Verification of an efficiency model for large wind farm clusters

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The issues/Data

- Wake losses within large offshore wind farms – predicted to be 5-15% on average
- State of the art models not designed for large wind turbine numbers
- Siting of multiple clusters – defining the optimal distance
- Model developed (Frandsen et al, EWEC 2004)

Horns Rev

- Vestas V80 2 MW h.h. 70 m
- 80 turbines (8x10)
- Distance 7 D

Middelgrunden

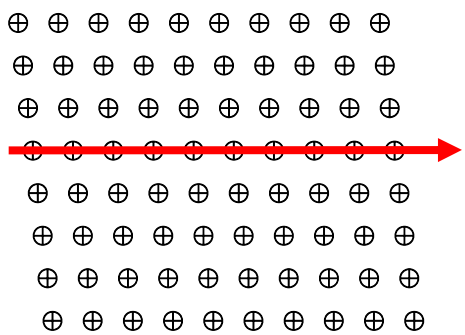
- Bonus 2 MW h.h. 67 m
- 20 turbines
- Distance 2.6 D

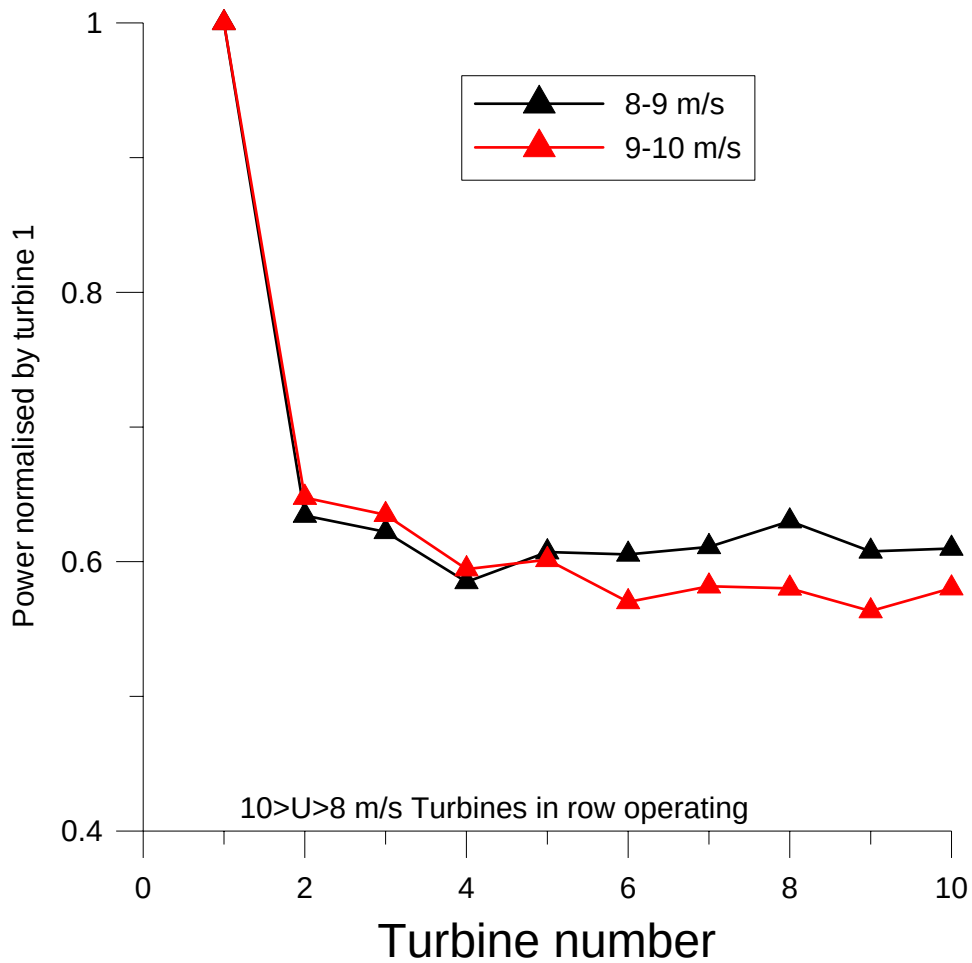
Nørrekær Enge

- Nordtank 300 kW h.h. 28 m
- 42 turbines
- Distance 7-8 D

Direct wakes

- All turbines in row operating
- Direction ±2.5°
- 8<U<10 m/s





Frandsen et al. (COW 2005)

