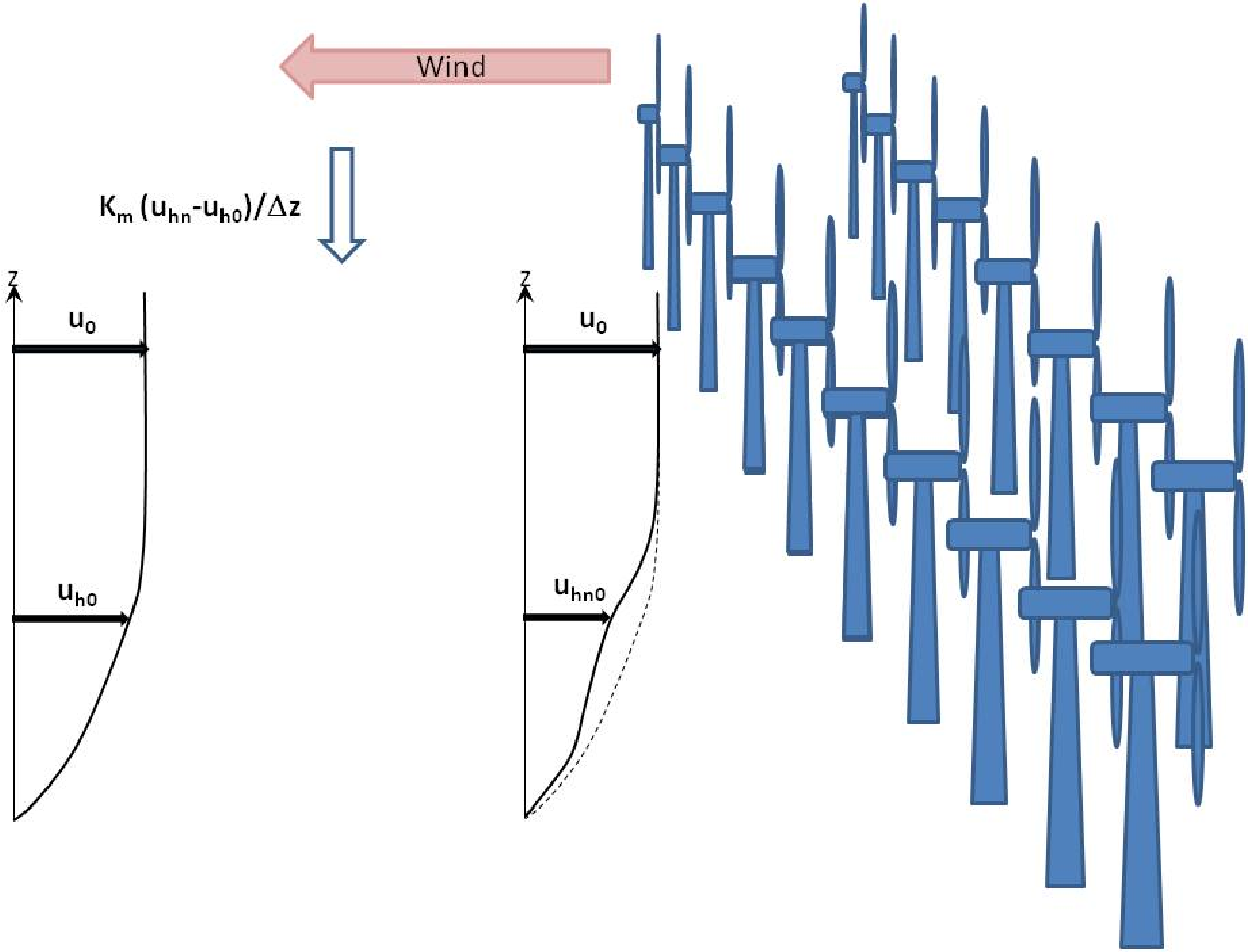


Barthelmie R, Frandsen ST, Rethore PE, Jensen L., 2007: Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm. Proceedings of the European Offshore Wind Conference, Berlin 4.-6.12.2007.

