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The Physics of Wind Park Optimization

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Photo: Vattenfall/C. Steiness

Energy from the wind

$$P \leq \frac{16}{27}\frac{1}{2}\rho A v^3$$

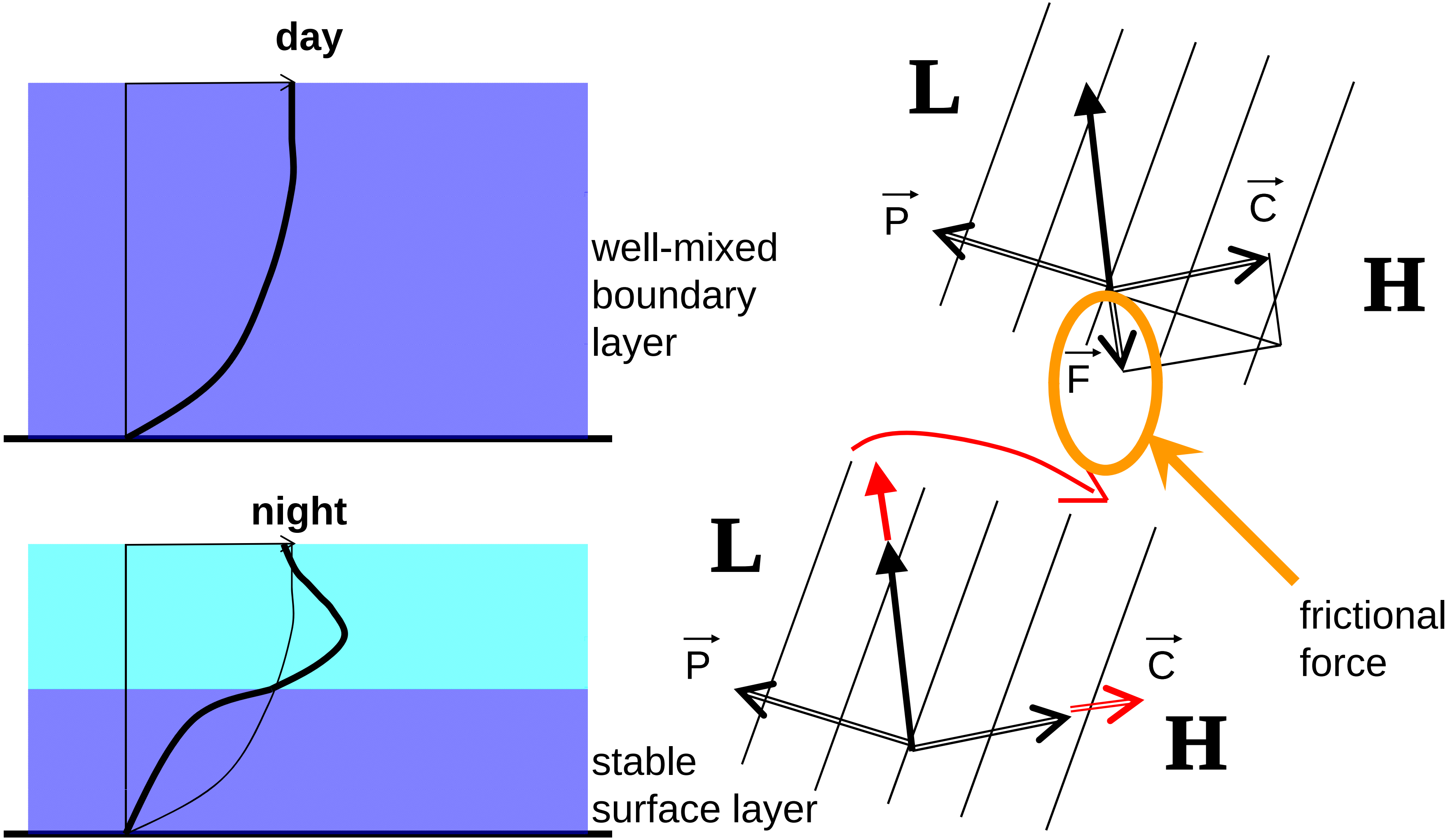
P	**power**	**W**
ρ	**air density**	**kg m^{-3}**
A	**rotor area**	**m^{2}**
v	**wind speed**	**m s^{-1}**
16/27	**Betz' factor**	**-**

but is it this simple? …

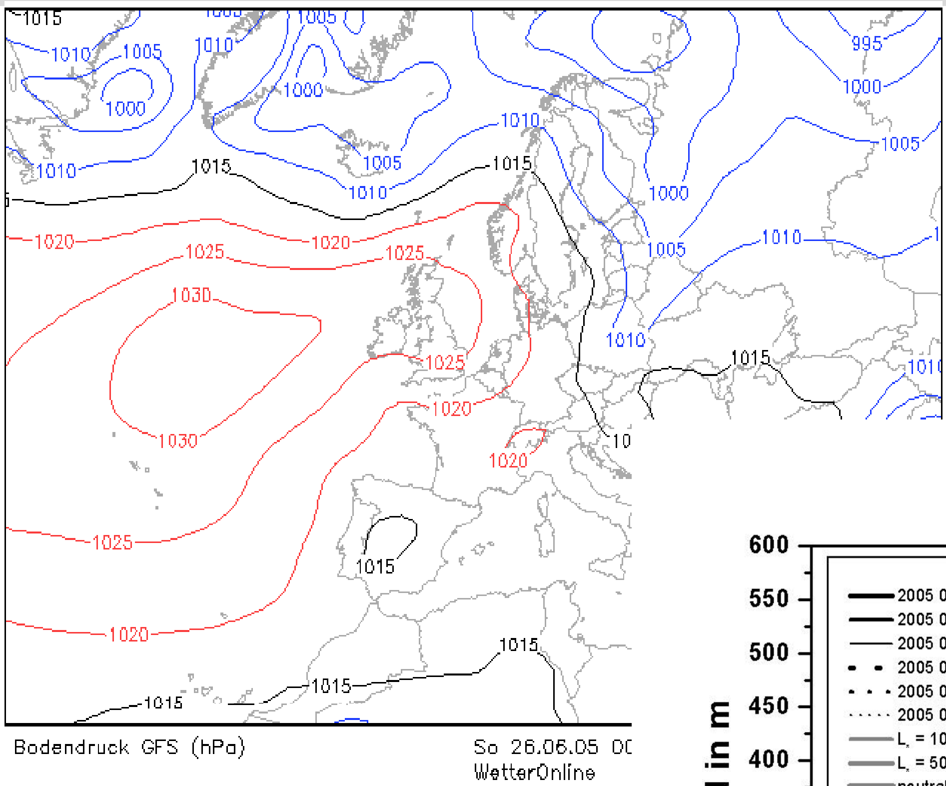
Meteorological phenomena effecting energy generation from the wind (yields and loads)

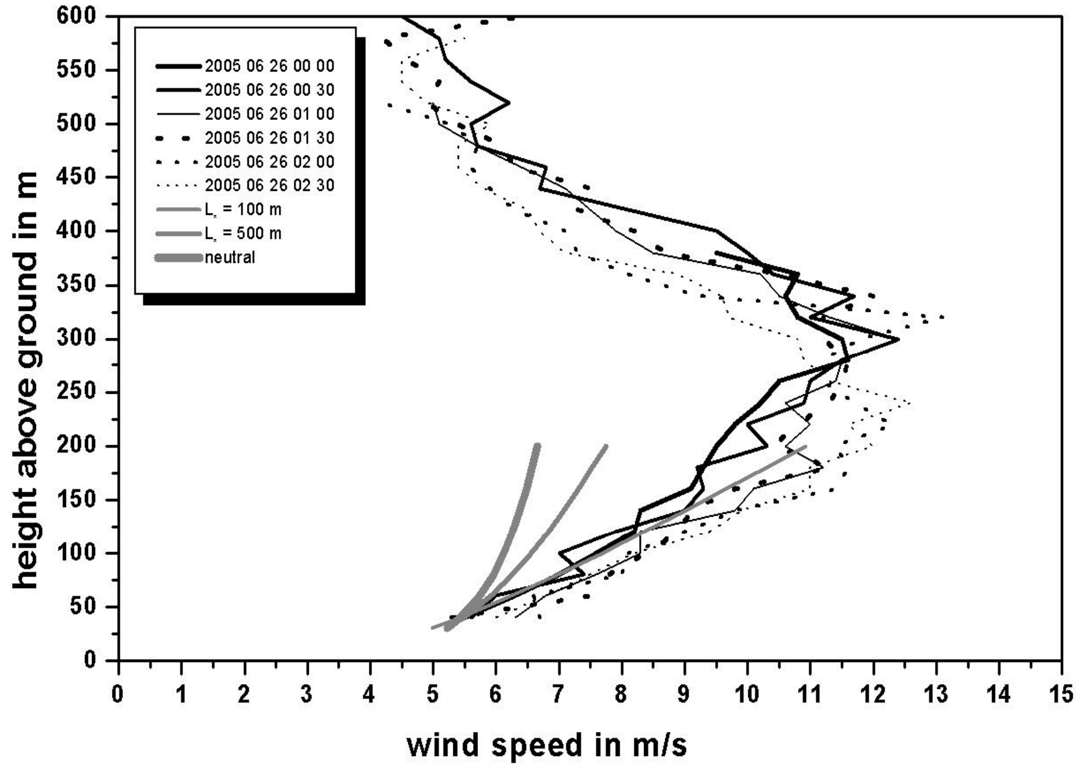
phenomenon	effect on yield	effect on loads
vertical wind profile	increase with growing hub height	increase with growing hub height
shear layers (inversions)		differential loads
low-level jets	nocturnal maxima	nocturnal maxima
extreme winds	shut-down of turbines	extreme loads, immediate damages
turbulence intensity	higher yields reduced wake lengths	higher loads
turbulence profile with height		differential loads

