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On wind speed reductions within and wake lengths behind wind parks – an analytical model

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

momentum extraction decelerates the wind

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

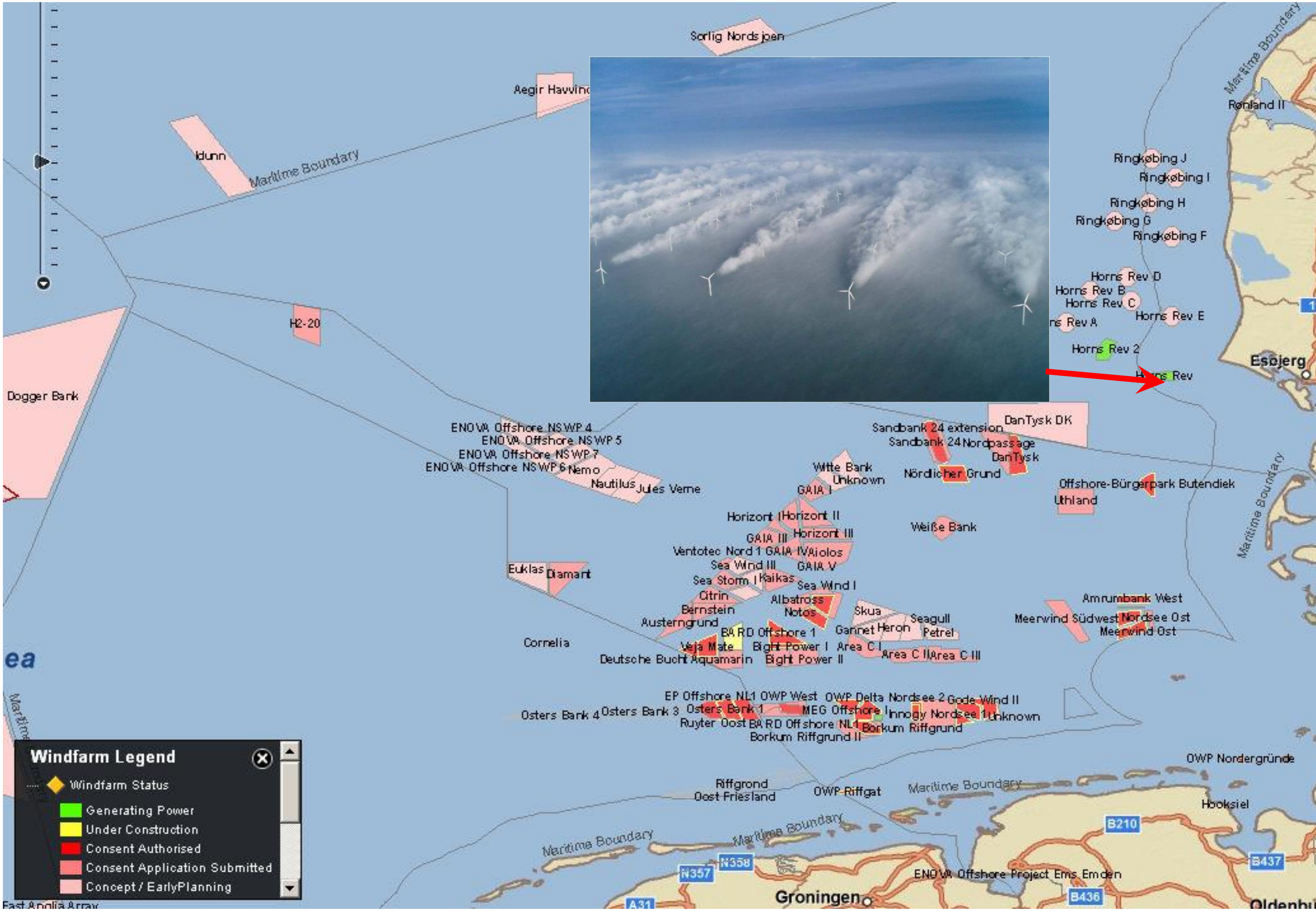
- equilibrium between extraction and re-supply of momentum

➔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:

a) the magnitude of wind speed reduction in the park interior
b) the length of wakes