Atmospheric stability definition

- Stability describes stratification of the atmosphere
- Use Monin-Obukhov length
- Ratio mechanically generated to buoyancy generated turbulence
- L > 0 stable

  (limited energy transfer)
- L < 0 unstable

  (convective conditions)
- | L | > 1000 neutral

$$U_z = \frac{u_*}{\kappa}\left[ln\frac{z}{z_0} - \Psi_m\left(\frac{z}{L}\right)\right]$$

$$L = -\left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{3/4} / \left(\kappa(g/\overline{\theta_v})(\overline{w'\theta_v'})\right)$$

$$L > 0 \quad \Phi_m = \frac{\kappa z}{u_*}\left[\left(\frac{\partial \overline{U}}{\partial z}\right)^2 + \left(\frac{\partial \overline{V}}{\partial z}\right)^2\right]^{1/2} = 1 + 4.7\frac{z}{L}$$

$$\Psi\left(\frac{z}{L}\right) = \frac{4.7z}{L}$$

$$L < 0 \quad \Phi_m = \frac{\kappa z}{u_*}\left[\left(\frac{\partial \overline{U}}{\partial z}\right)^2 + \left(\frac{\partial \overline{V}}{\partial z}\right)^2\right]^{1/2} = \left(1 - 15\frac{z}{L}\right)^{-1/4}$$

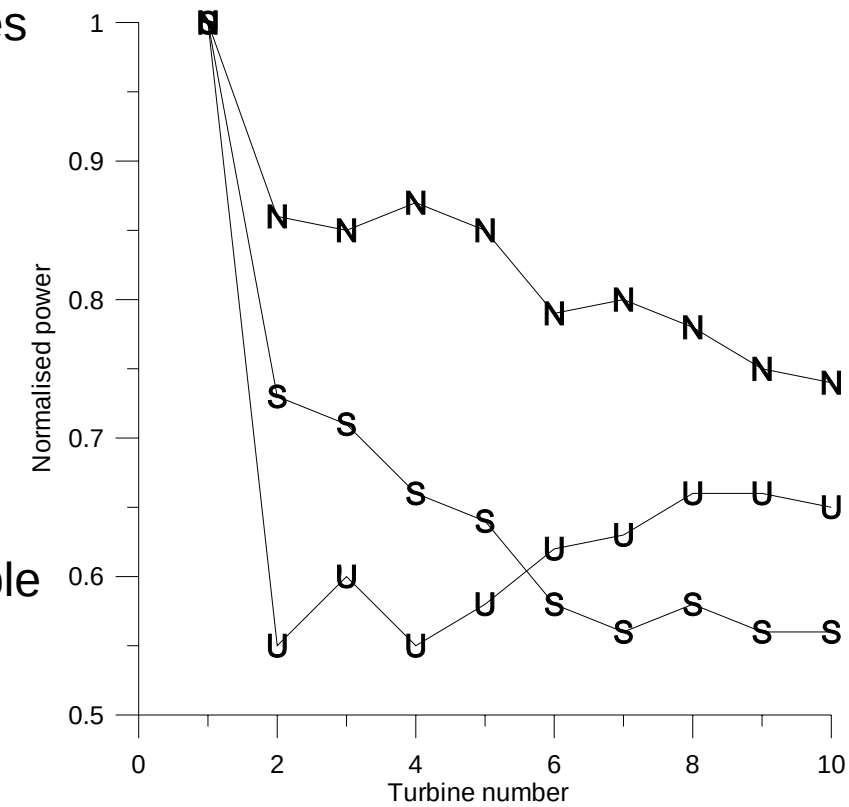
$$\Psi\left(\frac{z}{L}\right) = -2ln\left[\frac{(1+x)}{2}\right] - ln\left[\frac{(1+x^2)}{2}\right] + 2tan^{-1}(x) - \frac{\pi}{2}$$

$$where\ x = \left[1 - (15z/L)\right]^{-1/4}$$

Barthelmie et al. (MA 1998)

Stability impacts wake losses

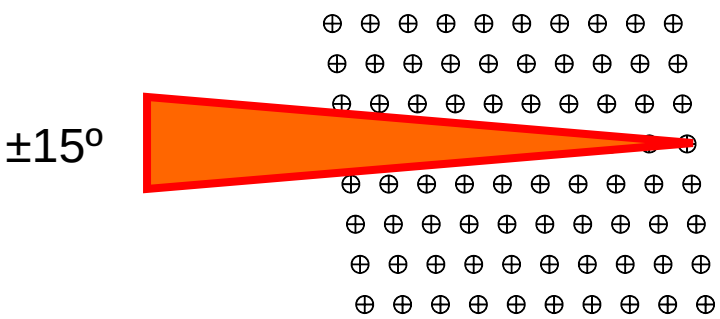
- Few unstable observations. Tendency is likely wake losses smaller.
- Stable conditions:
  - wake losses are larger
  - wakes persist over longer distances
- Important if conditions are frequently non-neutral at U>4m/s
- E.g. Middelgrunden 50% stable conditions