Nocturnal low-level jet (LLJ) and turning of wind direction with height (northern hemisphere)

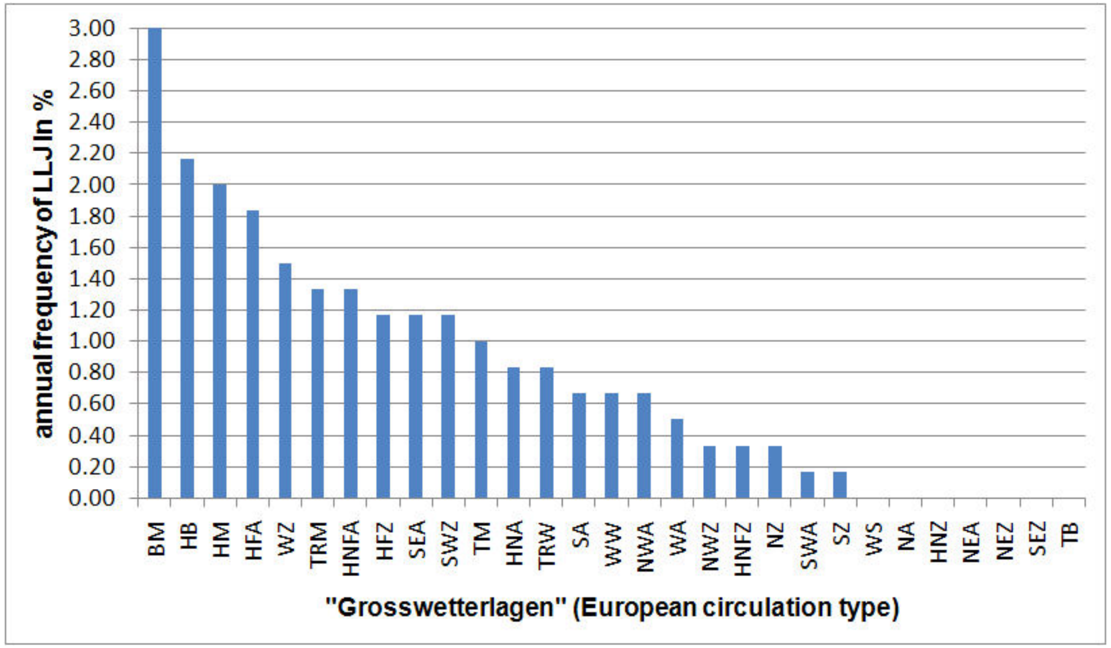


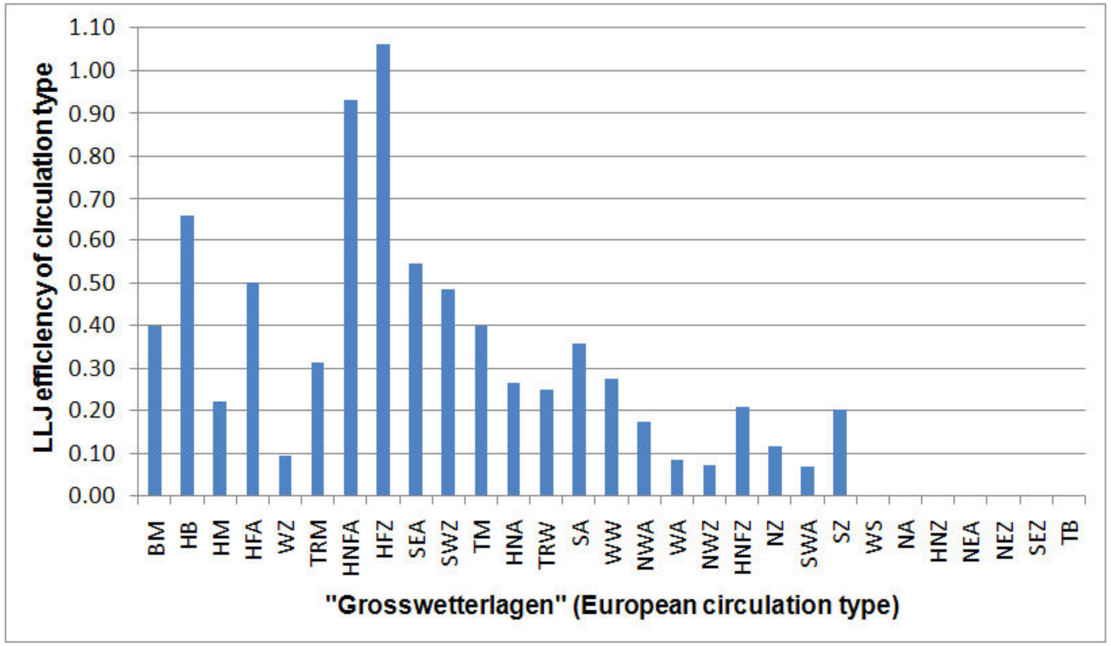
LLJ





26 June 2005
Paris, Ch. de Gaulle airport
SODAR measurements





frequency of LLJ over Hanover for 20 months in the years 2001 to 2003

total is 23.17% of all nights

circulation types:

BM ridge over Central Europe
HB high over British Isles
HM high over Central Europe
...

HFZ high over Scandinavia
HNFA high over North Atlantic
...

"efficiency" of a circulation type to produce a LLJ over Hanover for 20 months in the years 2001 to 2003

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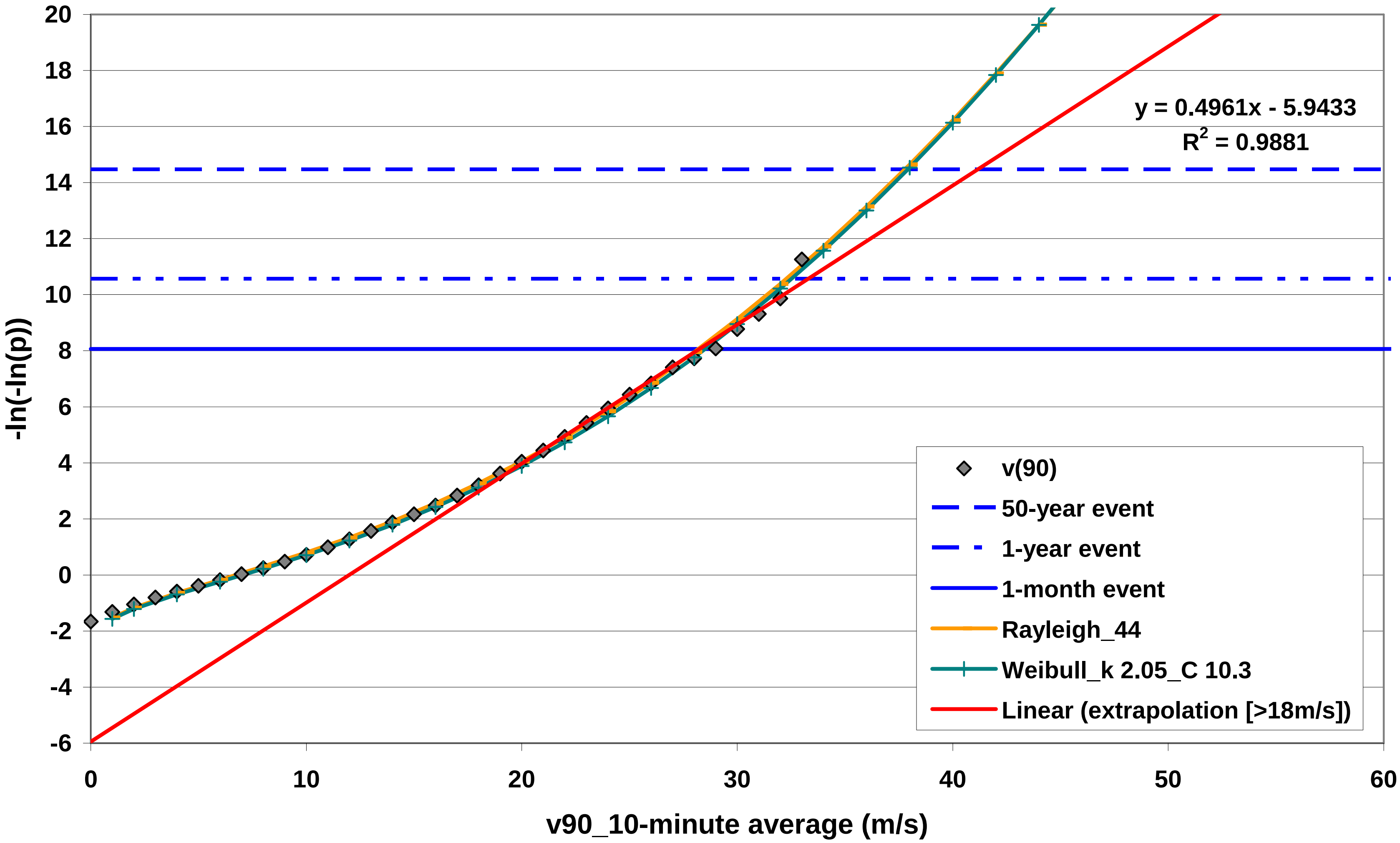
10 min extreme wind speed at FINO1