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

basic idea of the analytical model

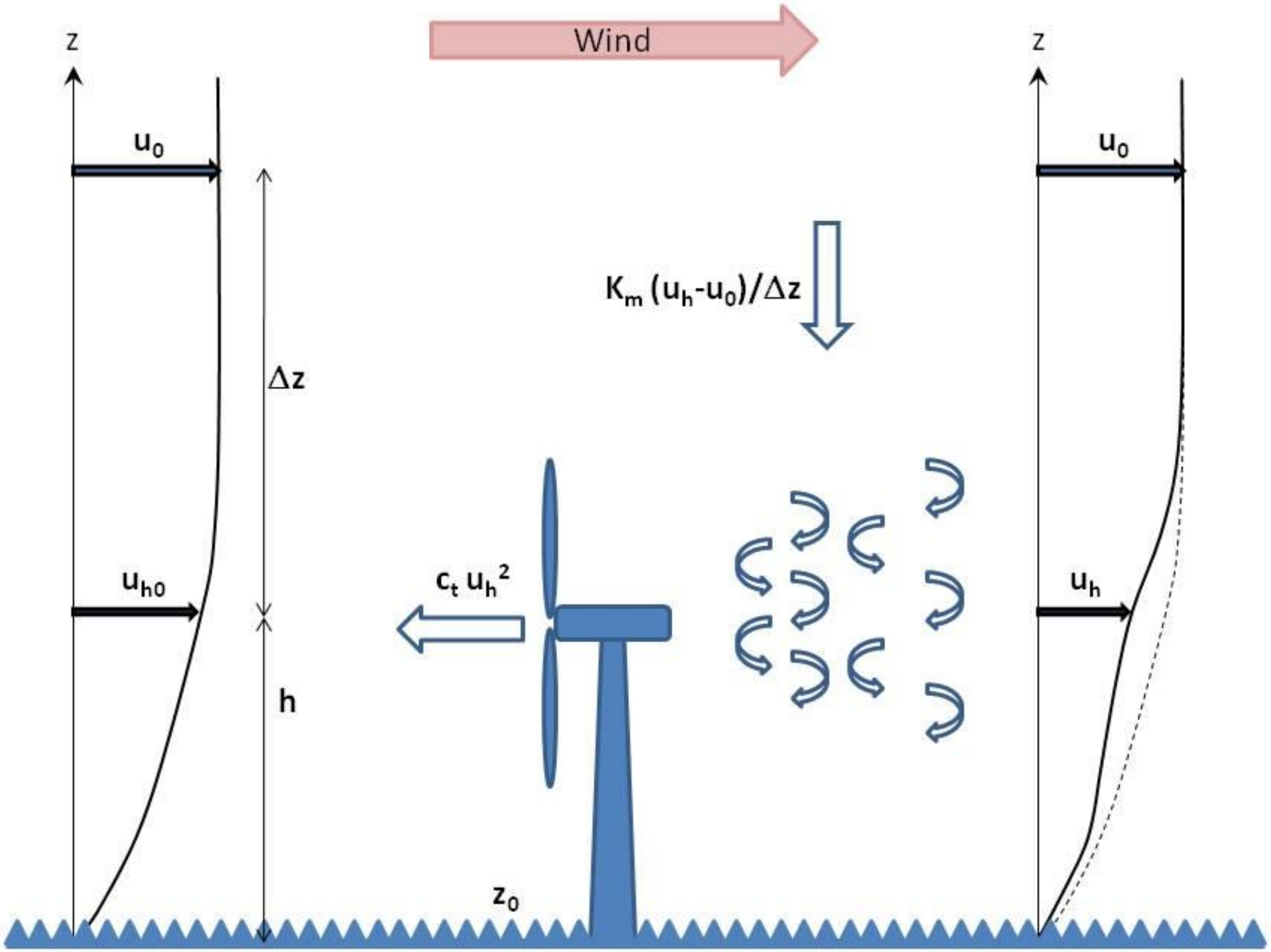
a) reduction of wind speed in the park interior (calculation of the equilibrium condition for the momentum fluxes)

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

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.


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

solution of the analytical model

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

momentum extraction by the turbines

surface roughness

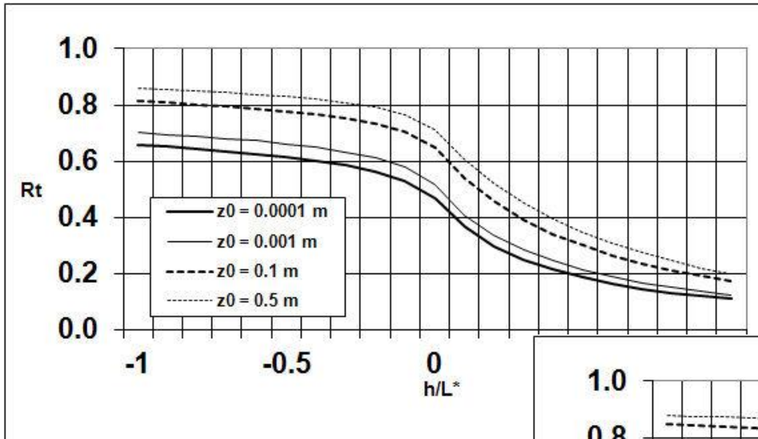
thermal layering of the PBL

turbine-induced turbulence

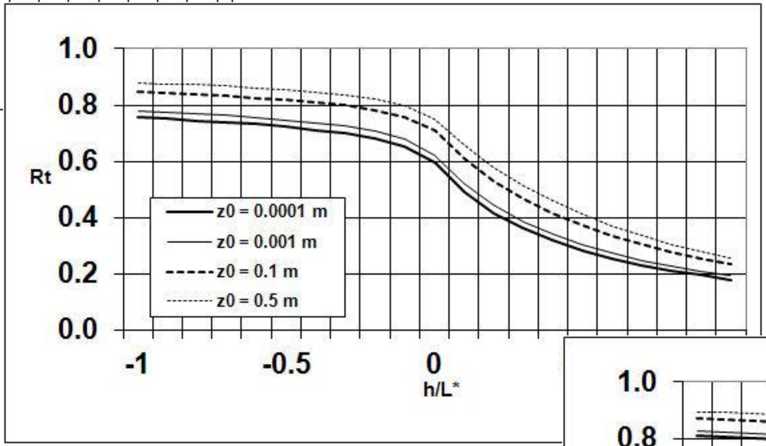
$$R_t = \frac{\left(f_{h,\Delta z} T_i + \frac{\phi_m}{\kappa^2} c_{s,h} \right)}{\left(f_{h,\Delta z} T_i + \frac{\phi_m}{\kappa^2} c_{teff} \right)}$$