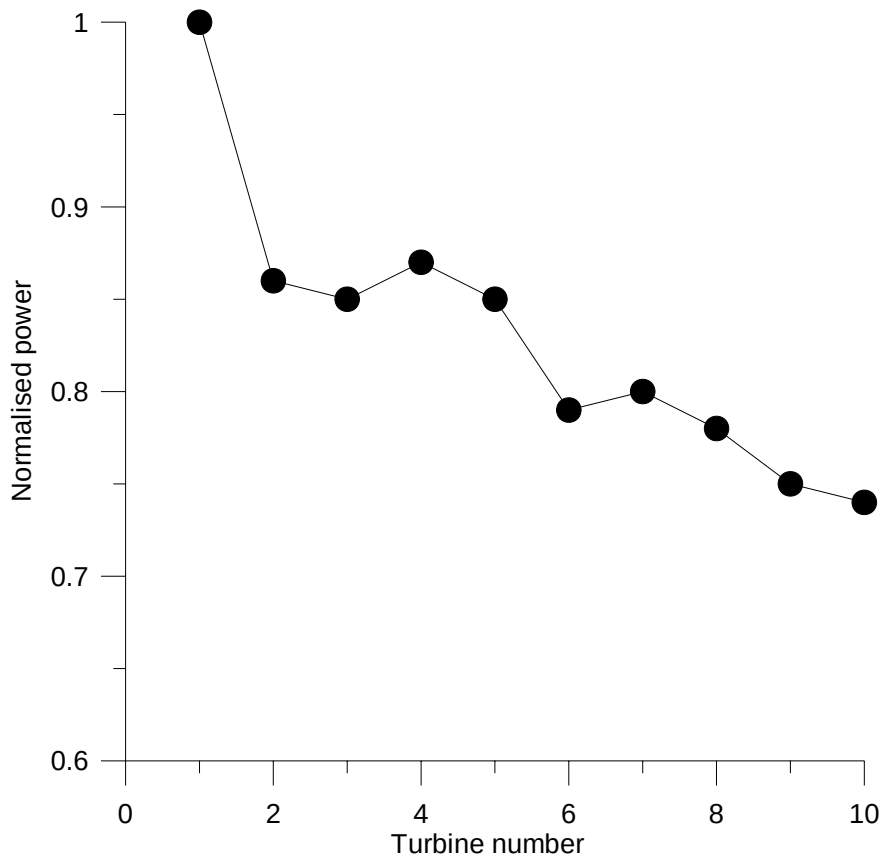


30º, 8-12 m/s, all row turbines operating

Indirect wakes

- As angle increases, power drop decreases
- So overall wake losses are a combination of direct and indirect wakes and are predicted to be 5-15%