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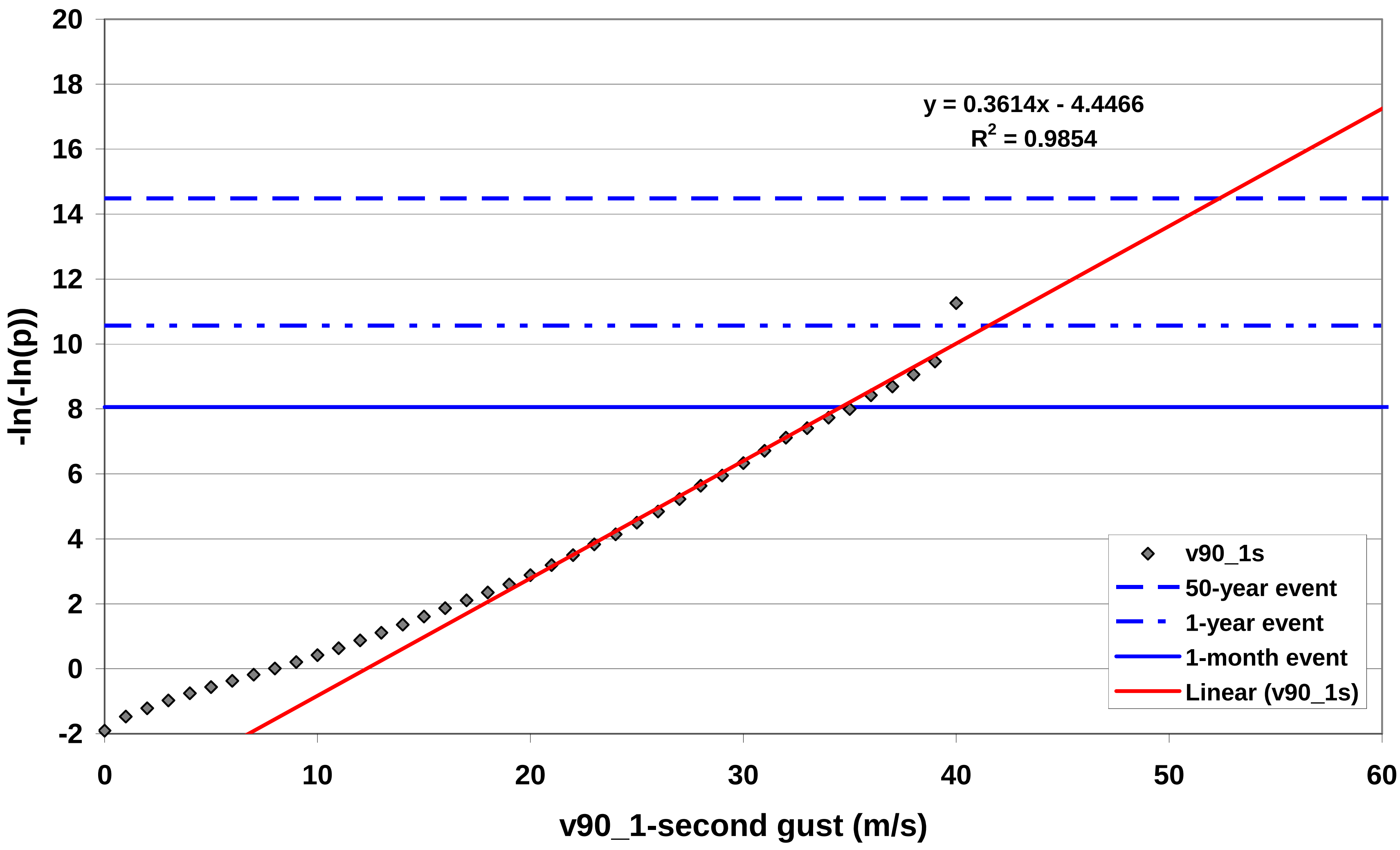
1 sec extreme wind speed at FINO1



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extreme winds **shut-down of turbines** **extreme loads, immediate damages**

This turbine has been damaged by gale force winds in Northern Germany in February 2011

➔forecasts of extreme wind conditions important

Photo: dpa, Hamburger Abendblatt, February 6, 2011
http://www.abendblatt.de/region/article1778907/Niedersachsen-duchgewirbelt-Feuerwehr-im-Dauereinsatz.html

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Wind parks

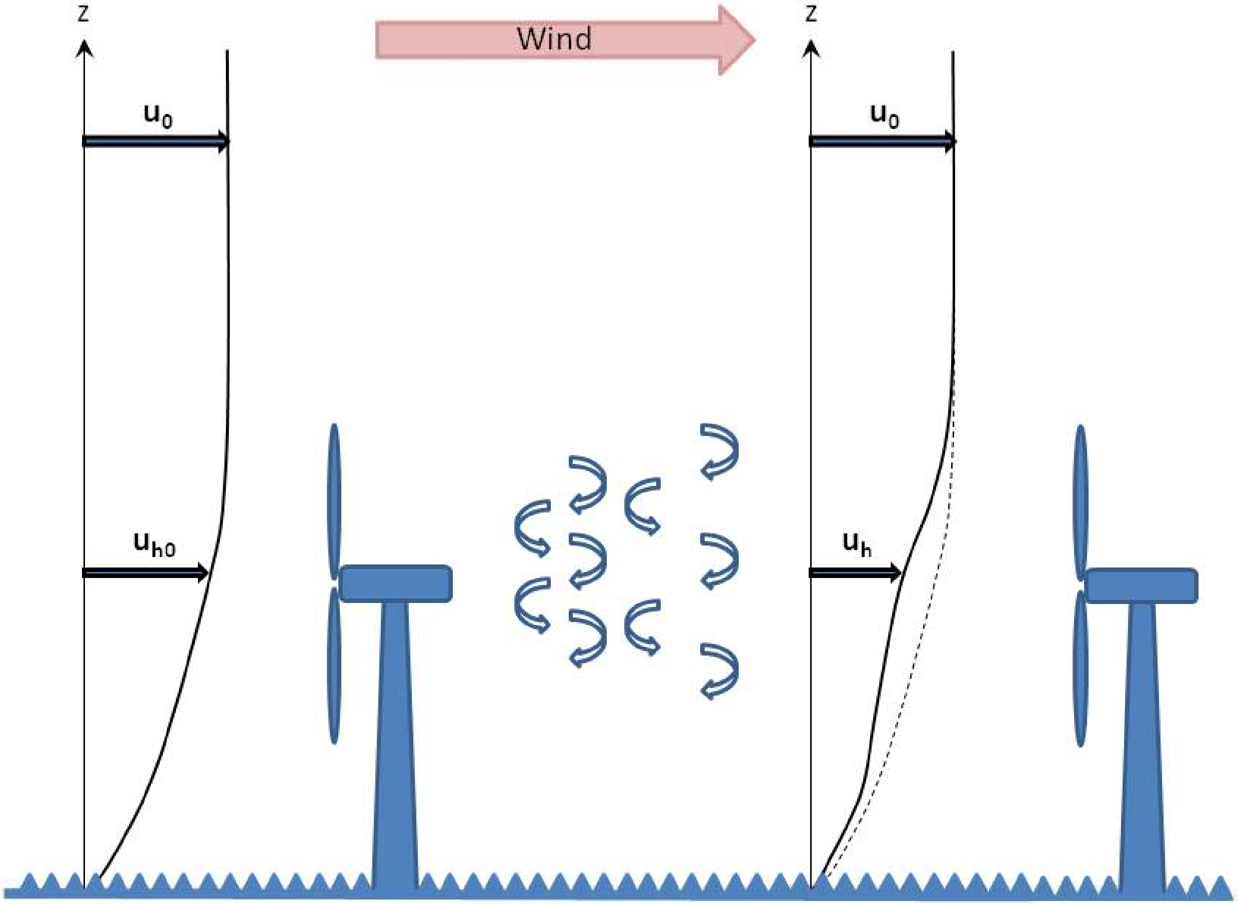
what happens when turbines are close together? …