a) reduction of wind speed in the park interior

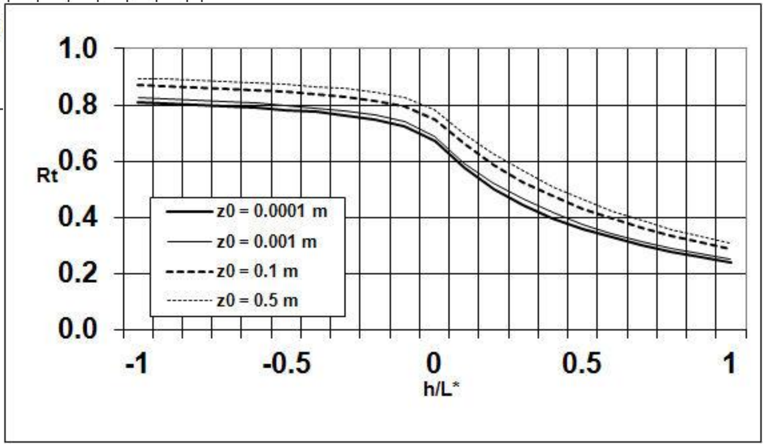
turbine-induced turbulence = 0.00



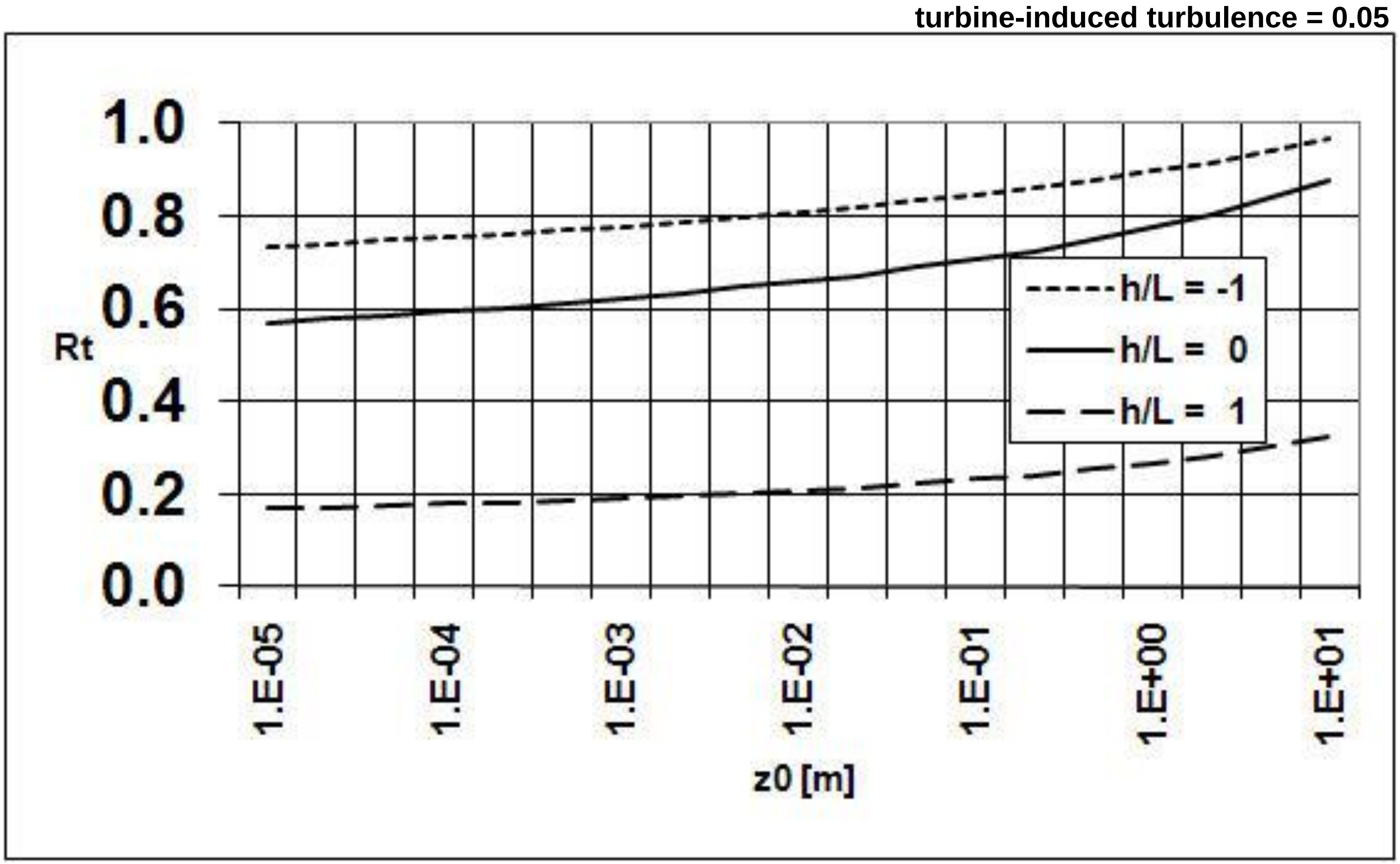
turbine-induced turbulence = 0.05



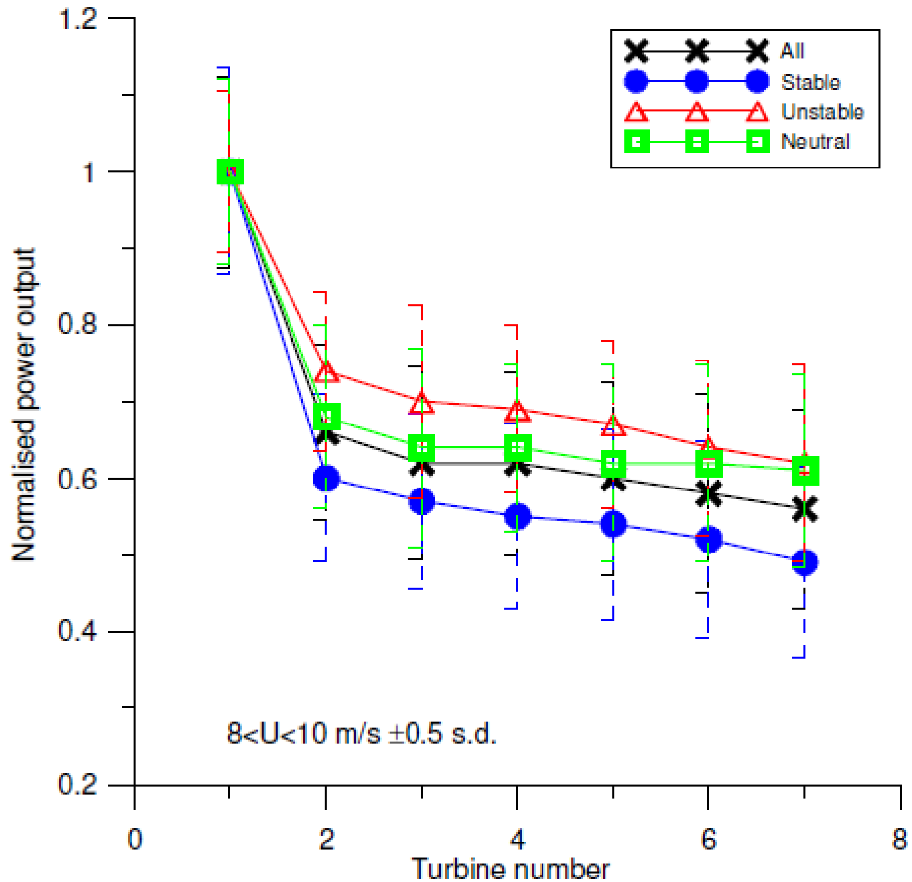
turbine-induced turbulence = 0.10



a) reduction of wind speed in the park interior



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