Optimization of turbine density in a wind park



2) the length of wakes



Wind
$K_m (u_{hn}-u_{h0})/\Delta z$
z
u_0
u_{h0}
z
u_0
u_{hn0}

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basic idea of the analytical model

speed-up of wind speed downstream of a wind park:

$$\frac{\Delta u_{hn}}{\Delta t} = \frac{\kappa u_* z}{\Delta z^2}(u_{h0} - u_{hn})$$

speed-up = re-supply from above

Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, 13, 459-469.

solution of the analytical model

momentum extraction by the turbines

surface roughness

thermal layering of the PBL

turbine-induced turbulence

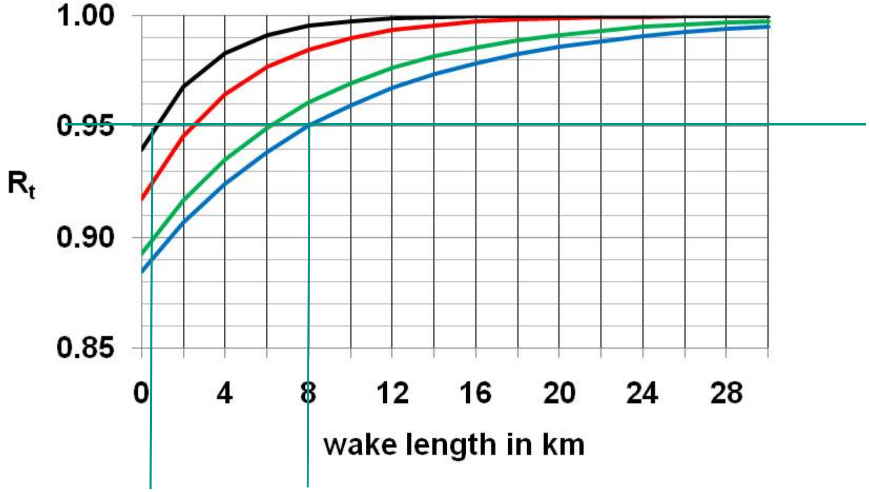
speed-up of wind speed downstream of a wind park:

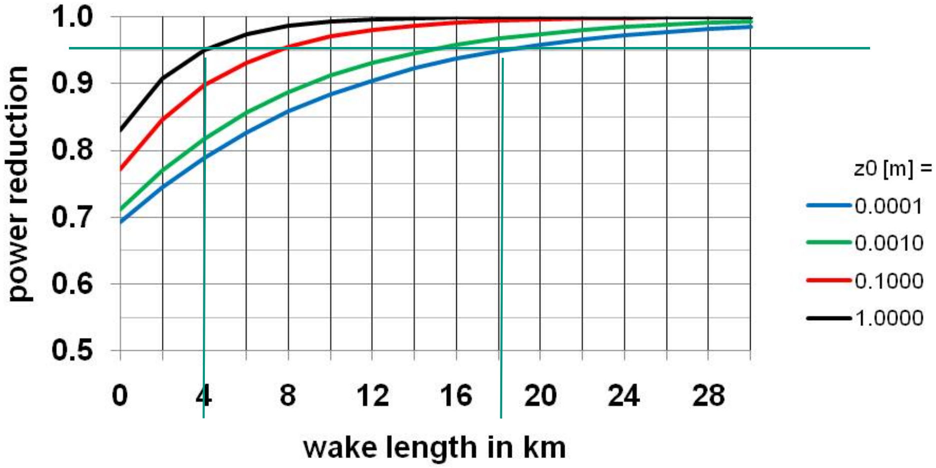
$$R_n = \frac{u_{hn}(t)}{u_{h0}} = 1 + \left(\frac{u_{hn0}}{u_{h0}} - 1 \right) \exp(-at)$$

Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, 13, 459-469.

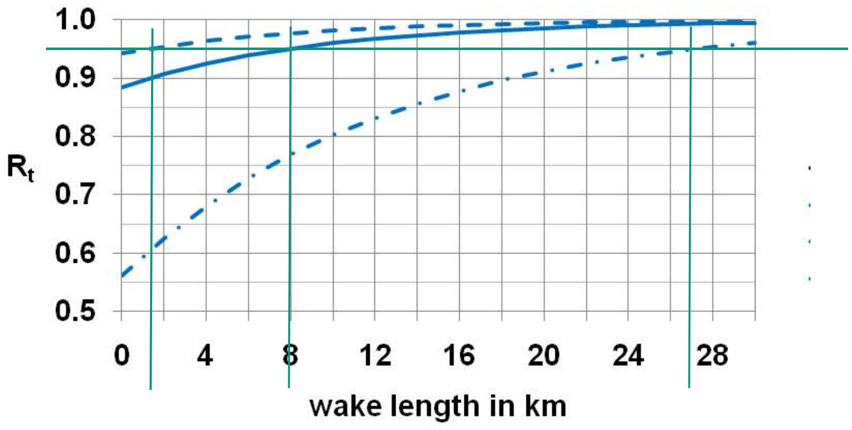
recovery of wind speed (left) and power (right) behind a wind park, mean turbine density: 8 rotor diameters

