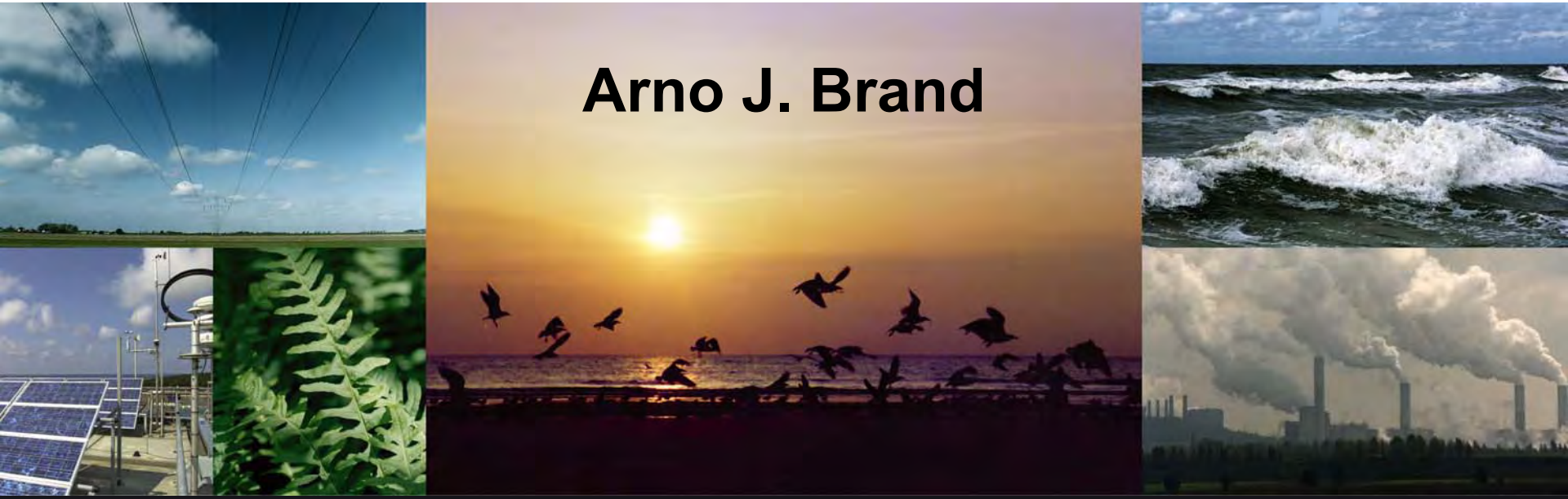
ECN

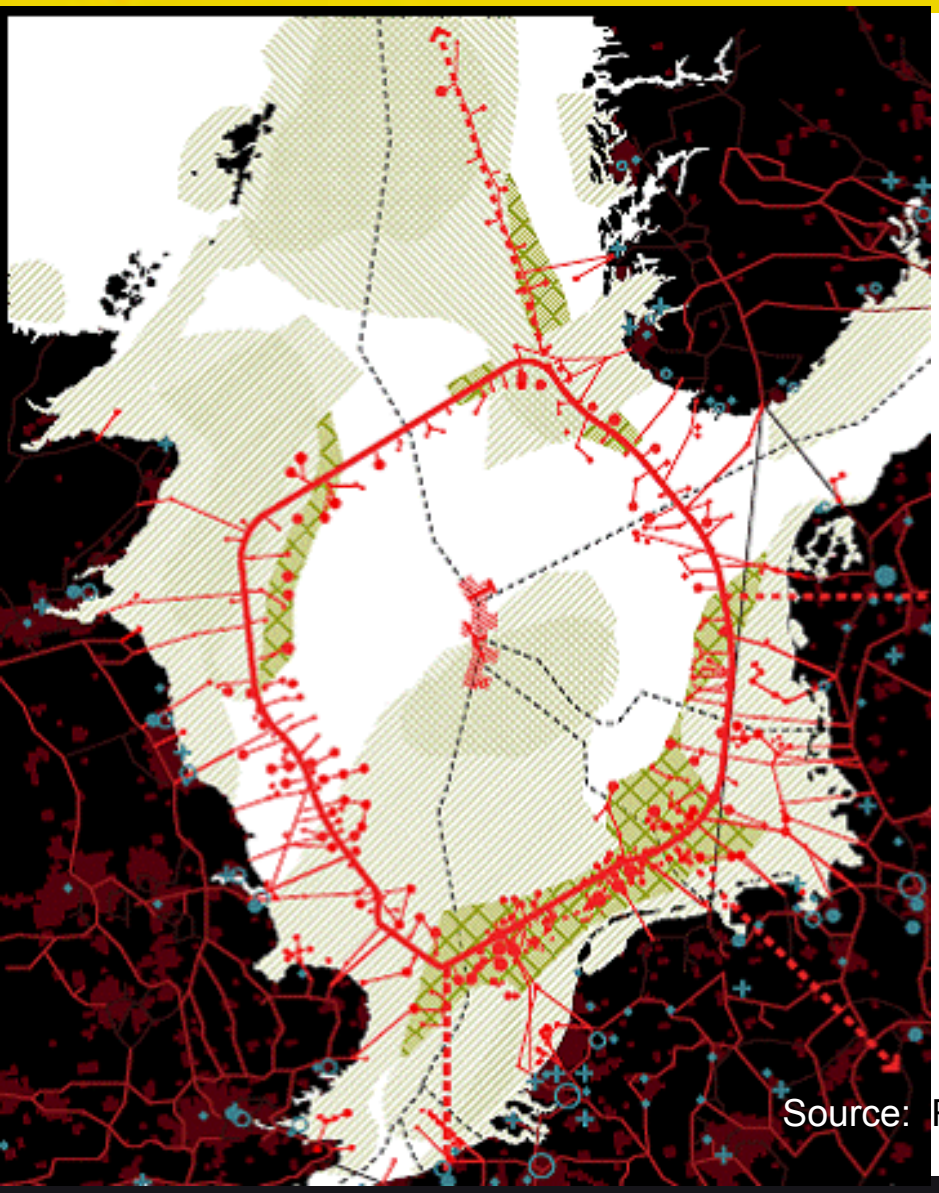
Energy research Centre of the Netherlands

Wind Farm Design
When other wind farms are close



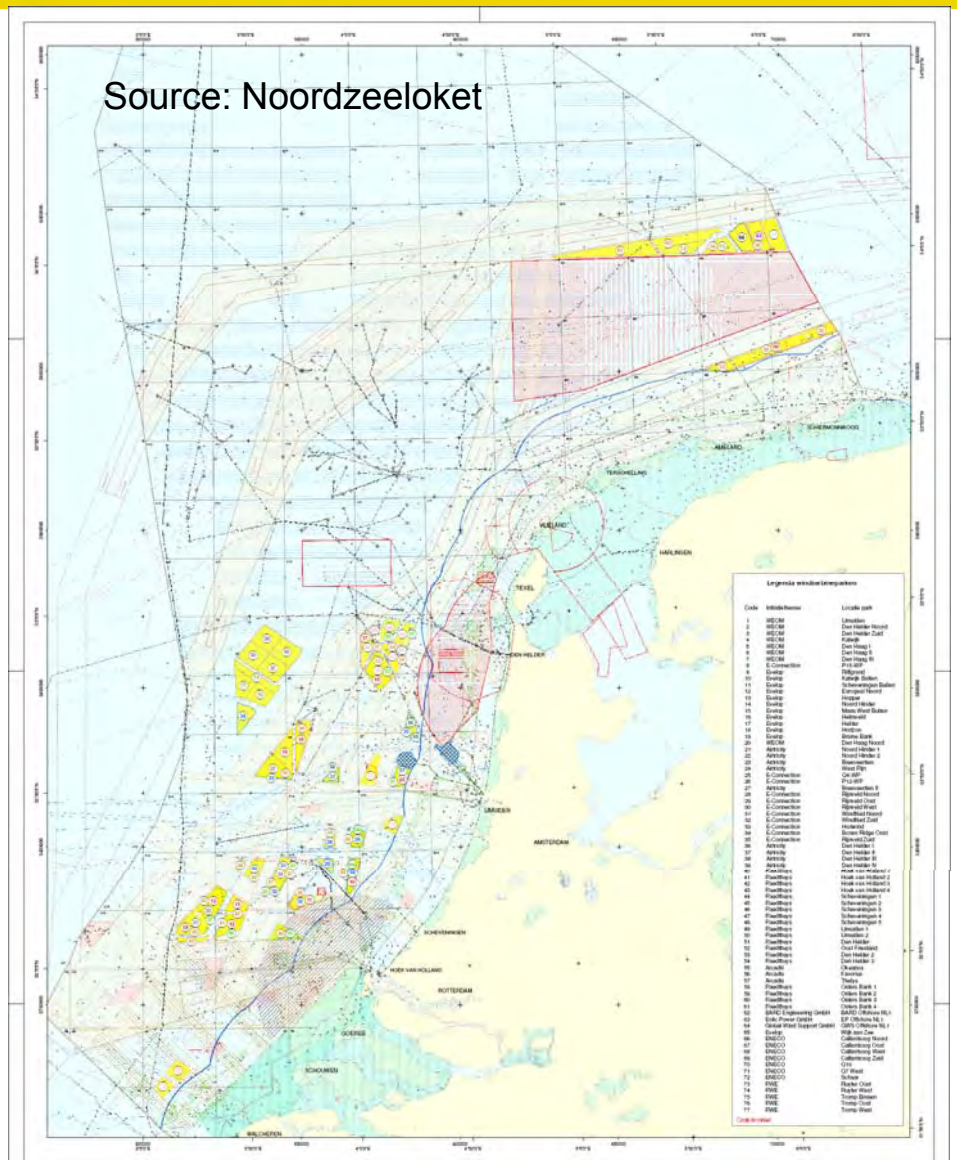
Arno J. Brand

Motivation



Source: Rem Koolhaas' Office for Metropolitan Architecture (OMA)