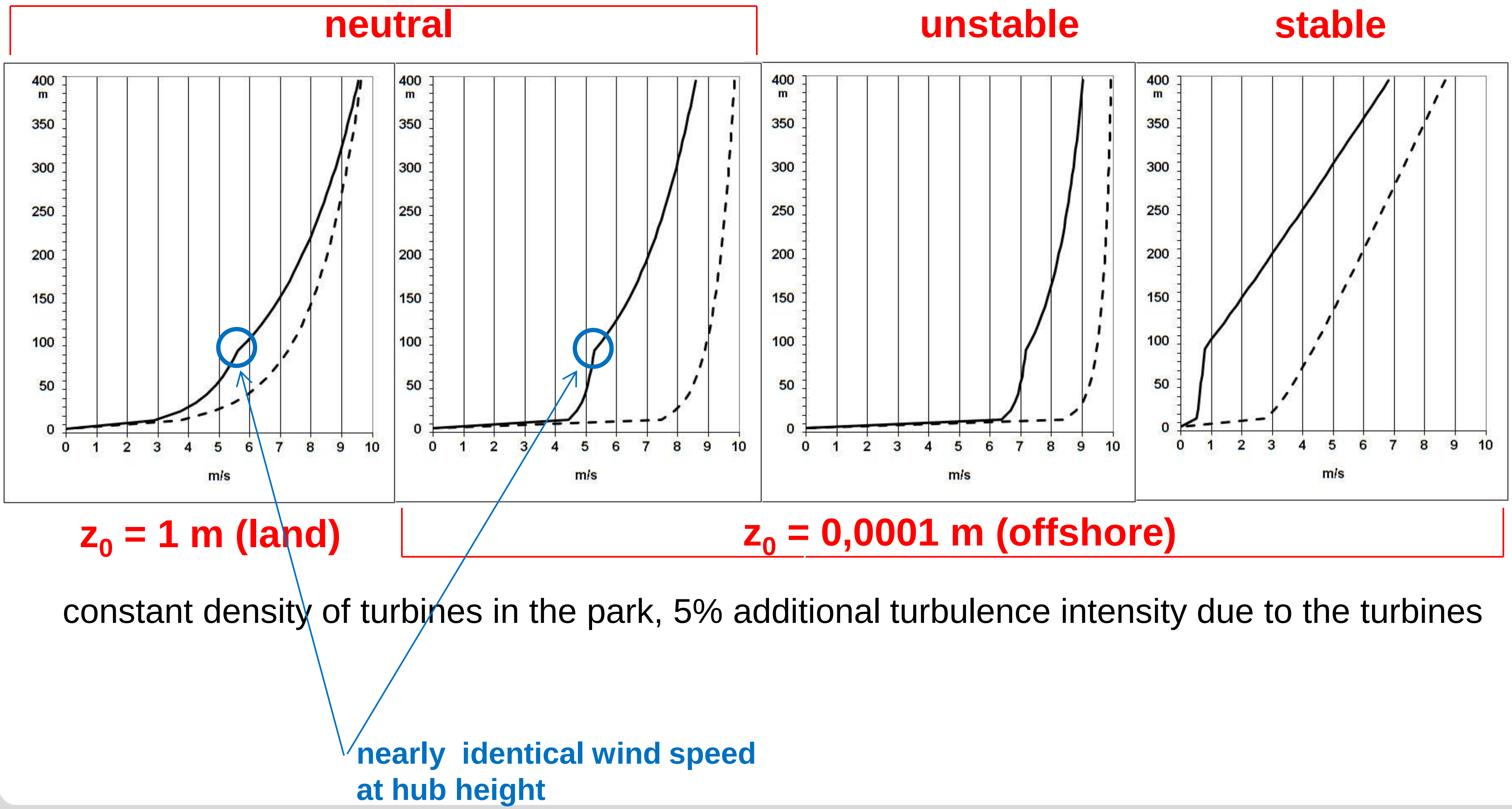


Barthelmie R, Frandsen ST, Rethore PE, Jensen L., 2007: Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm. Proceedings of the European Offshore Wind Conference, Berlin 4.-6.12.2007.

a) reduction of wind speed in the park interior

vertical wind profiles in the park ————————

and upstream (undisturbed) - - - - - - - - - - -