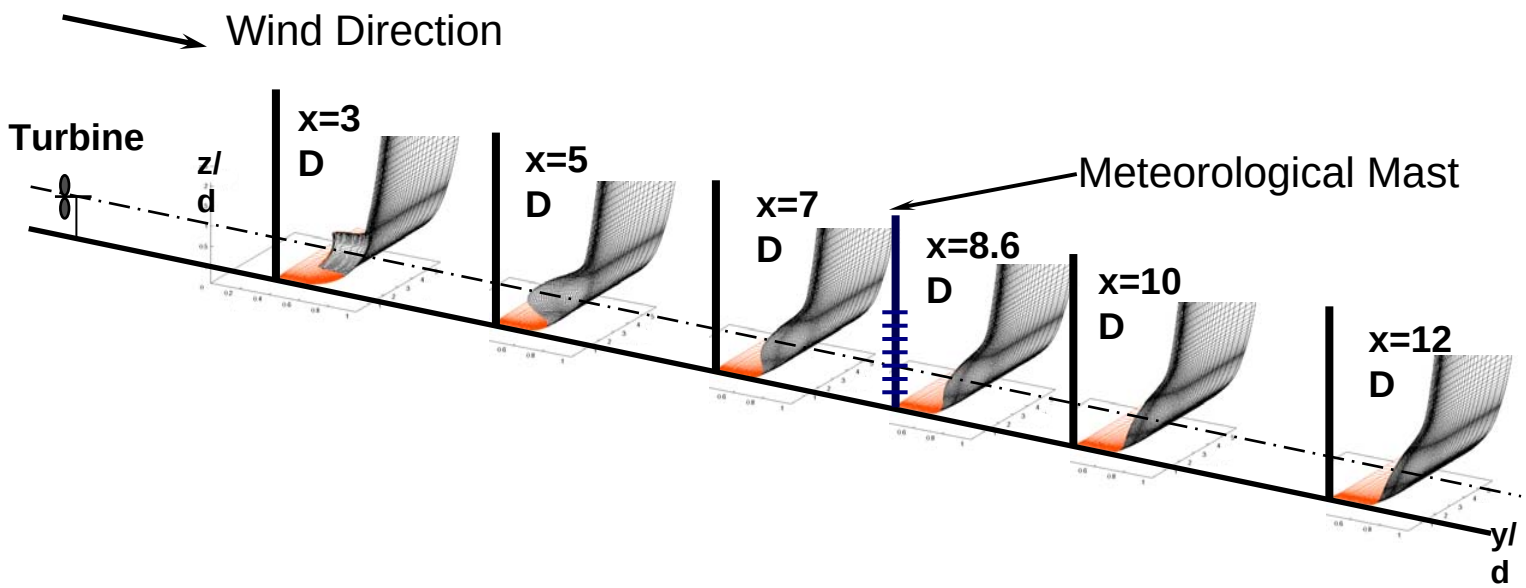




Frandsen et al. (COW 2005)

Wake models

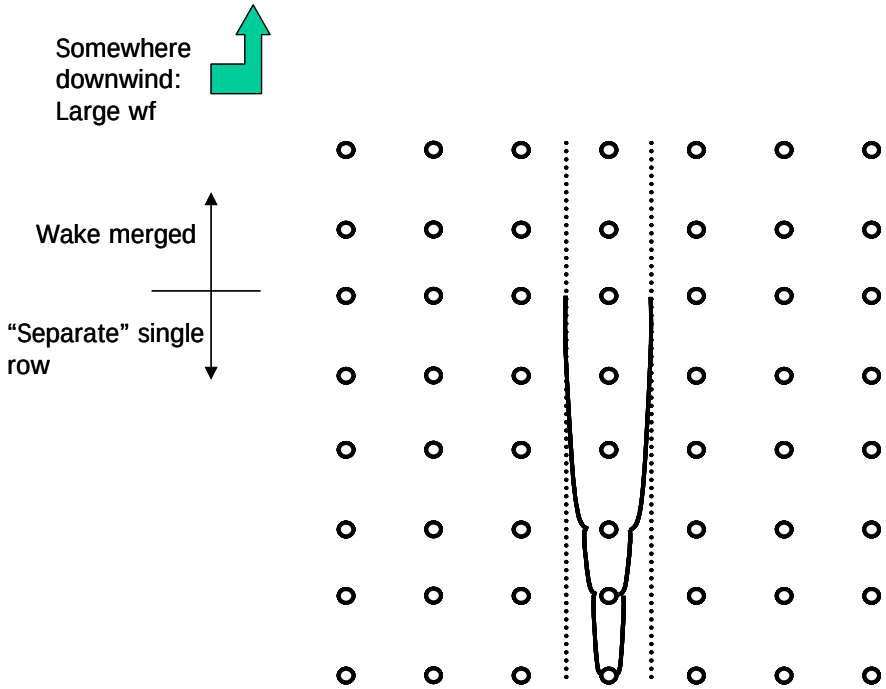
- Most developed in 1980's for single wakes over land
- Three types evaluated for offshore in ENDOW
  - CFD (HAWC, RGU & Windfarm)
  - Ainslie group (Flap, Windfarmer) ← New analytical model
  - Engineering models (WAsP)
- Best agreement – moderate wind speeds and turbulence

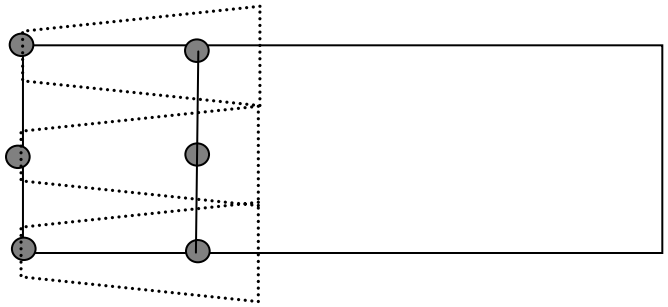


Barthelmie et al. (JAOT 2005 accepted)