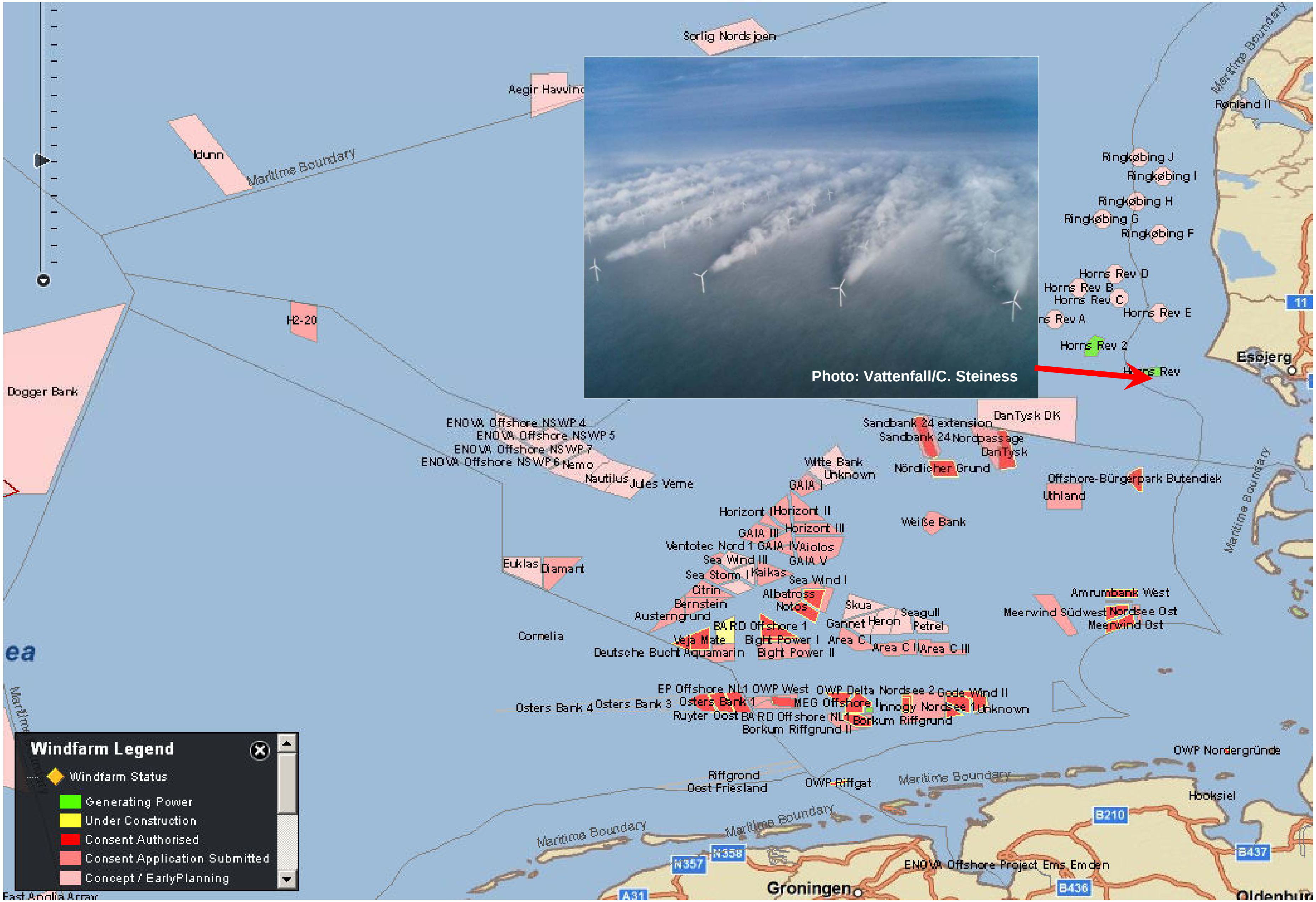
wake formation behind a wind turbine

- 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**

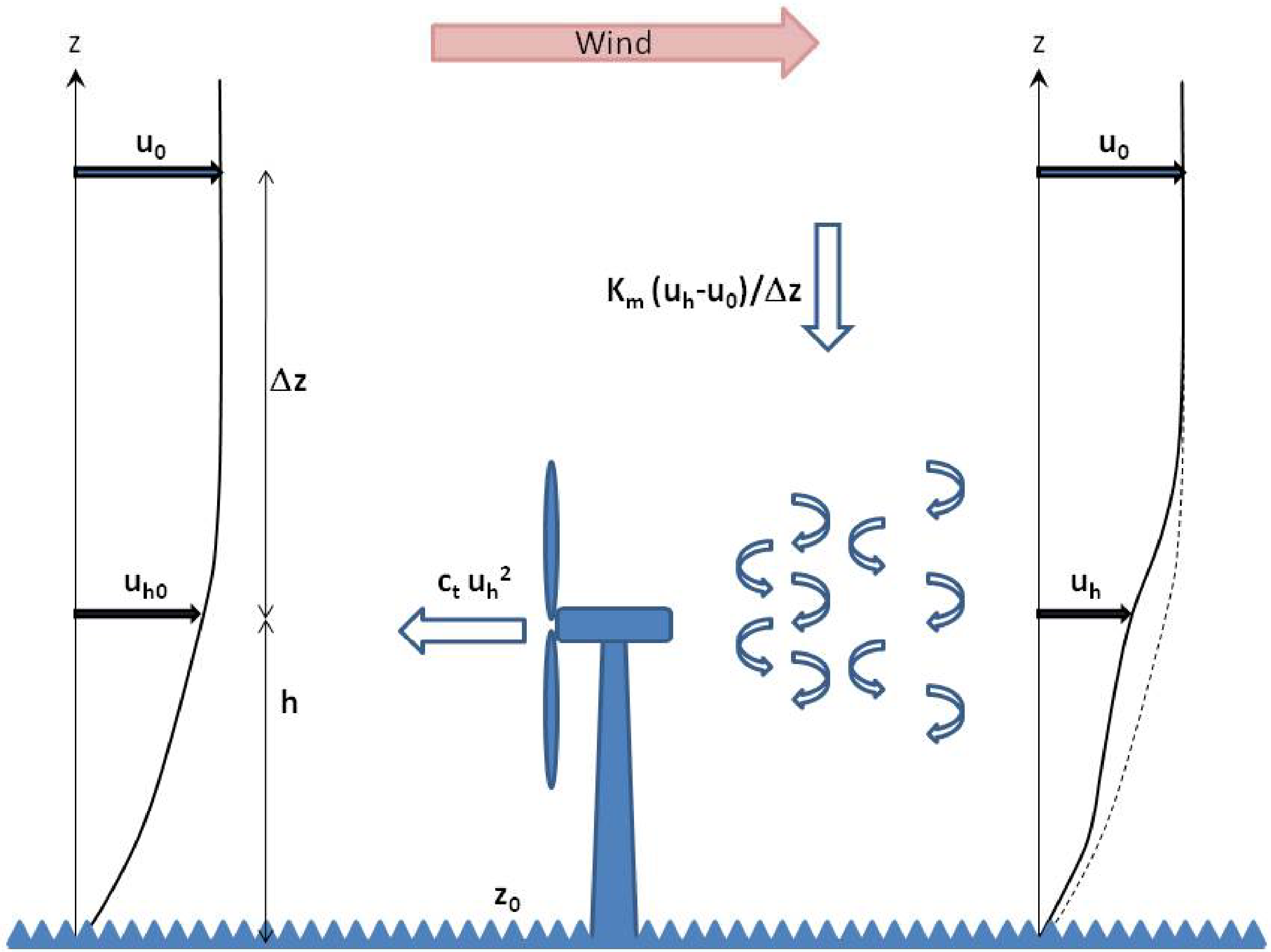
- equilibrium between extraction and re-supply of momentum