constant density of turbines in the park, 5% additional turbulence intensity due to the turbines

basic idea of the analytical model

b) speed-up of wind speed downstream of the 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

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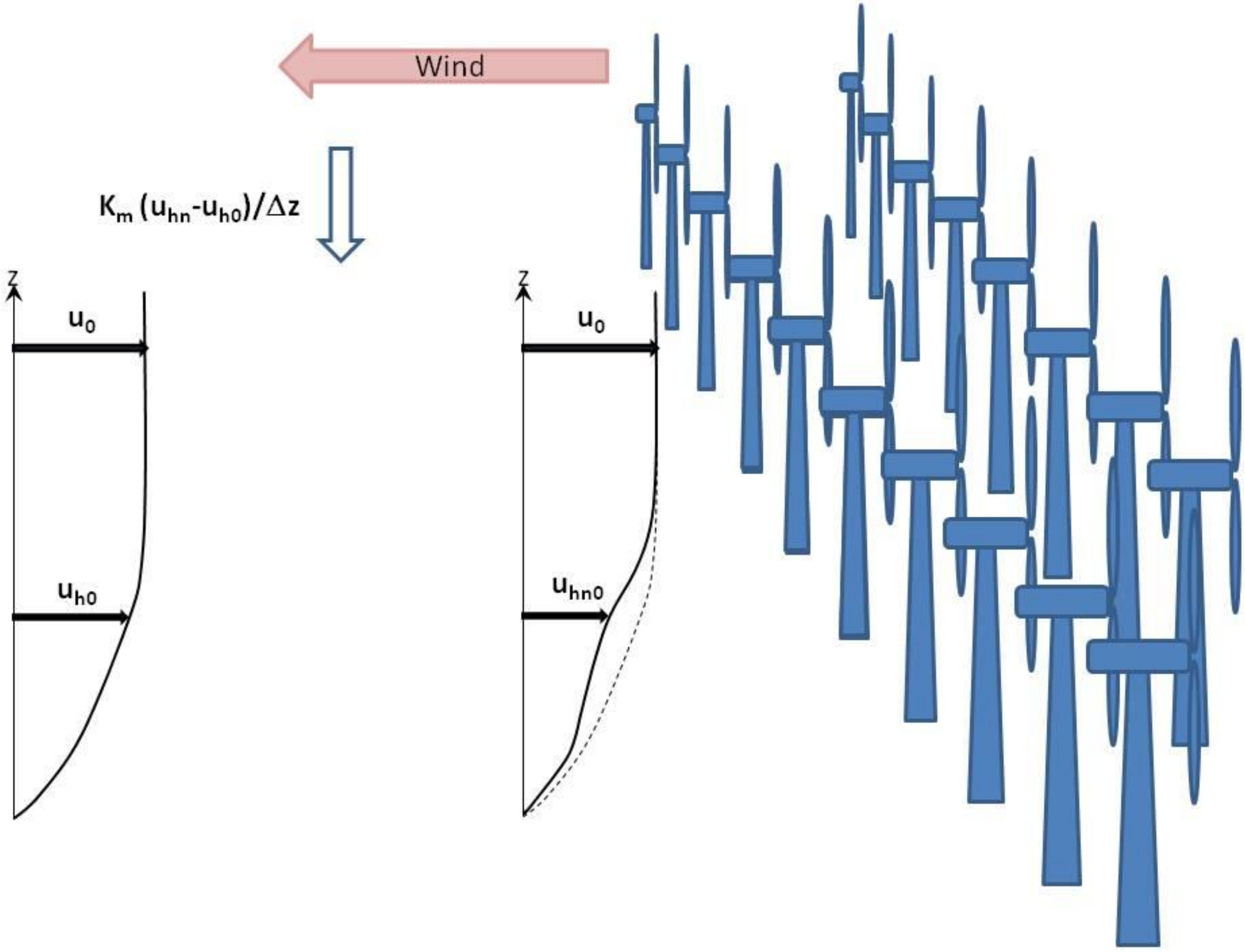
Wind
$K_m (u_{hn}-u_{h0})/\Delta z$
z
u_0
u_{h0}
z
u_0
u_{hn0}