New analytical windfarm model

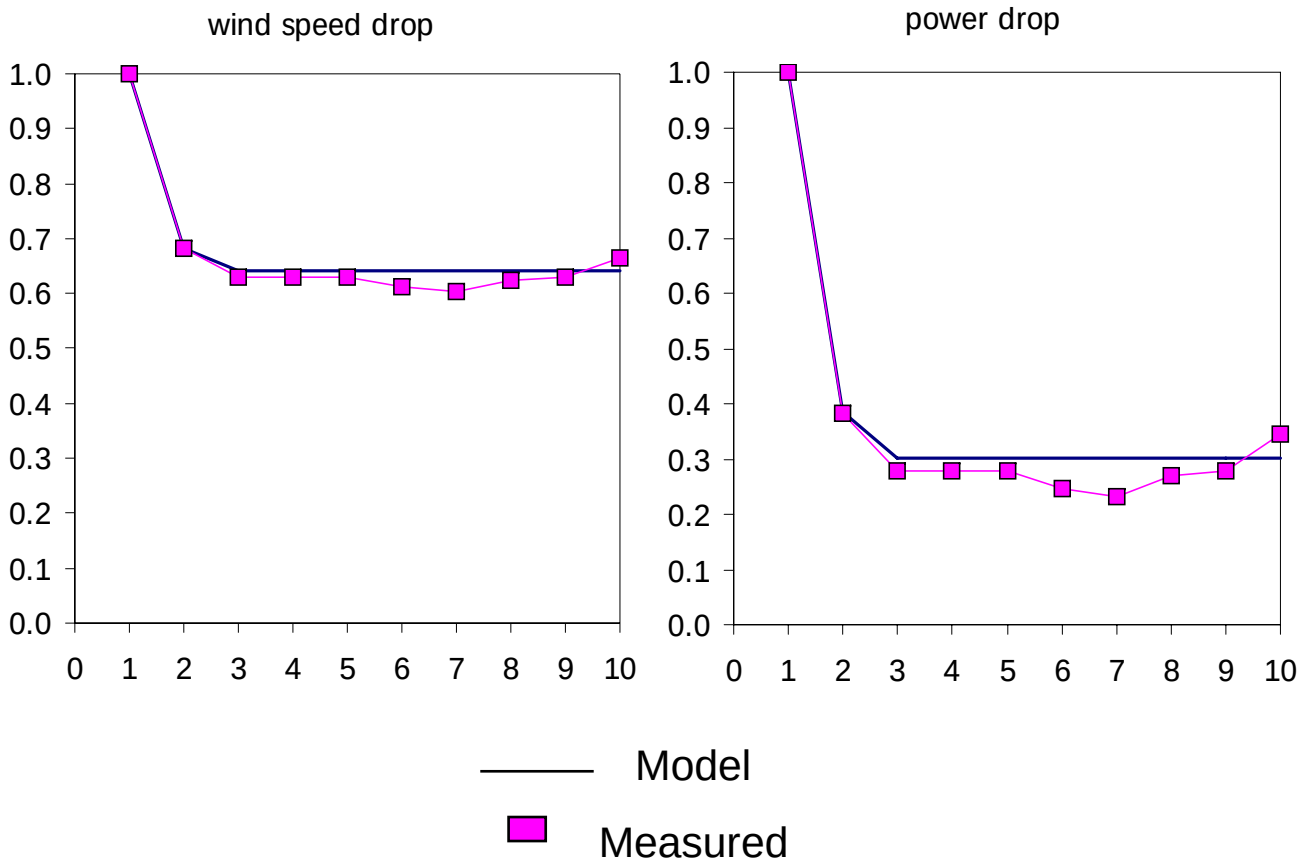
1. Different regimes for wake expansion
2. Accounts for wakes hitting the ground and impacting laterally
3. Conserves momentum deficit in multiple wakes
4. Aimed at prediction of wake losses within and downwind of large wind farms





Frandsen et al. (EWEC 2004 & Wind Energy in review)

Analytical model 10-11m/s



Future work

- New datasets are invaluable for evaluating wake models
- New model appears to give good results in comparison with data for direct wakes
- Work to do for all conditions (indirect wakes, wind speed/direction & turbulence/stability)
- Farm design – layout to minimize wake effects & loads esp. in comparison with standard tools.