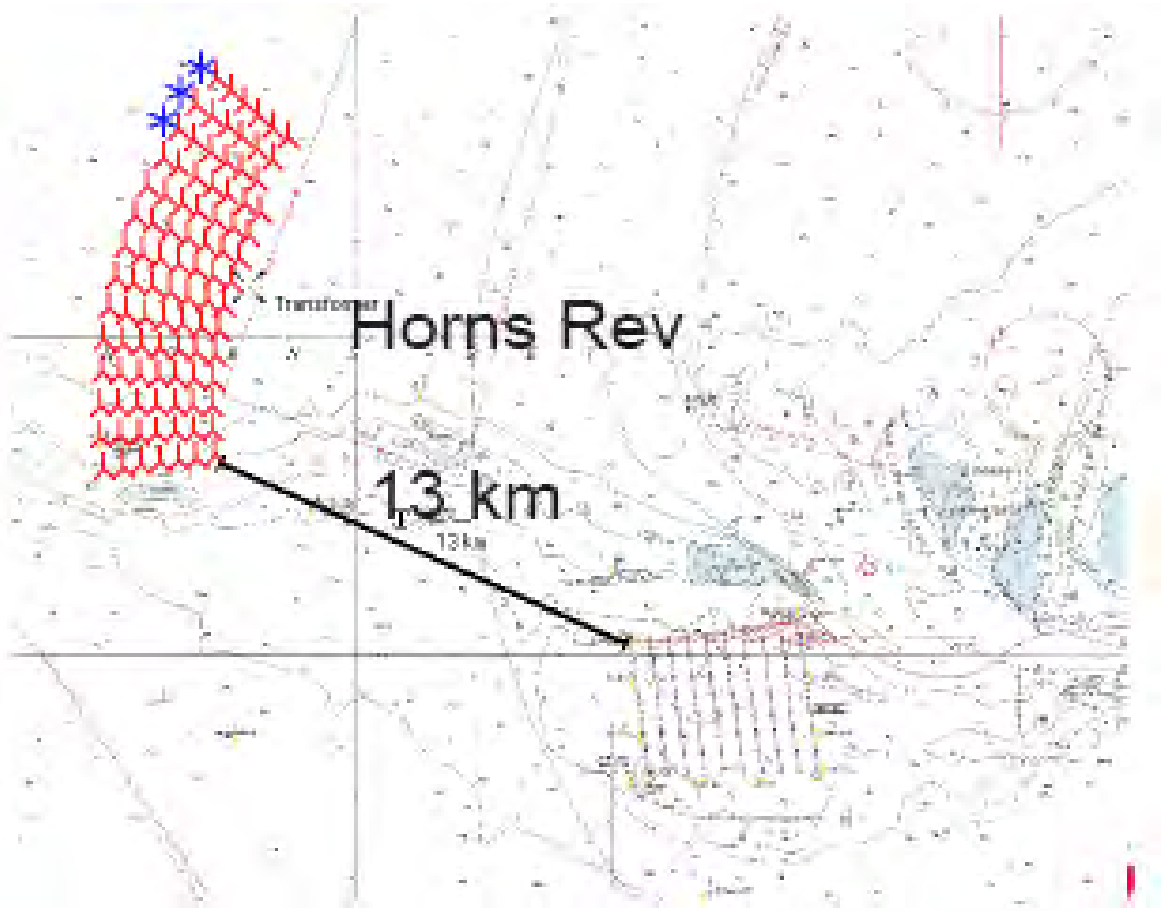
Motivation



Motivation

Source: Wind Service Holland

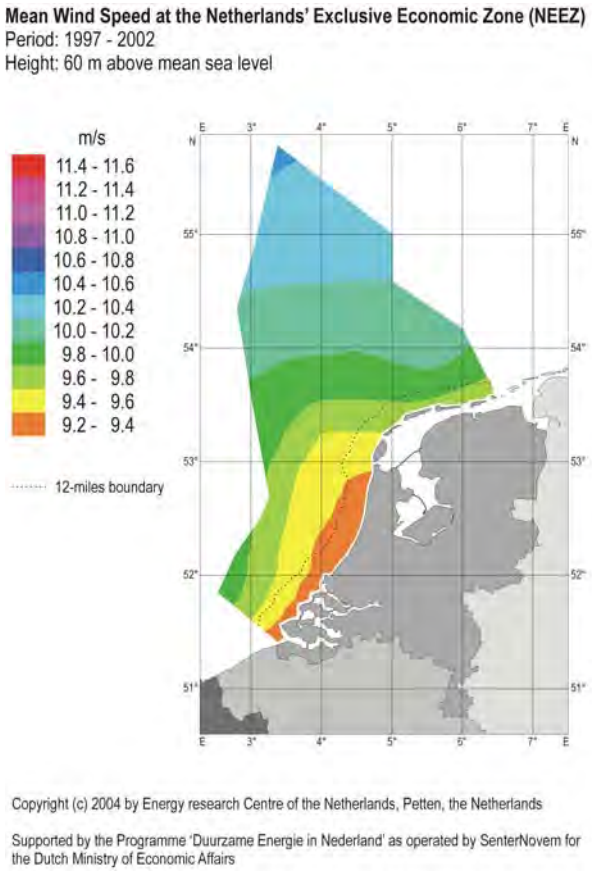
Motivation

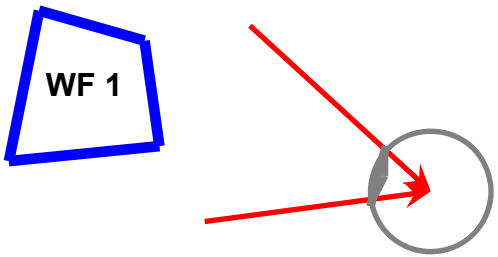


Source: DONG Energy

Motivation

Large offshore wind farms may affect each other's wind resource





velocity deficit

disturbed wind rose

Challenge

Can we design a wind farm when other sites are close?

Challenge

Can we design a wind farm when other sites are close?

Yes

How?

Challenge

Can we design a wind farm when other sites are close?

Yes

How?

By determining the local wind climate

How?

Challenge

Can we design a wind farm when other sites are close?

Yes

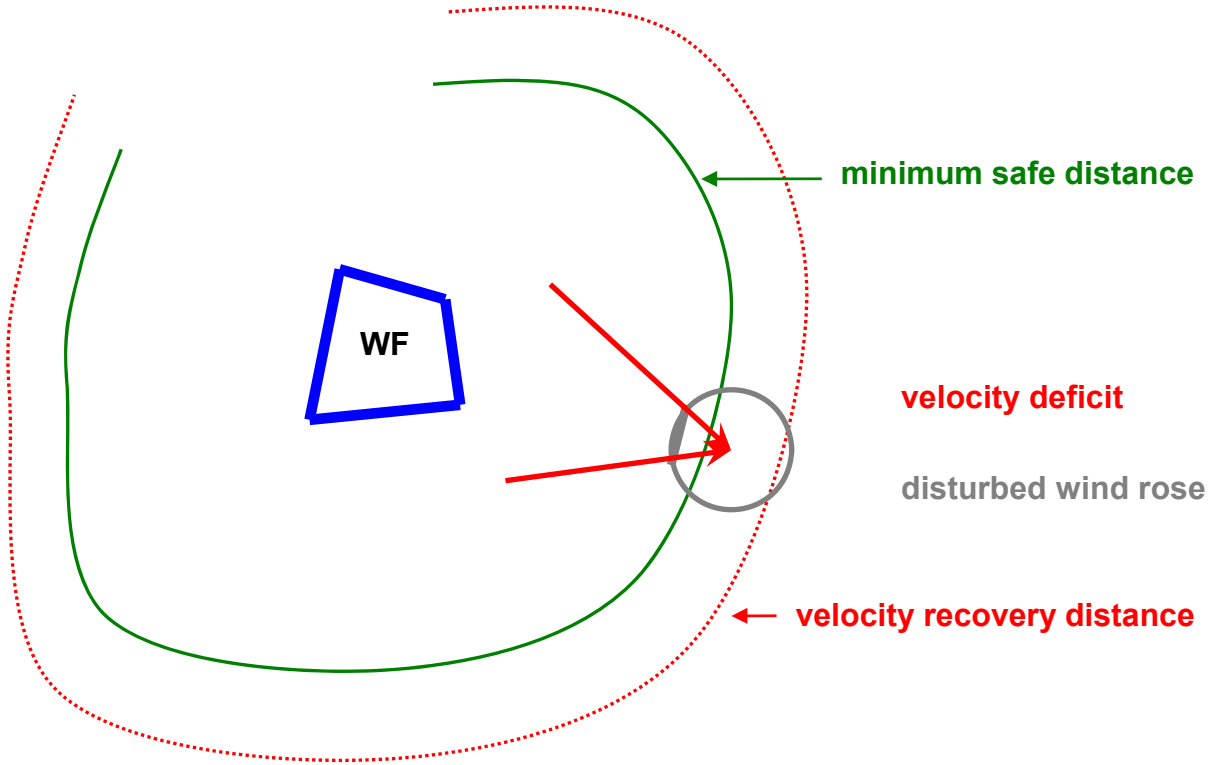
How?