solution of the analytical model

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b) speed-up of wind speed downstream of the wind park:

momentum extraction by the turbines

surface roughness

thermal layering of the PBL

turbine-induced turbulence

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

b) speed-up of wind speed behind the wind park

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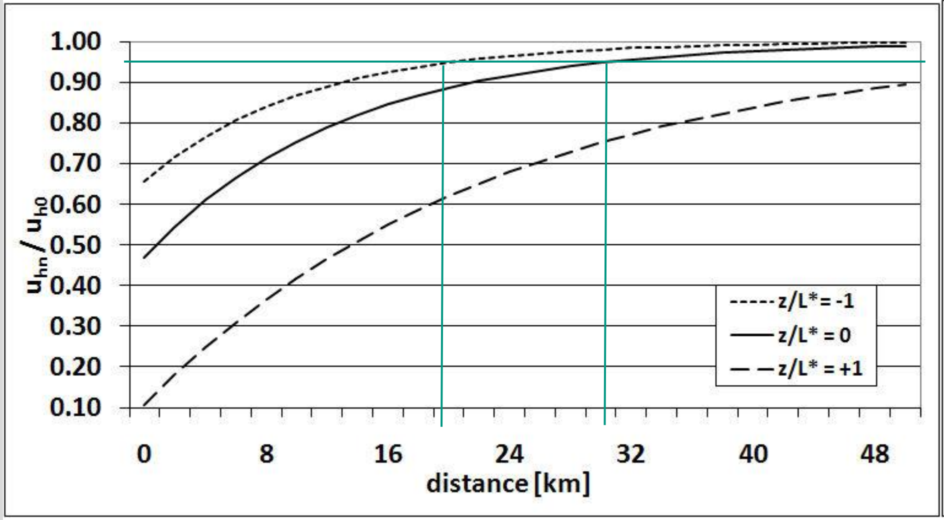
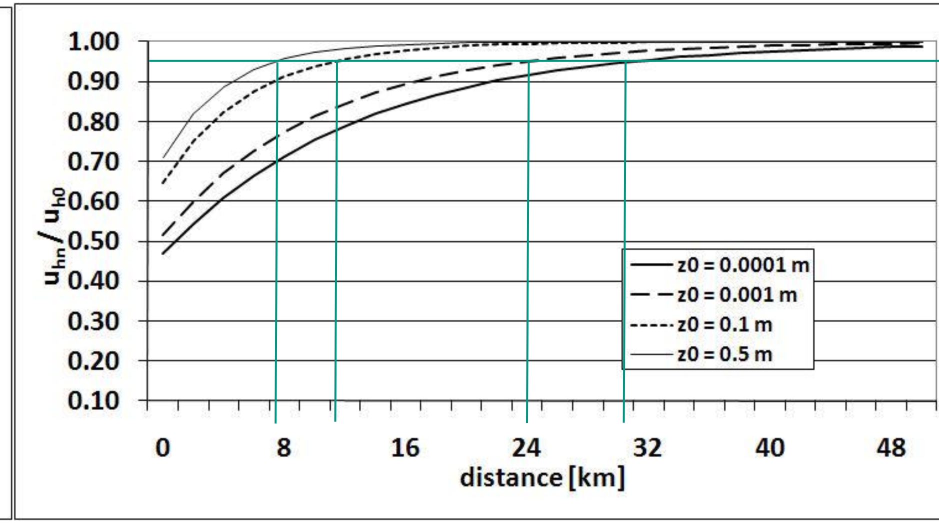
turbine-induced turbulence = 0.00