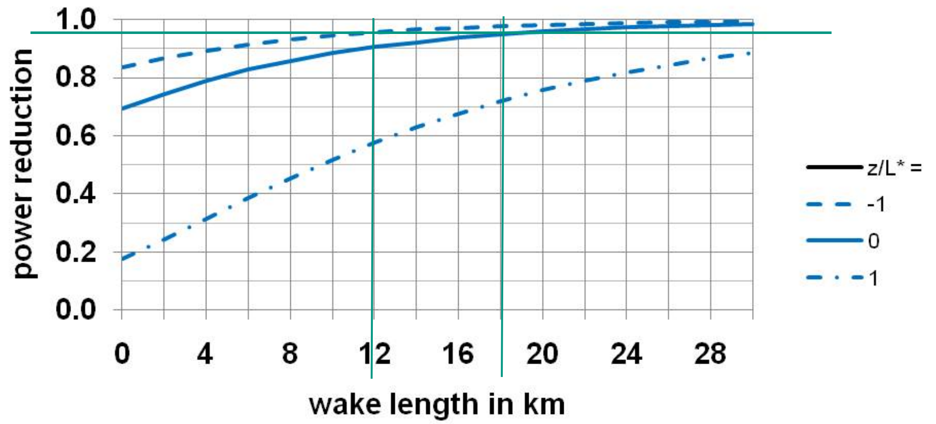
onshore (z_0 = 1.0 m) – offshore (z_0 = 0.0001 m)