By determining the local wind climate

How?

By modelling planetary boundary layer flow with wind farming

Conclusion


minimum safe distance
WF
velocity deficit
disturbed wind rose
velocity recovery distance

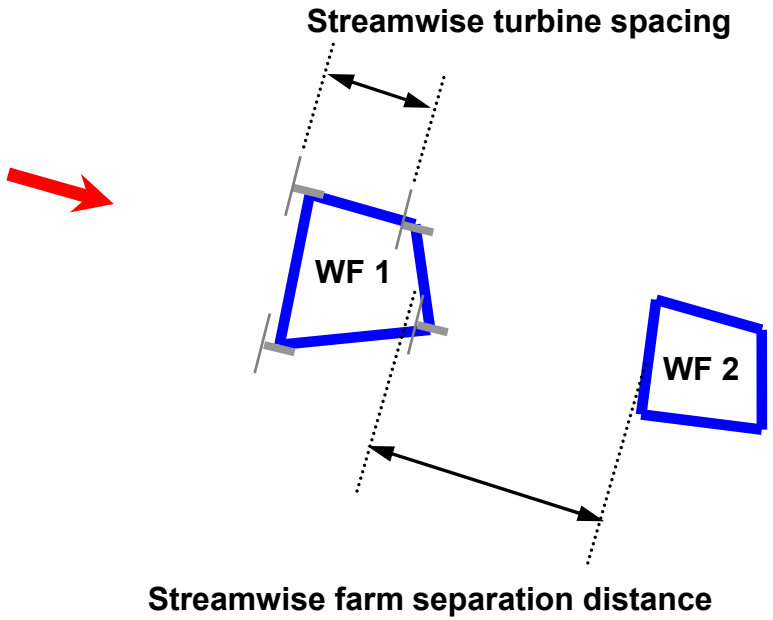
Outline

- Concepts
- Approach
- Validation
- Predictions

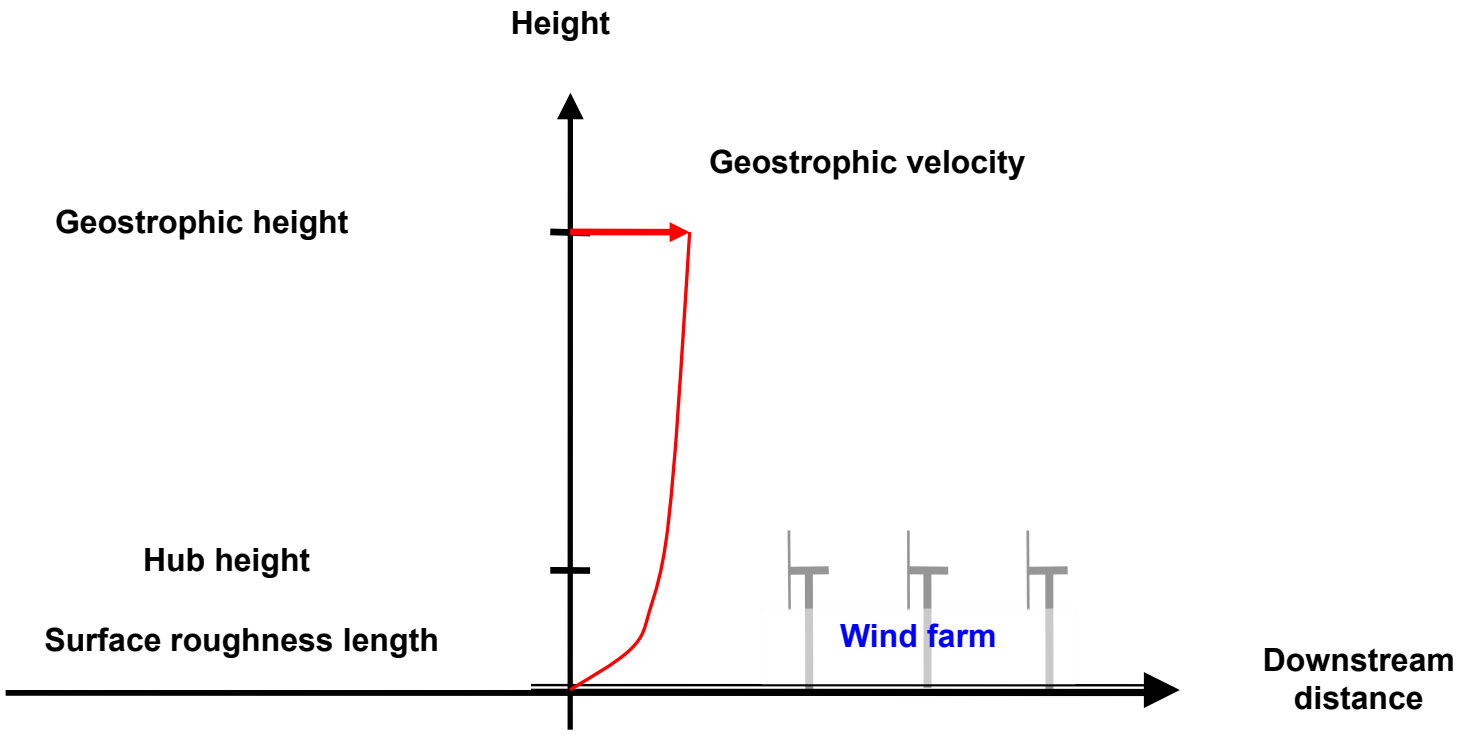
Design parameters

- Wind farm design parameters
  - Farm separation distance
  - Turbine spacing
  - Hub height
  - Rotor diameter
  - Nominal power
- Meteorological design parameters
  - Geostrophic velocity
  - Geostrophic height
  - Surface roughness length