➔ **(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
Km (uh-u0)/Δz
Δz
uh0
ct uh2
uh
h
z0

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

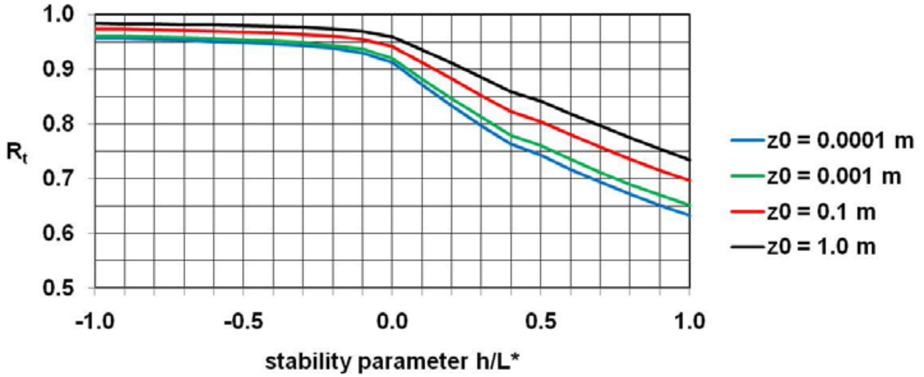
thermal layering of the PBL

turbine-induced turbulence

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

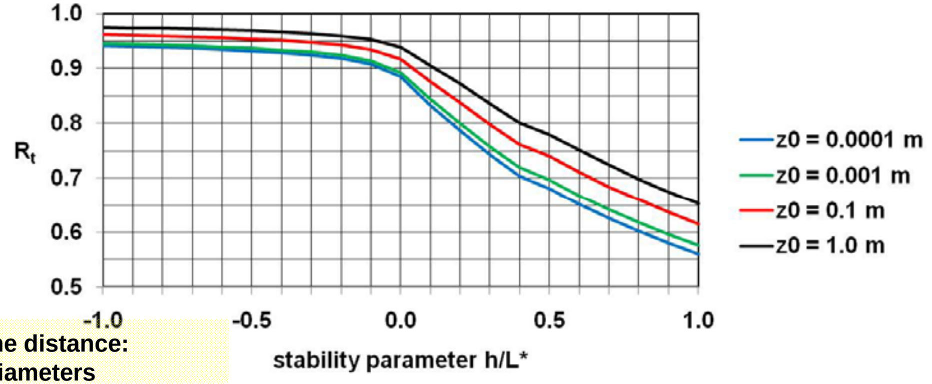
Emeis, S., 2010: A simple analytical wind park model considering atmospheric stability. Wind Energy, 13, 459-469.

reduction of wind speed in the park interior



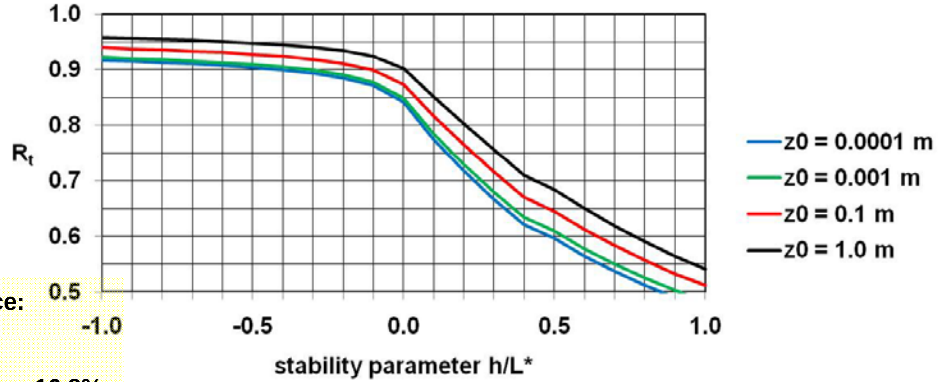
mean turbine distance:
10 rotor diameters

➔ turbine-induced turbulence 10.1%



mean turbine distance:
8 rotor diameters

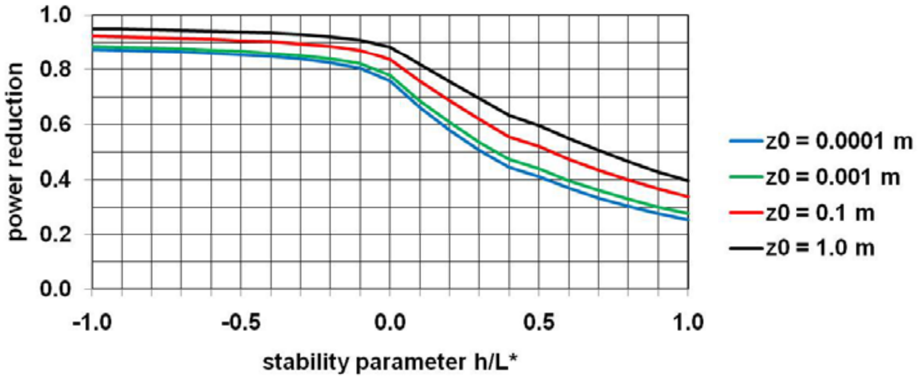
➔ turbine-induced turbulence 12.6%



mean turbine distance:
6 rotor diameters

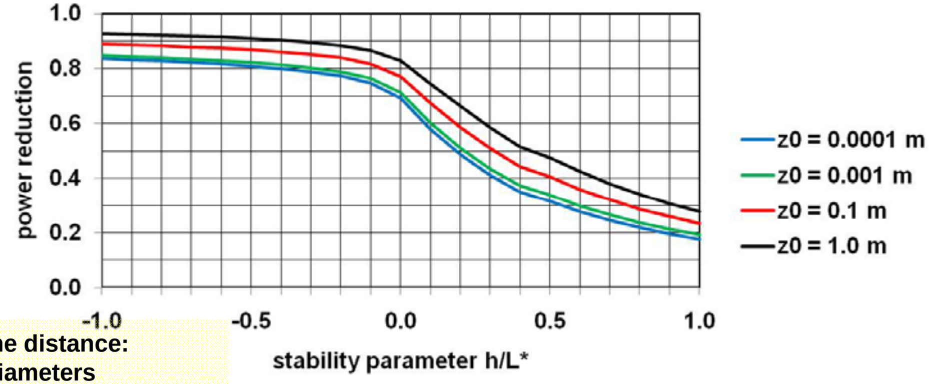
➔ turbine-induced turbulence 16.8%

reduction of wind power in the park interior



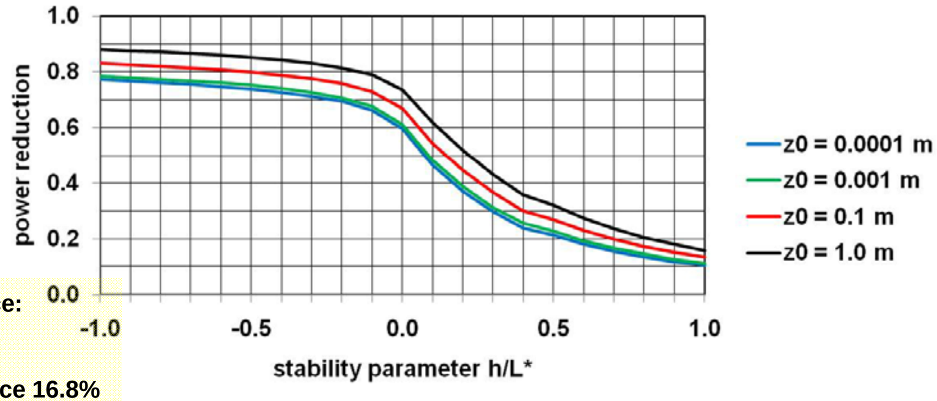
mean turbine distance:
10 rotor diameters