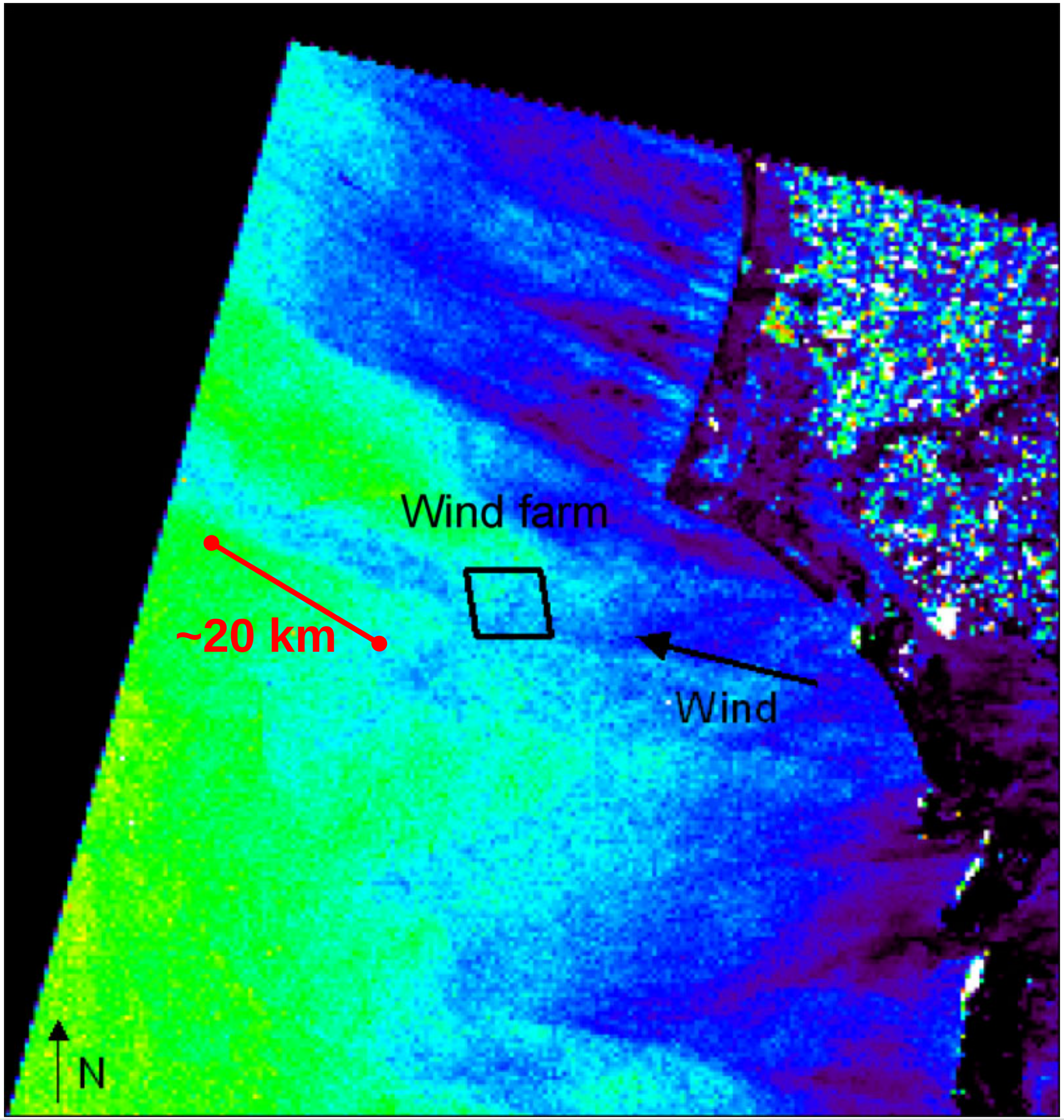


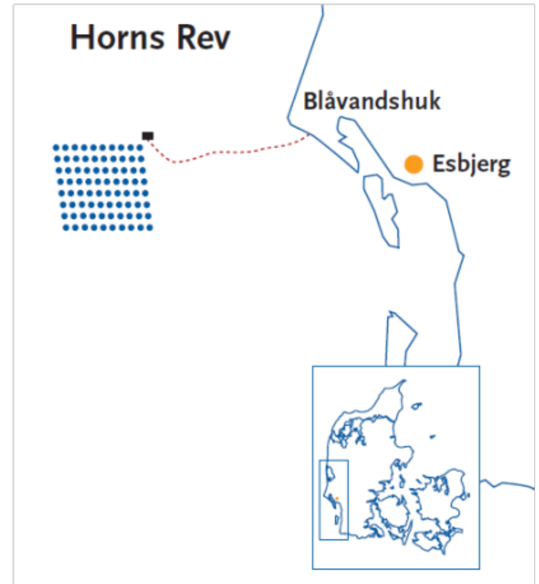
unstable (h/L_* = -1) – neutral – stable (h/L_* = 1)





speed-up of wind speed behind the wind park measurements (Envisat, SAR) at Horns Rev (4 km x 5 km)





http://www.hornsrev.dk/nyheder/brochurer/Horns_Rev_TY.pdf

25. 02. 2003

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http://galathea3.emu.dk/satelliteeye/projekter/wind/back_uk.html

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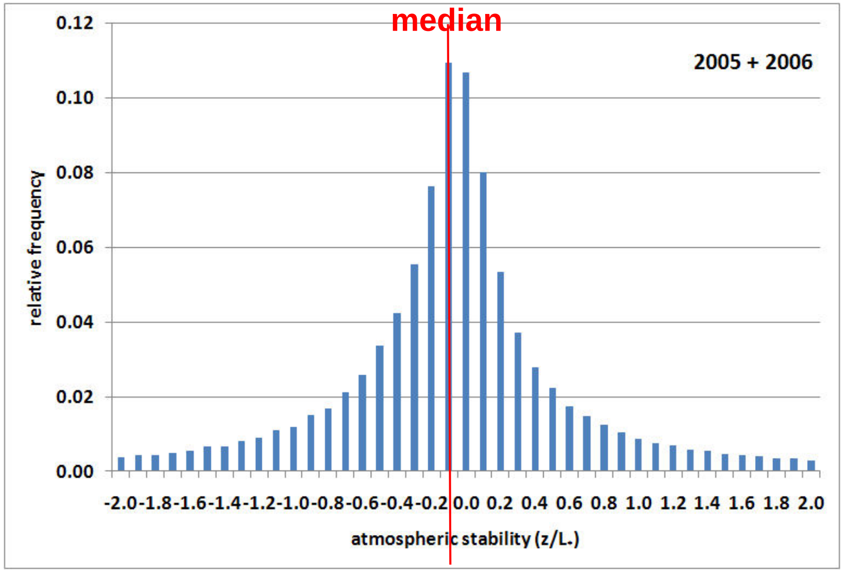
observed frequency distr. of atm. stability at FINO1 (80 m, 2005-2006