Design parameters



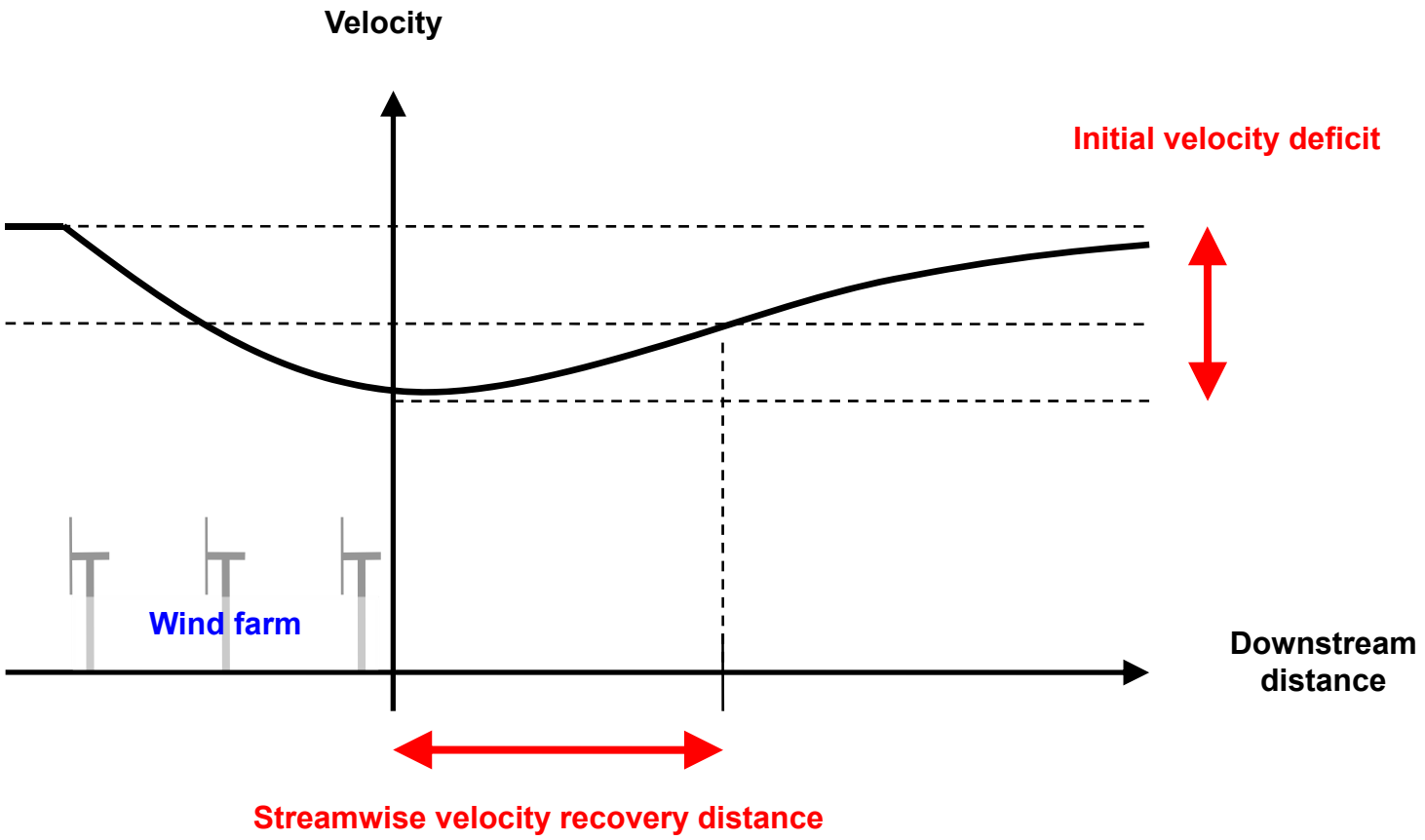
Design parameters



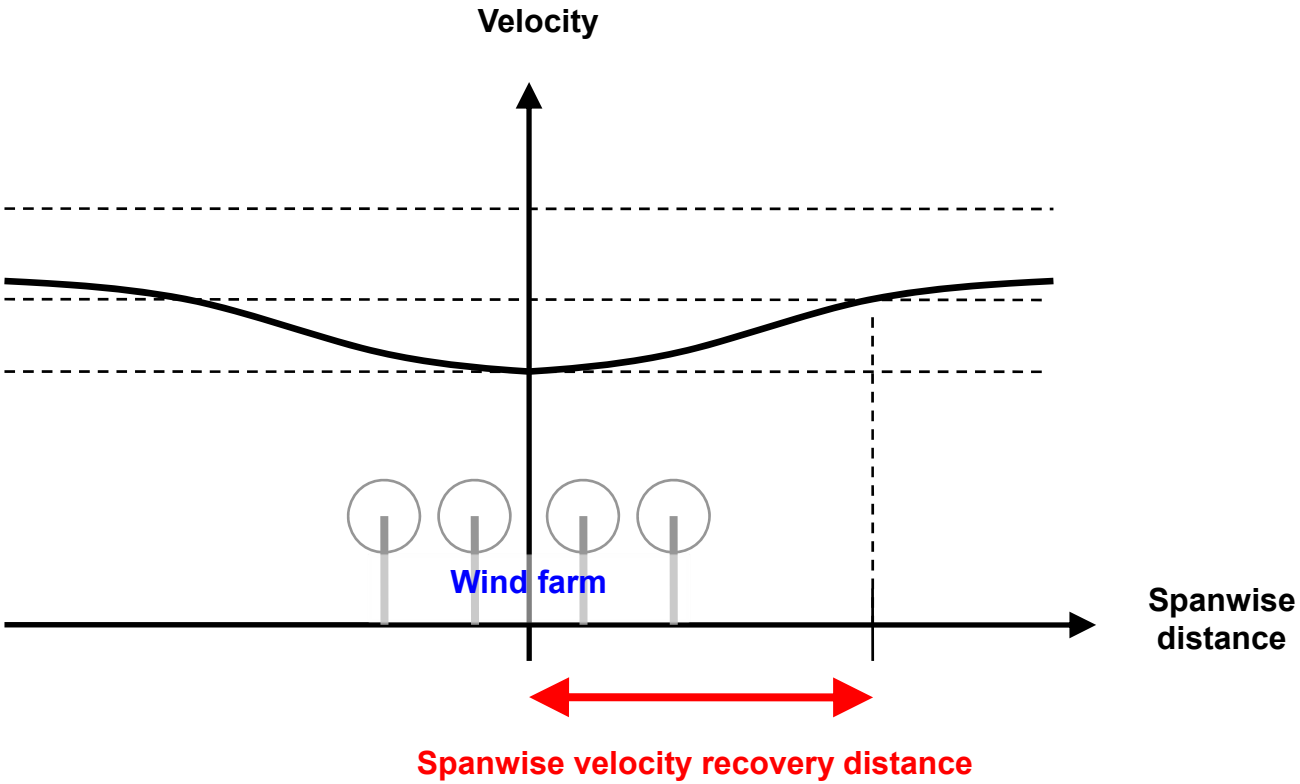
Impact parameters

- Velocity deficit
- Velocity recovery distance
- Minimum safe distance
- Disturbed sectors

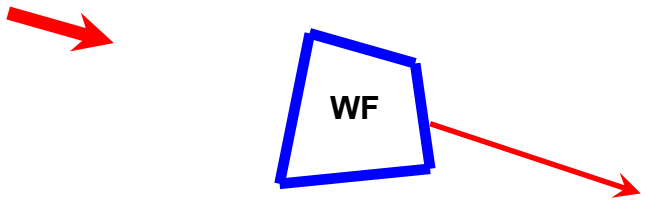
Velocity deficits and recovery distances