➔ **turbine-induced turbulence 10.1%**



mean turbine distance:
8 rotor diameters

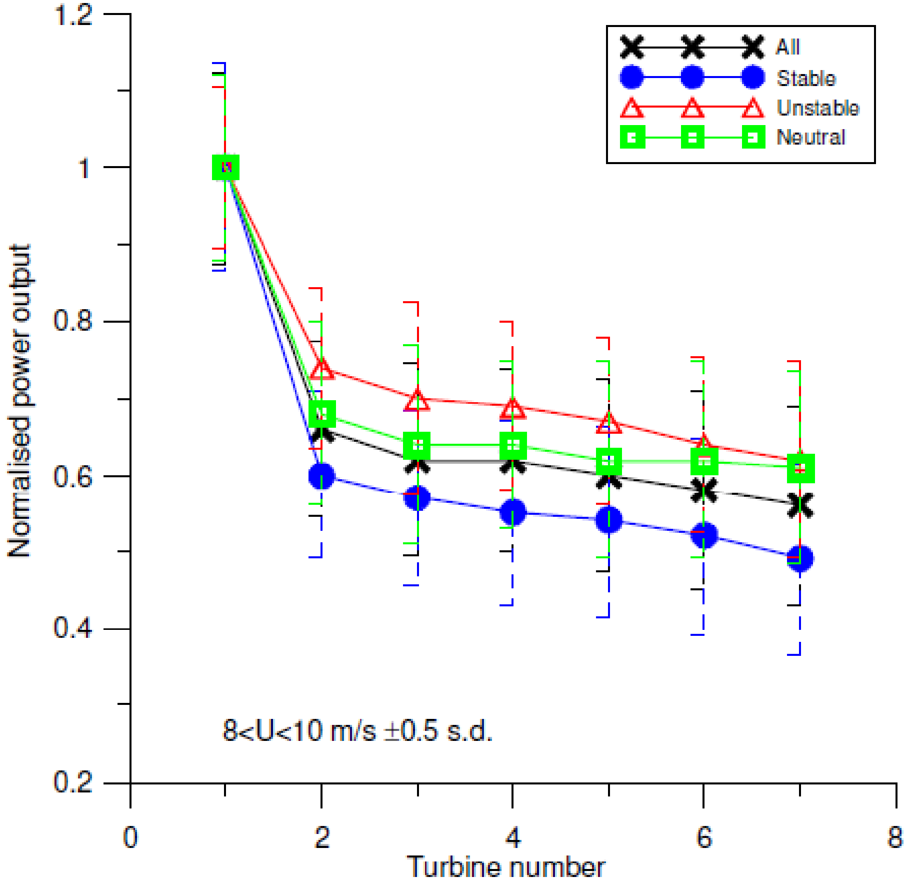
➔ **turbine-induced turbulence 12.6%**



mean turbine distance:
6 rotor diameters

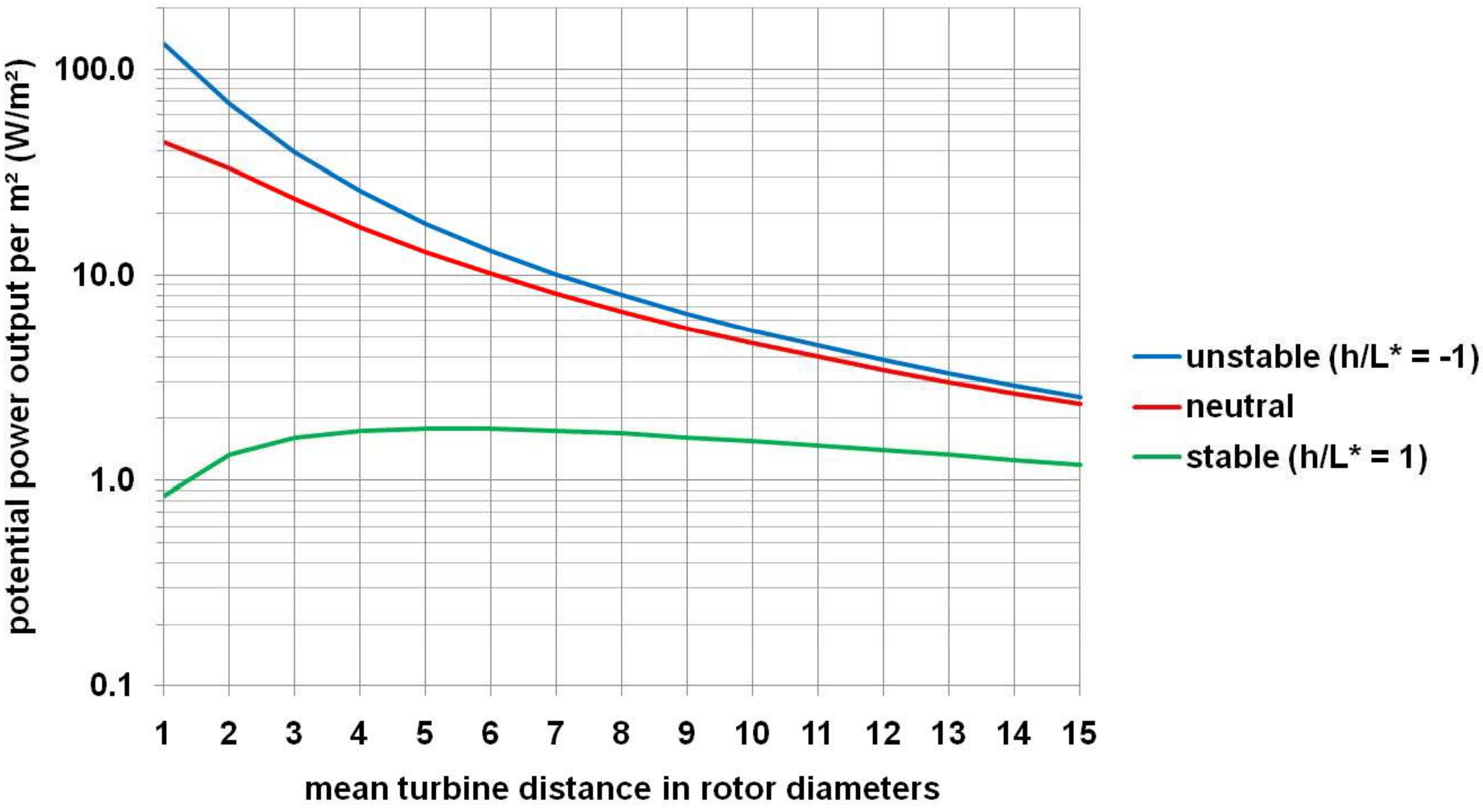
➔ **turbine-induced turbulence 16.8%**

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

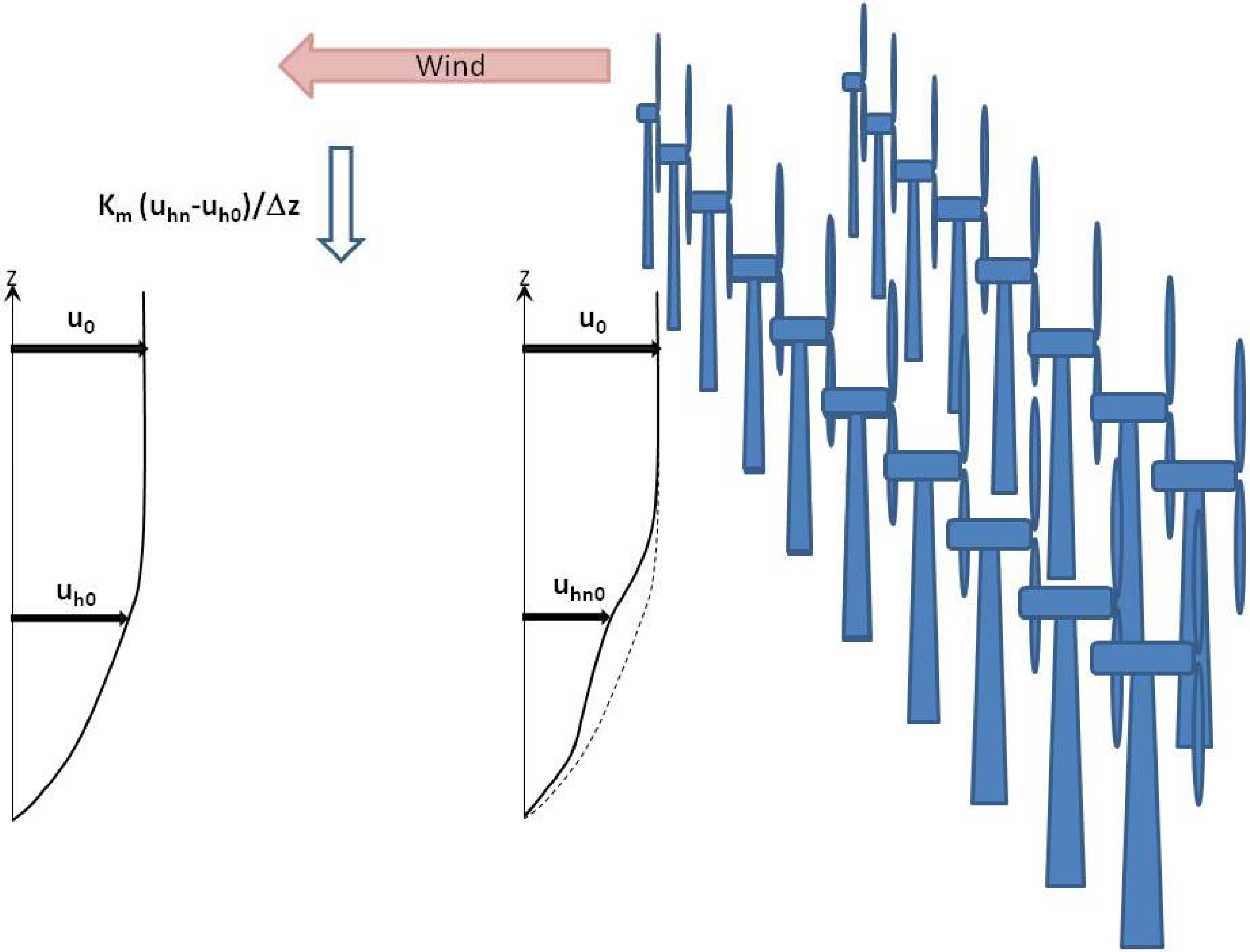


Barthelmie R, Frandsen ST, Rethore PE, Jensen L., 2007: Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm. Proceedings of the European Offshore Wind Conference, Berlin 4.-6.12.2007.

Optimization of turbine density in a wind park



2) the length of wakes


Wind
$K_m\,(u_{hn}\text{-}u_{h0})/\Delta z$