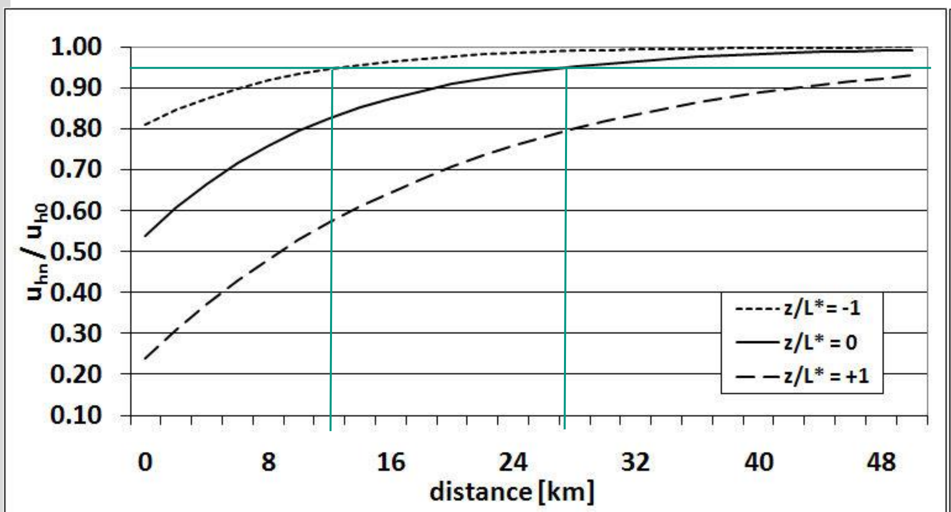


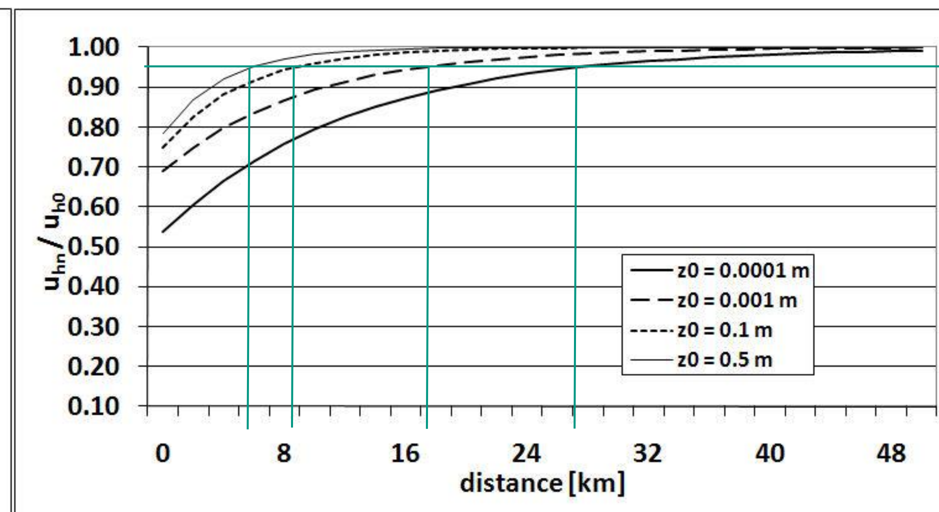


z_0 = 0.0001 m

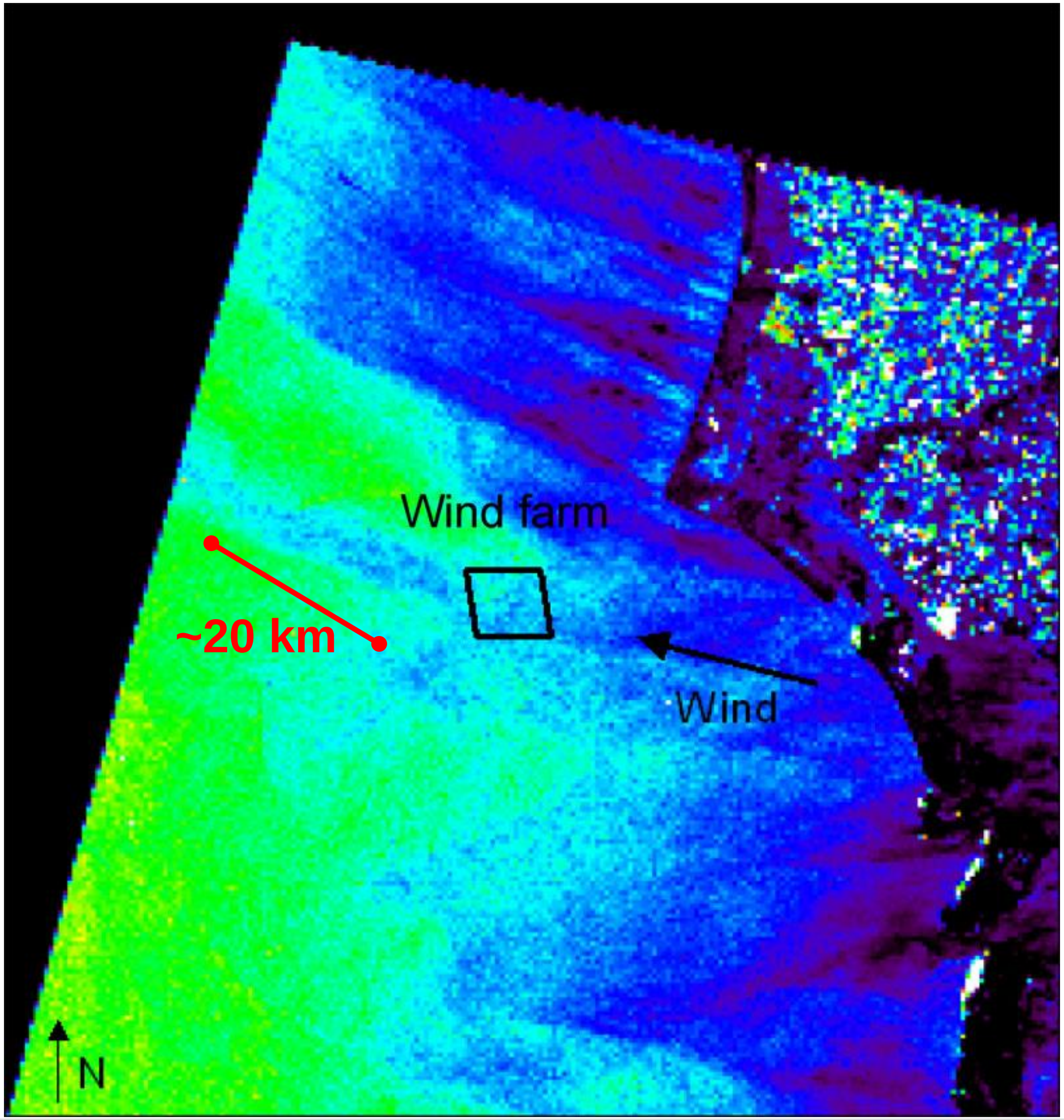
turbine-induced turbulence = 0.10

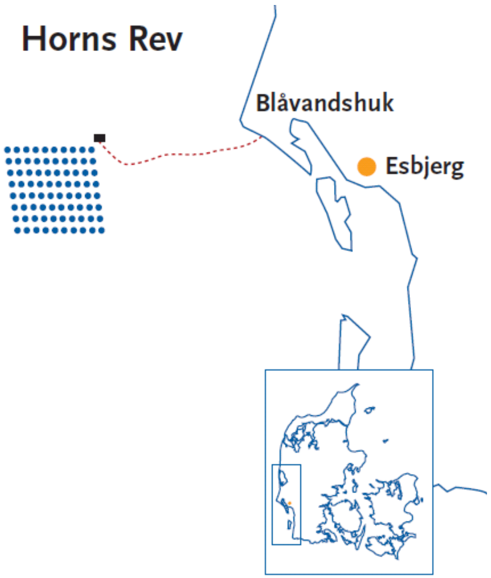
neutral





b) 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

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

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 three to four times larger than onshore