Spanwise recovery distance

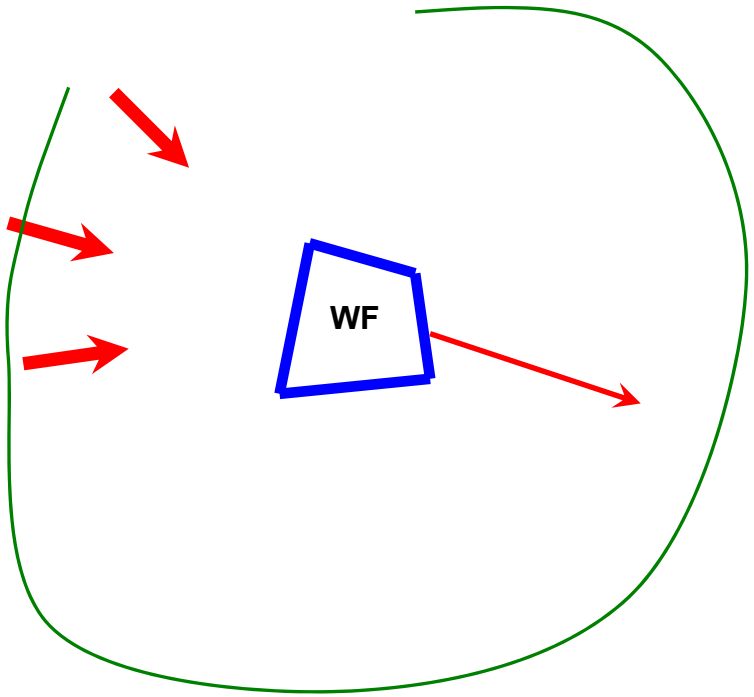


Velocity deficit



velocity deficit

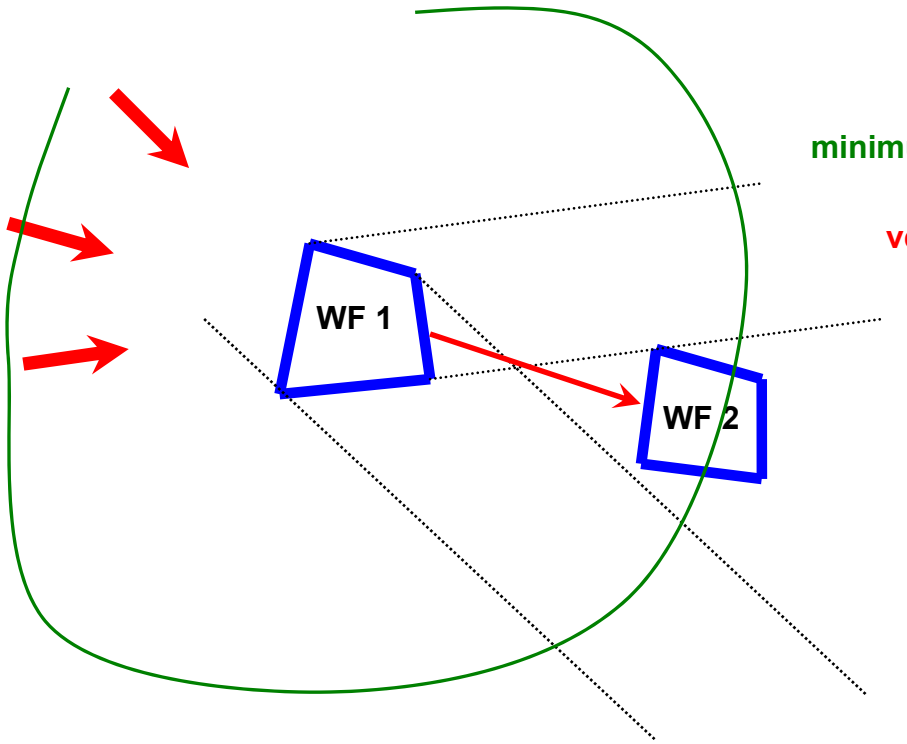
Minimum safe distance



minimum safe distance

velocity deficit

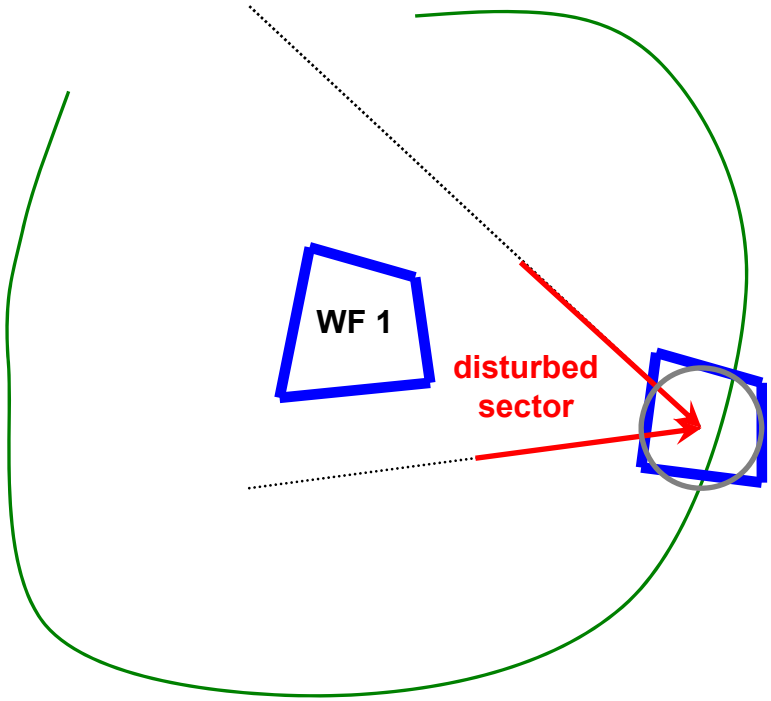
Disturbed sectors



minimum safe distance

velocity deficit

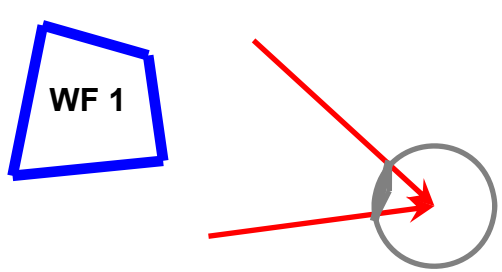
Disturbed sectors



minimum safe distance

velocity deficit

Disturbed wind rose



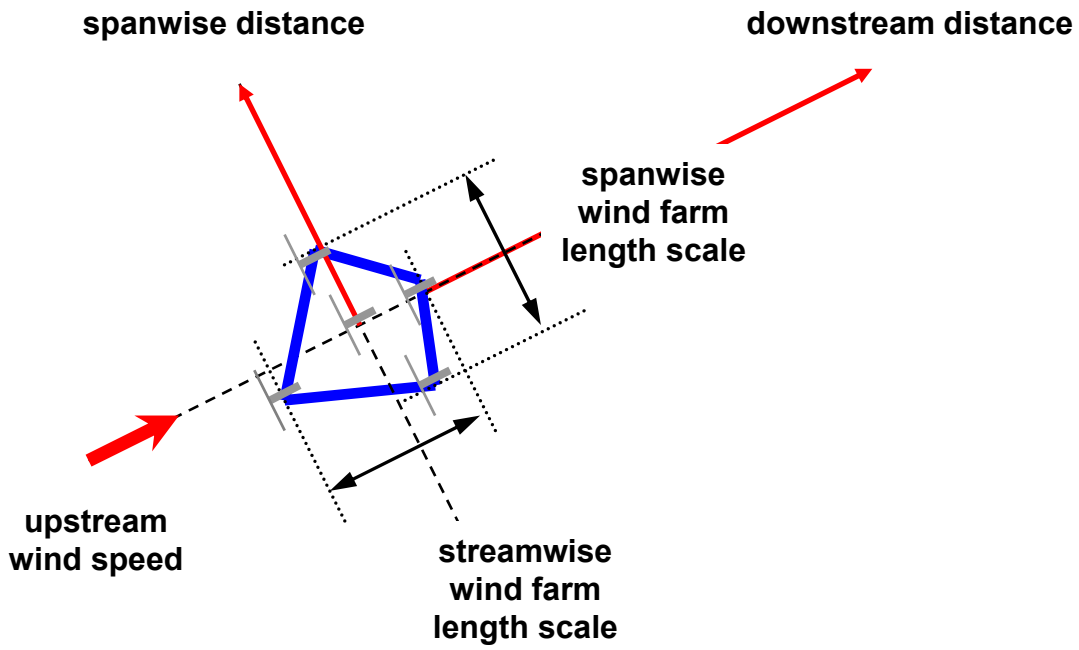
velocity deficit

disturbed wind rose

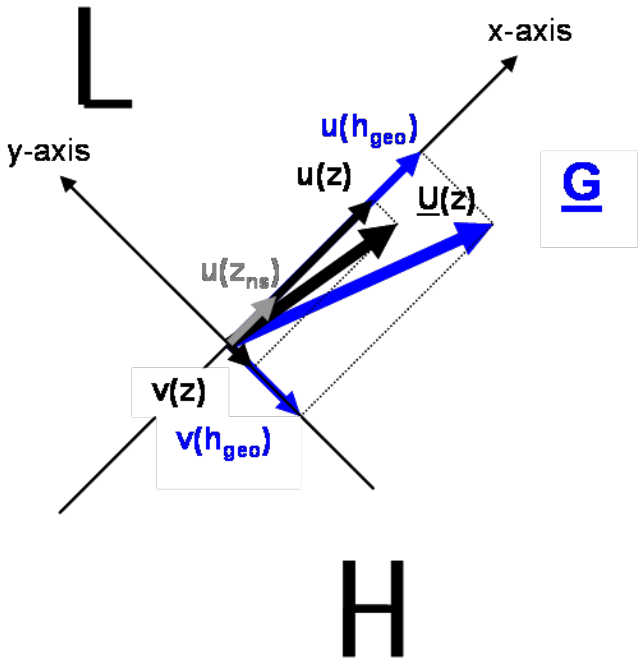
Flow solver

- Neutral planetary boundary layer flow with wind farming
  - Steady and two-dimensional
  - Equilibrium between convective and Coriolis forces …
  - … and vertical and spanwise turb. mom. flux gradients …
  - … and forces due to the wind turbines
- Numerical representation
  - Implicit solution in the vertical
  - Marching solution in horizontal directions
  - Implicit Lagrange multiplier velocity correction