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

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

momentum extraction by the turbines

surface roughness

thermal layering of the PBL

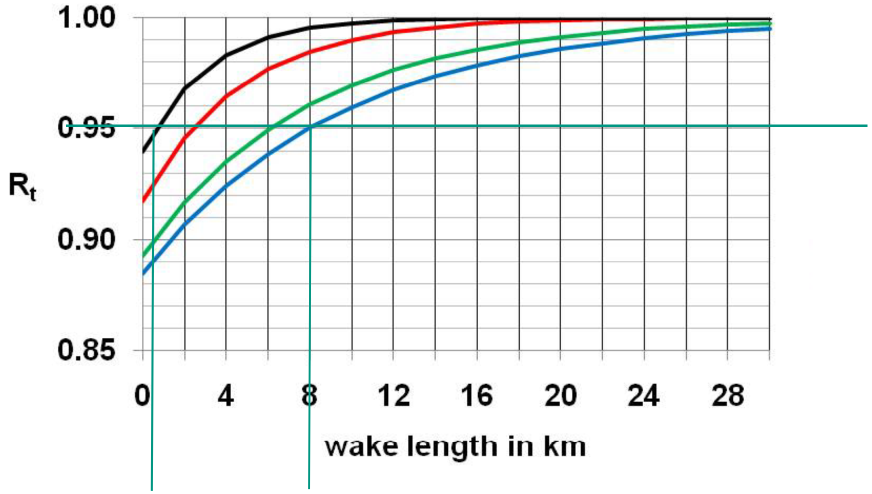
turbine-induced turbulence

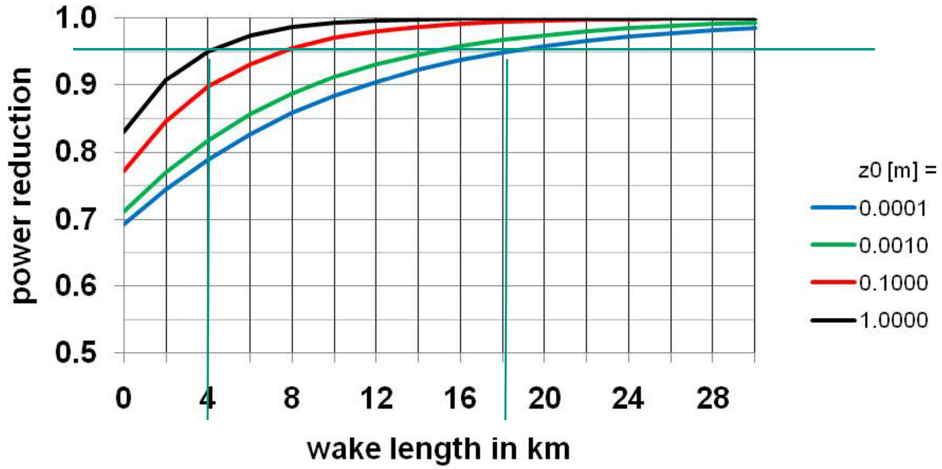
$$R_n = \frac{u_{hn}(t)}{u_{h0}} = 1 + \left(\frac{u_{hn0}}{u_{h0}} - 1 \right) \exp(-at)$$

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

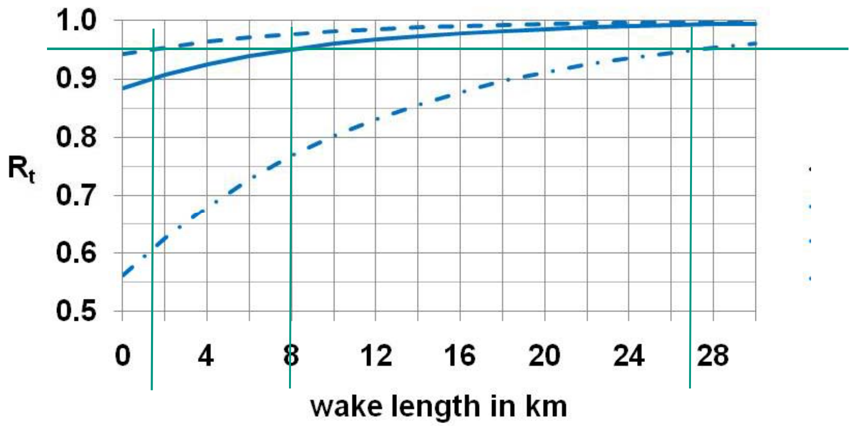
recovery of wind speed (left) and power (right) behind a wind park, mean turbine density: 8 rotor diameters

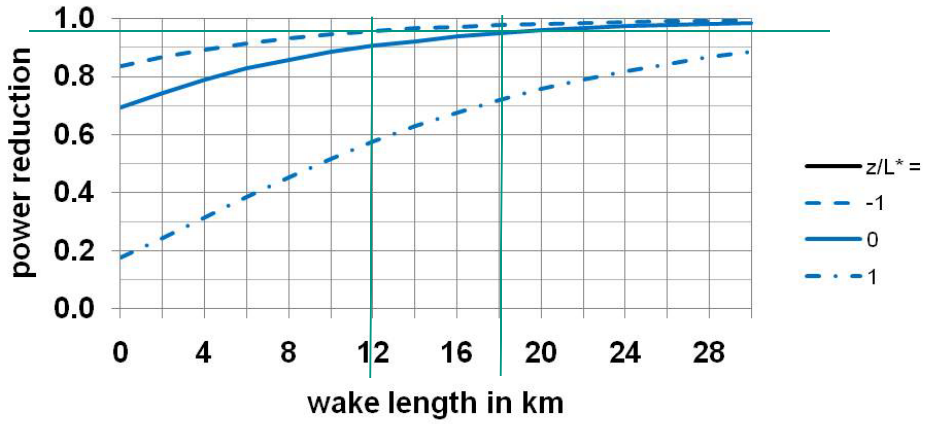
onshore (z_0 = 1.0 m) – offshore (z_0 = 0.0001 m)



