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? …
wake formation behind a wind turbine

- less wind speed
- more turbulence

ahead of the next turbine in a wind park
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
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

solution of the analytical model

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

\[
R_t = \frac{\left( f_{h,\Delta z} T_i + \frac{\phi_m}{K^2} C_{s,h} \right)}{\left( f_{h,\Delta z} T_i + \frac{\phi_m}{K^2} C_{teff} \right)}
\]

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

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

Optimization of turbine density in a wind park

Potential power output per m² (W/m²) vs. mean turbine distance in rotor diameters.

- **Unstable** ($h/L^* = -1$)
- **Neutral**
- **Stable** ($h/L^* = 1$)
2) the length of wakes
\[ \frac{K_m(u_{hr} - u_{h0})}{\Delta z} \]
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

solution of the analytical model

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

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

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

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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)

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
explanation of wake clouds: mixing fog

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