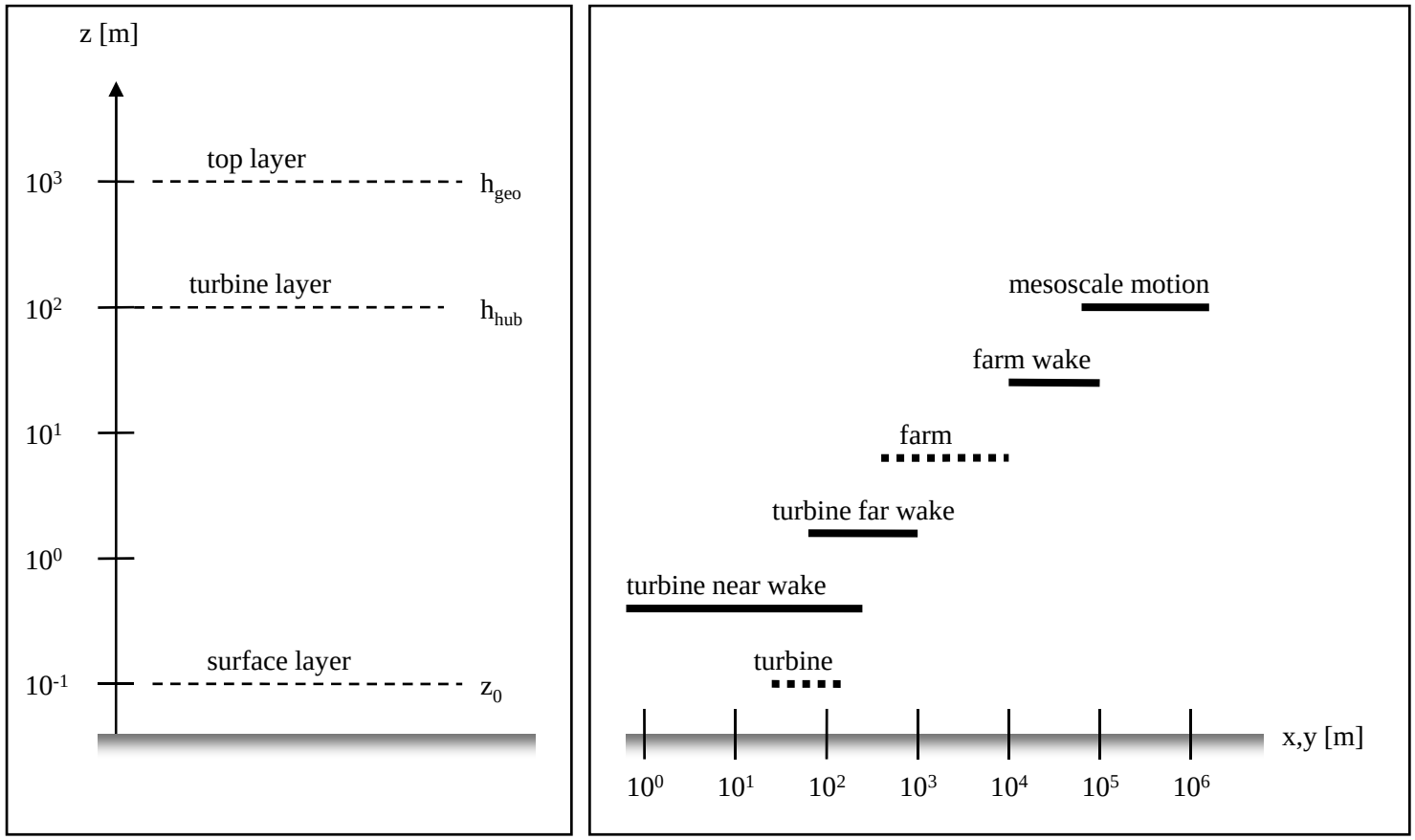
Flow problem



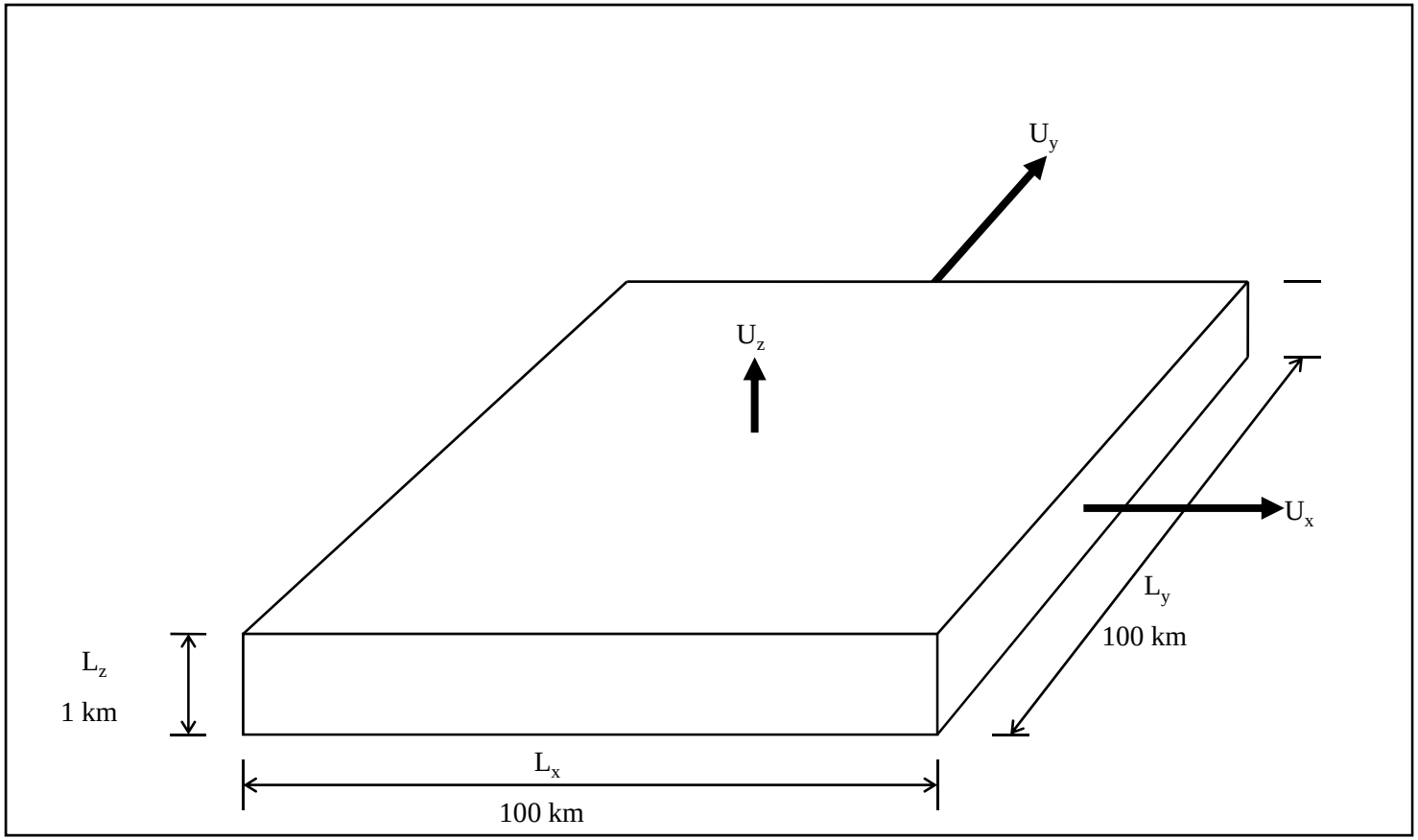
Velocity decomposition



Vertical and horizontal length scales



Length and velocity scales



Approach

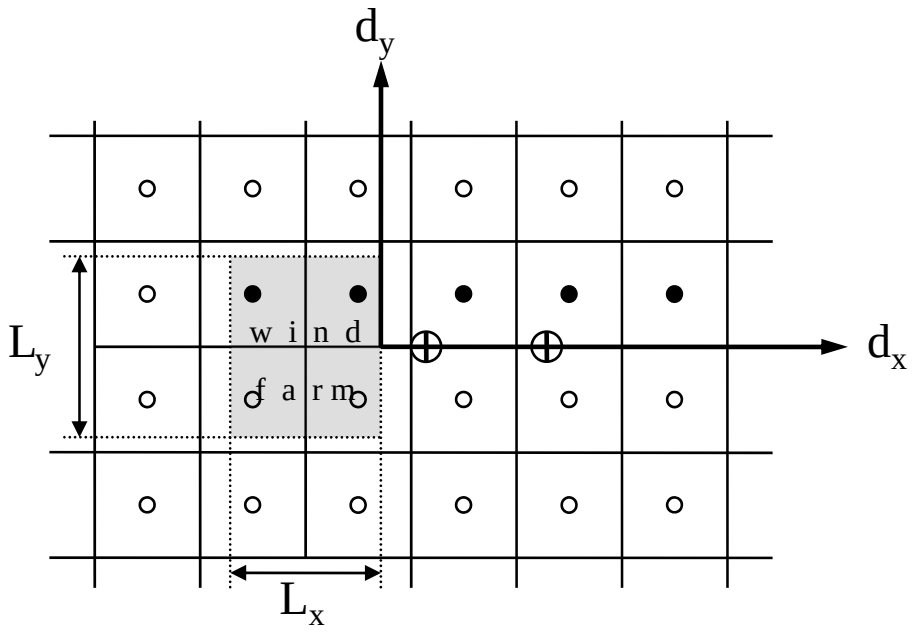
Governing equations

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = +f_{\phi}\left(\bar{v} - v_{g}\right) - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z} + \overline{a_{x}}$$

$$\bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} = -f_{\phi}\left(\bar{u} - u_{g}\right) - \frac{\partial \overline{v'v'}}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z} + \overline{a_{y}}$$

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0$$

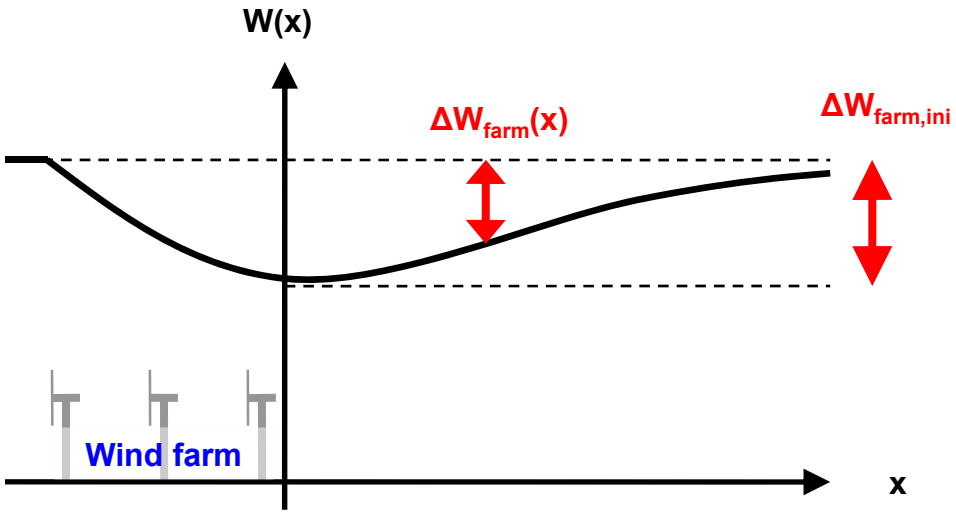
Layout of grid cells



- grid point (centre of cell)
- grid point where calculated velocity is evaluated
- ⊕ point where measured velocity is evaluated

Decay of velocity deficit

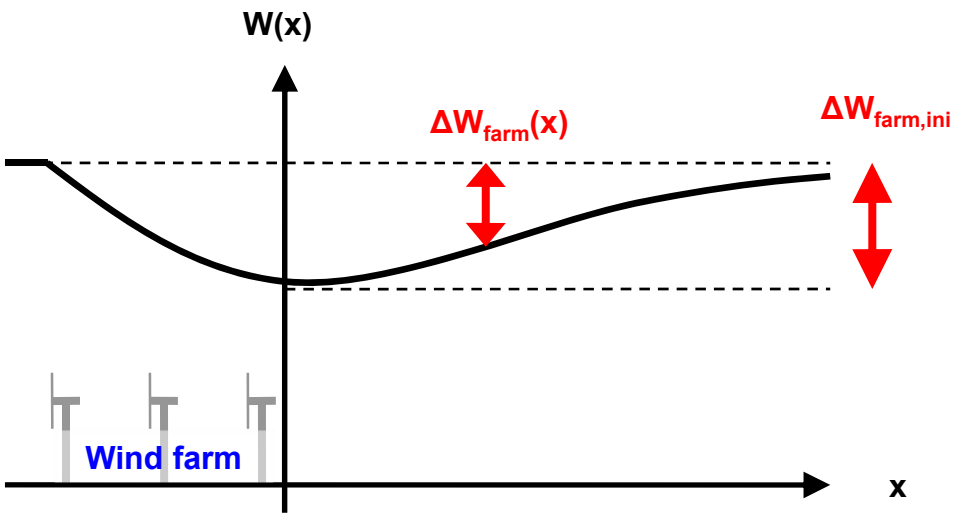
$$\frac{\Delta W_{farm}(x)}{\Delta W_{farm,ini}} = \left(\frac{x}{2D_{rot}} \right)^{m}$$