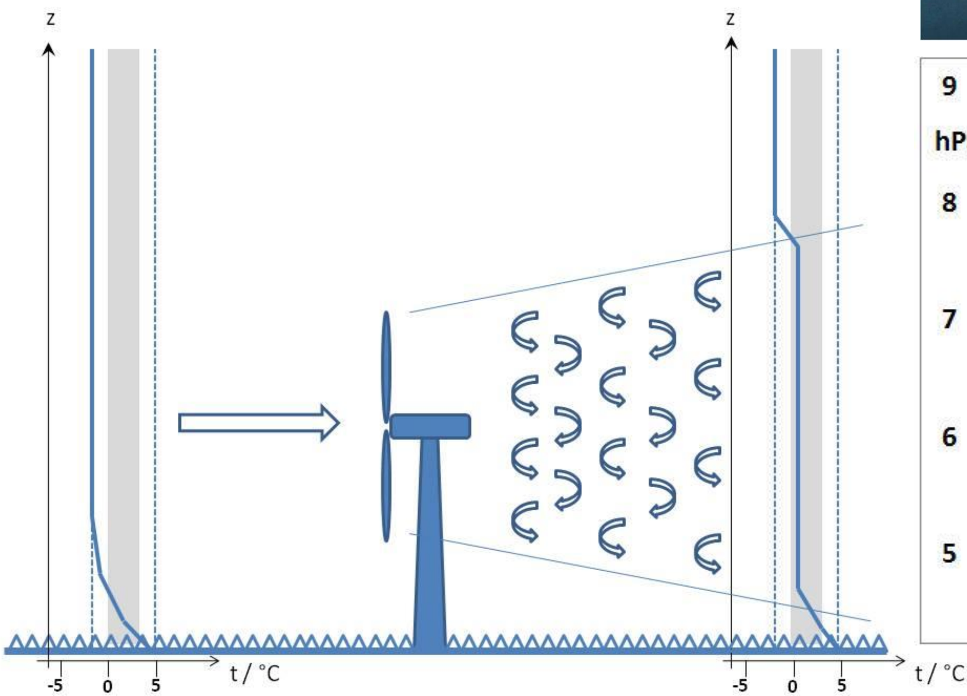
➔ offshore requires larger distances between wind parks

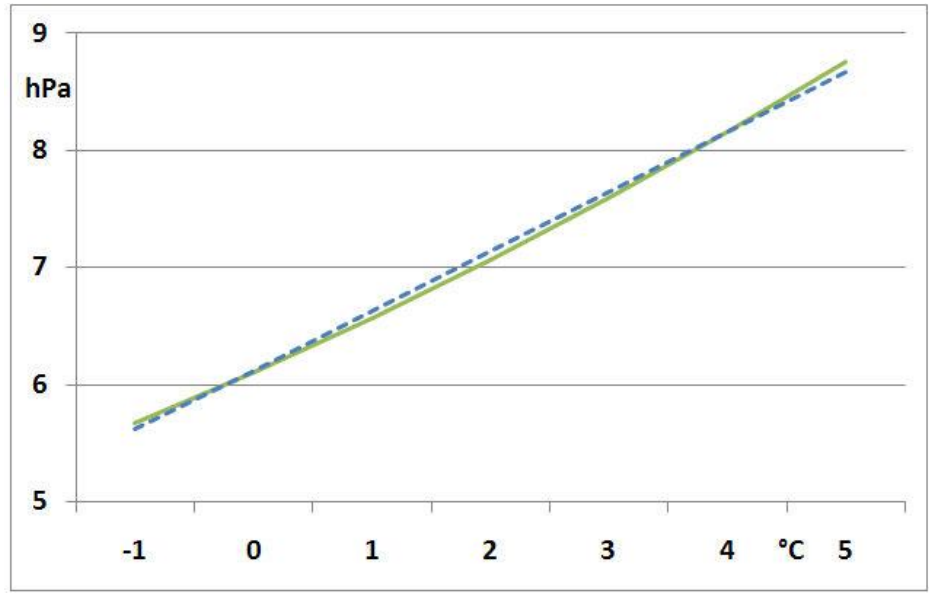
analytical model is strongly simplified

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

explanation of wake clouds:
mixing fog
(see poster outside!)

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