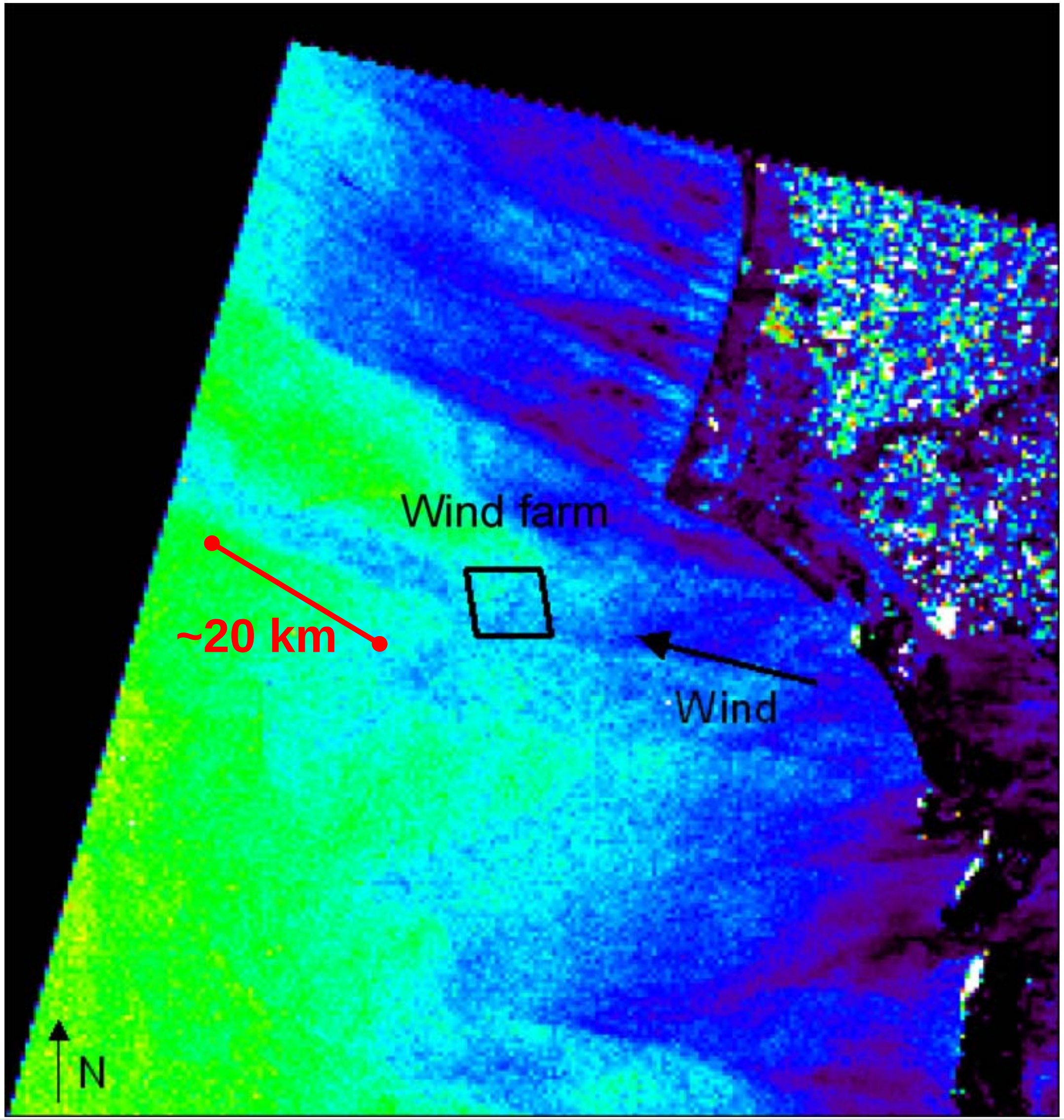


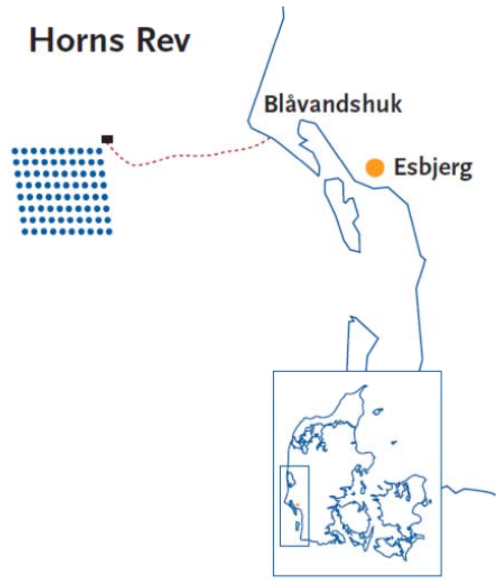
unstable (h/L_* = -1) – neutral – stable (h/L_* = 1)





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

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

Conclusions 1:

vertical wind profile important

- ➔ **higher hub heights lead to more power output**
- ➔ **nocturnal low-level jet frequency influences overall power output**
- ➔ **for large turbines (hub height more than 80-90 m), logarithmic or power wind profiles are too simple, turning of the wind becomes important, too**

extreme winds important

- ➔ **shut down of turbines**

turbulence important

- ➔ **higher power output**
- ➔ **higher loads**
- ➔ **reduced wake effects**

Conclusions 2 (wind parks):

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

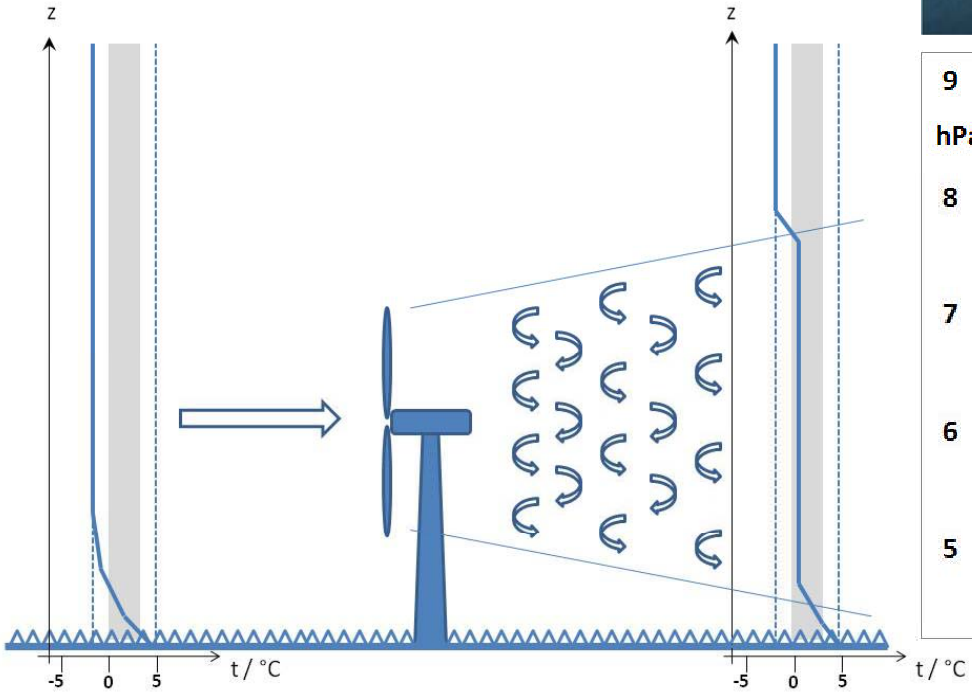
➔ offshore requires larger distances between wind parks

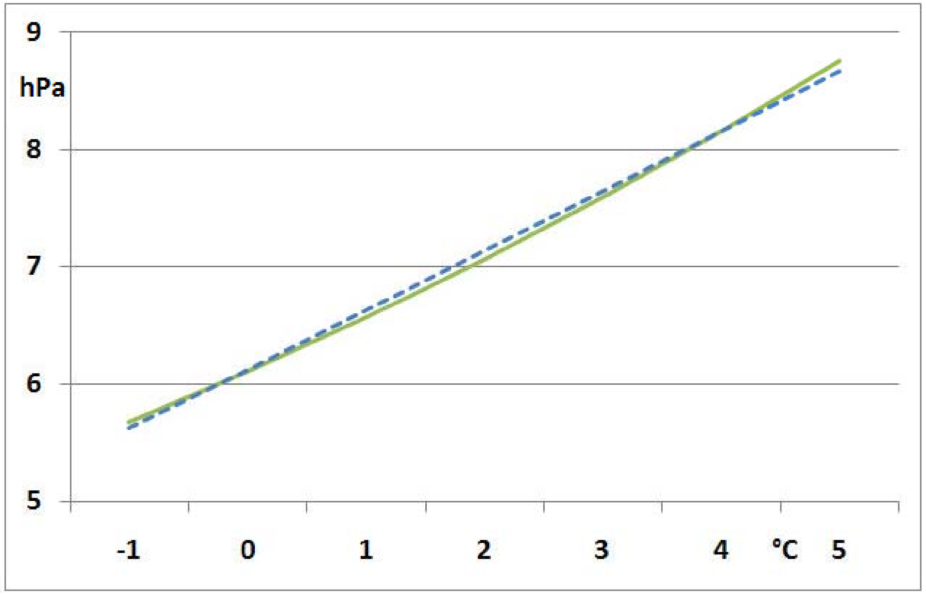
but, analytical model is strongly simplified

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

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