Inspiration: R.J. Barthelmie et al., 2008, EWEC 2008, Brussels, Belgium

Decay of velocity deficit

$$\frac{\Delta W_{farm}(x)}{\Delta W_{farm,ini}} = \left(\frac{x}{2D_{rot}} \right)^{m}$$



$\Delta W_{farm,ini}$ and m from calculations and measurements

Inspiration: R.J. Barthelmie et al., 2008, EWEC 2008, Brussels, Belgium

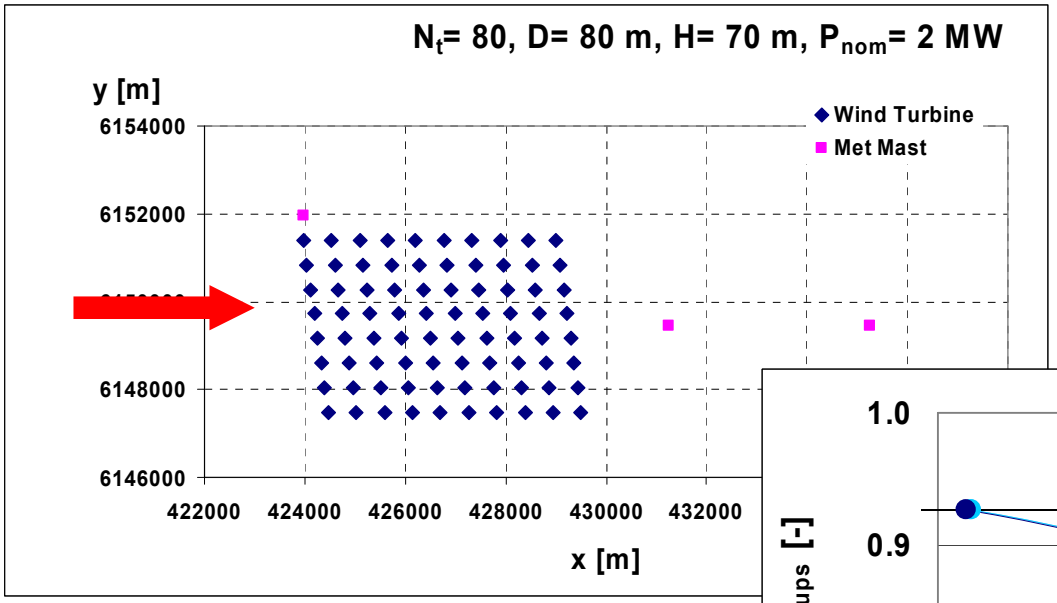
Grid-cell versus one-point velocities

Translation

$$\overline{W_{cell}(x_1, x_2)} = W_0 - f(m, \Delta W_{ini}; N_t, D, x_1, x_2, \Delta y)$$