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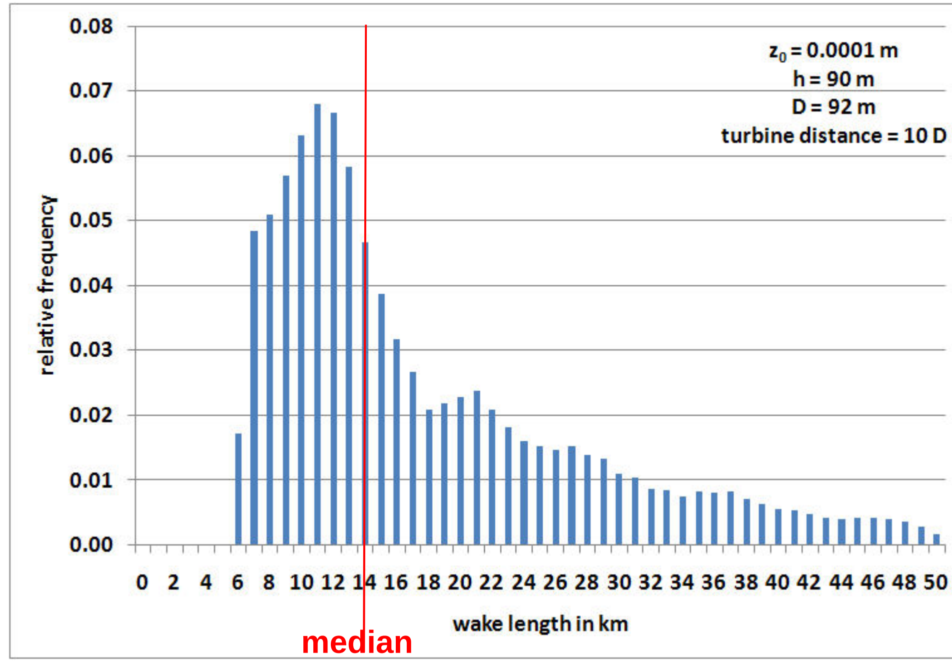
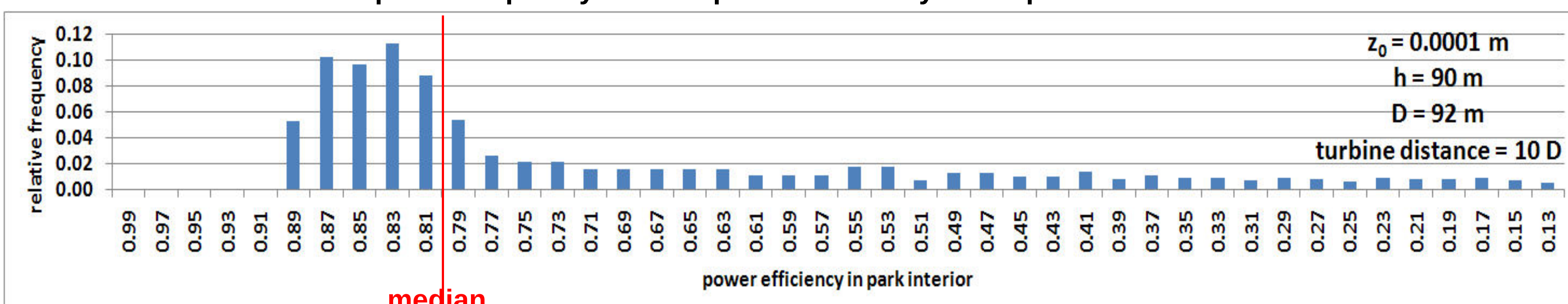
computed frequency distr. of wind park wake length



computed frequency distr. of power efficiency in the park interior



Conclusions:

wind speed reduction: offshore stronger than onshore

➔ (partial) compensation of higher offshore wind speed
➔ offshore requires a larger distance between turbines

larger harvest from wind parks during unstable stratification

➔ offshore: annual cycle of energy production
➔ onshore: diurnal cycle of energy production

offshore wake length is several times larger than onshore

➔ offshore requires larger distances between wind parks

but, analytical model is strongly simplified

➔ only for rough estimation, exact simulations with numerical models necessary

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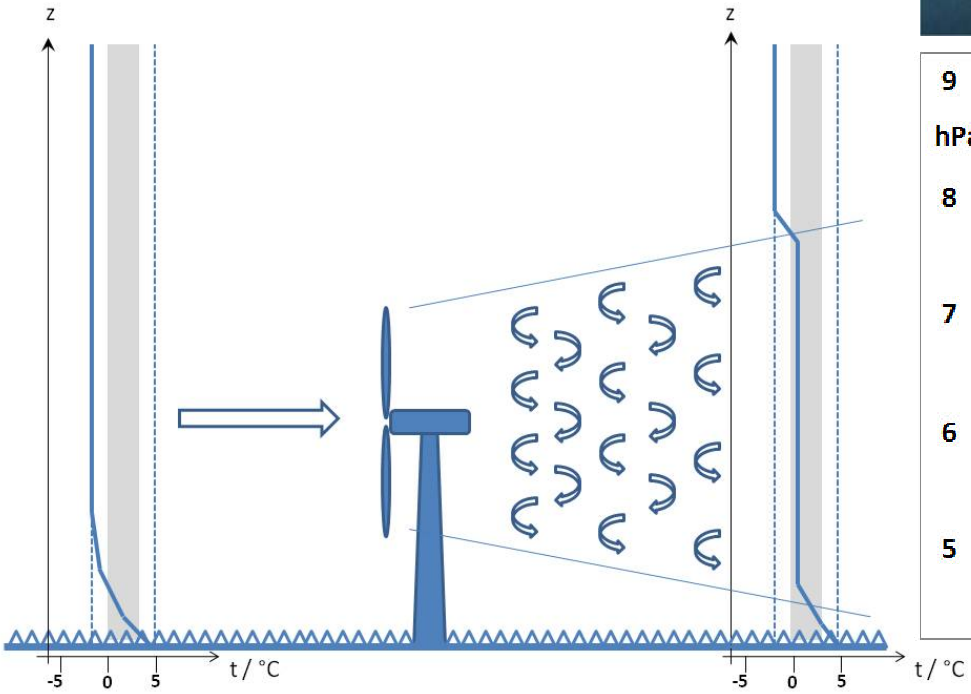
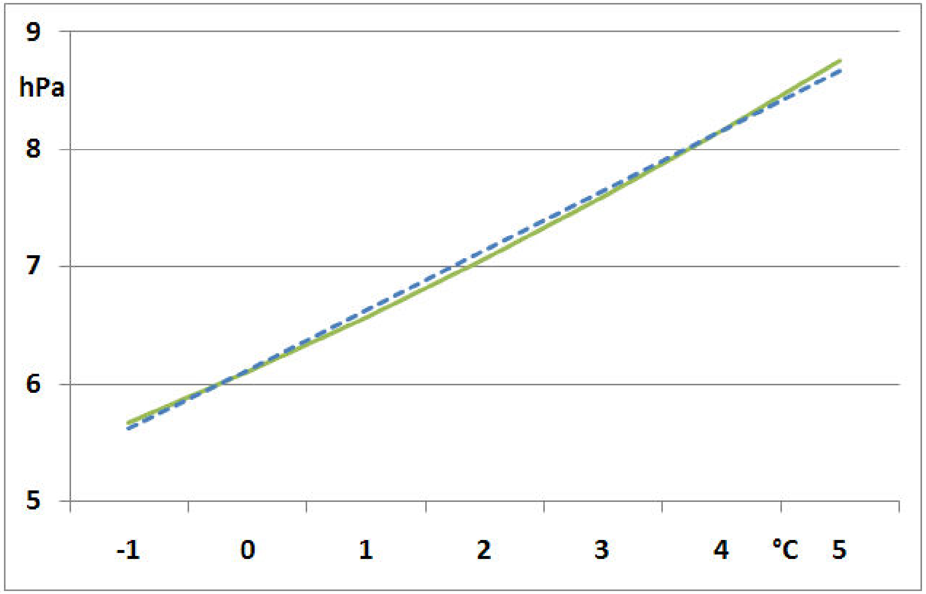
explanation of wake clouds: mixing fog

12. 02. 2008





air directly over the water:	5°C, more than 99% relative humidity
air at hub height:	-1°C, more than 99% relative humidity
after mixing:	2°C, above 101% humidity ➔ clouds

Thank you for your attention