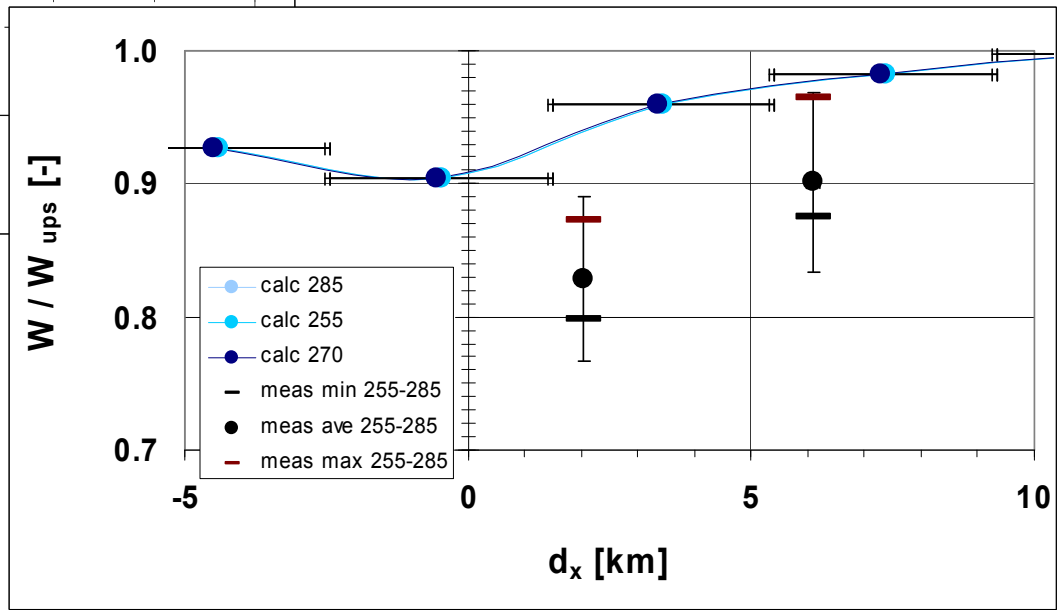
Validation

Horns Rev wind farm



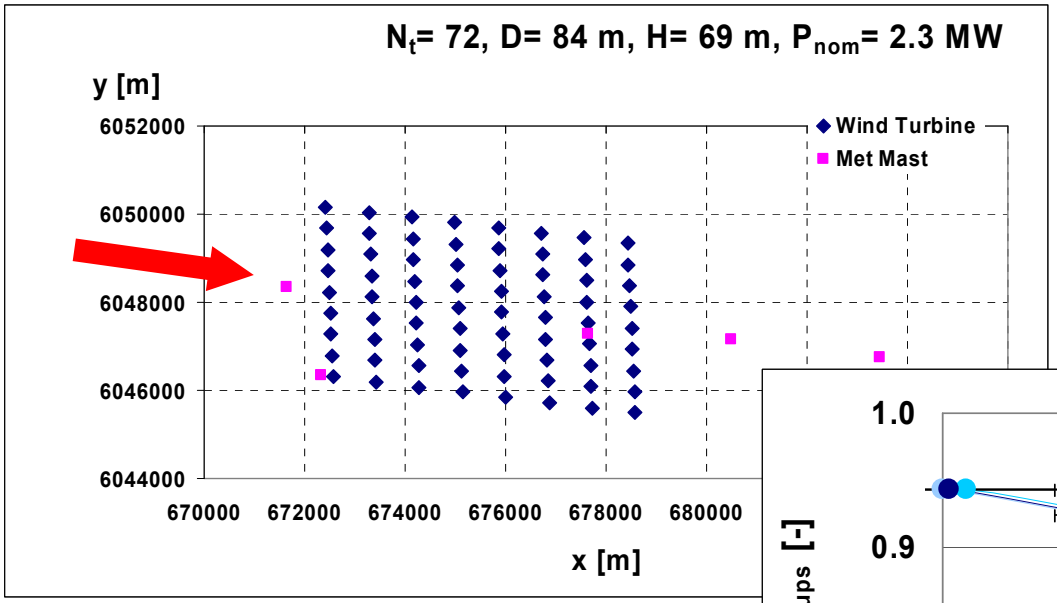
Grid-cell values

One-point values



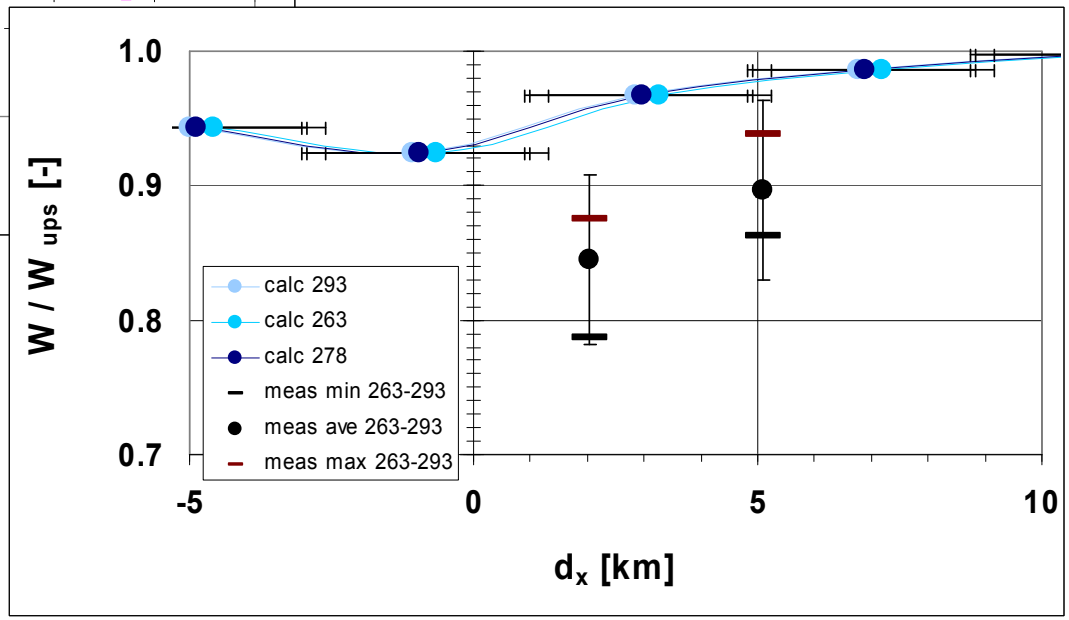
Source: DONG Energy

Nysted wind farm



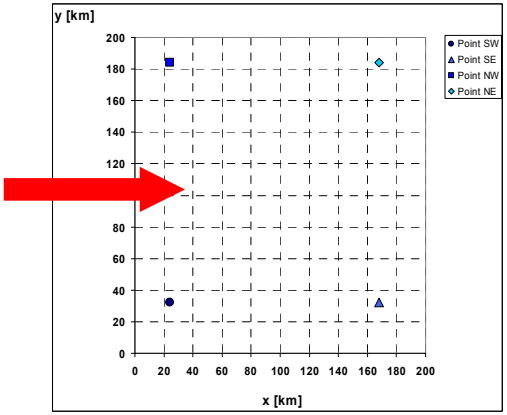
Grid-cell values

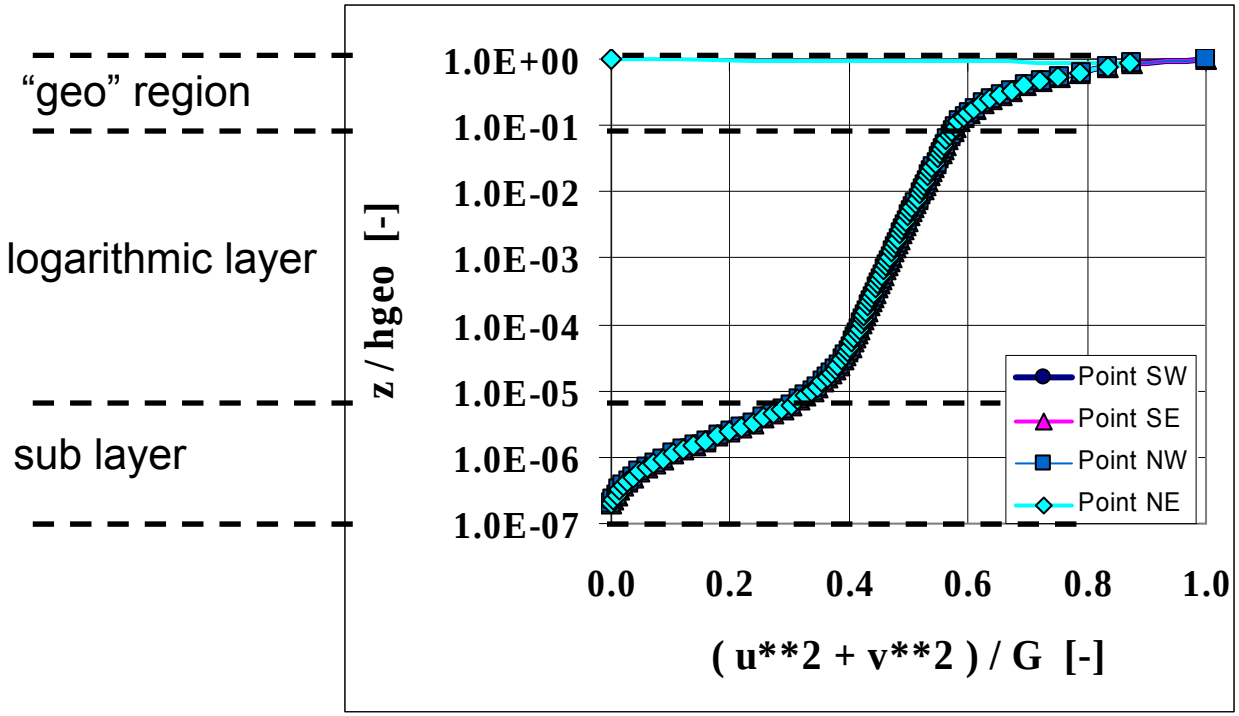
One-point values



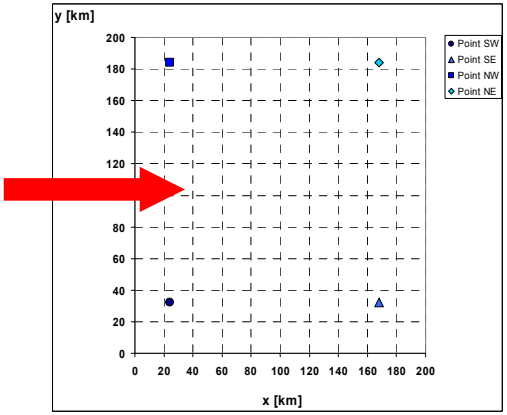
Source: DONG Energy

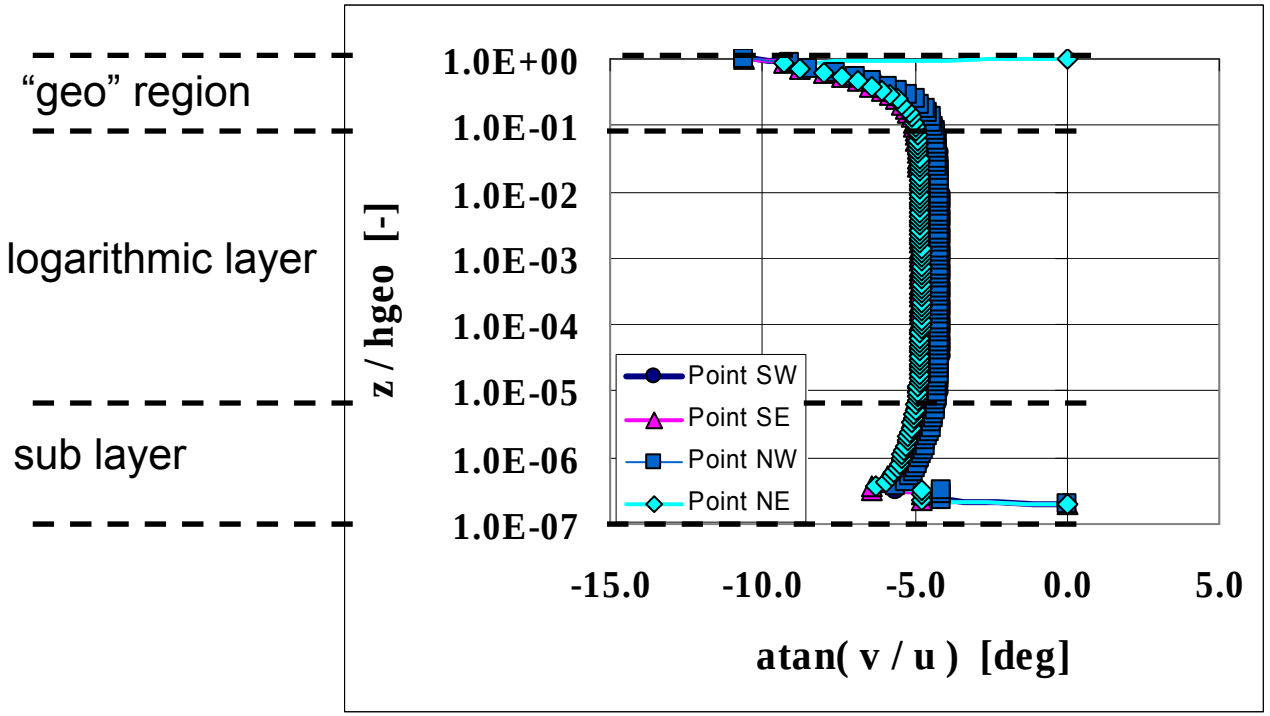
Velocity profile without a wind farm



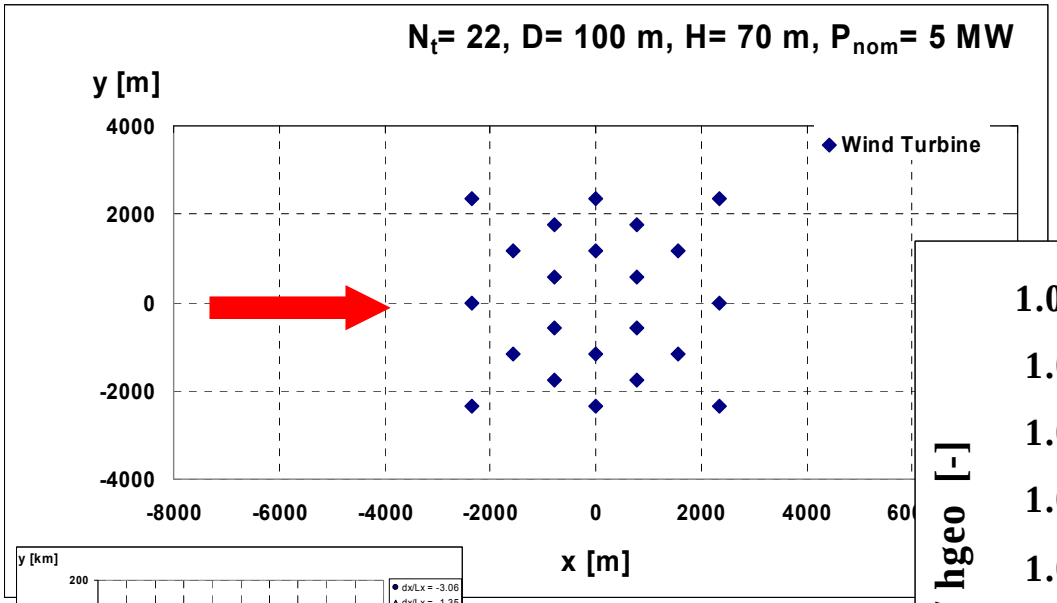


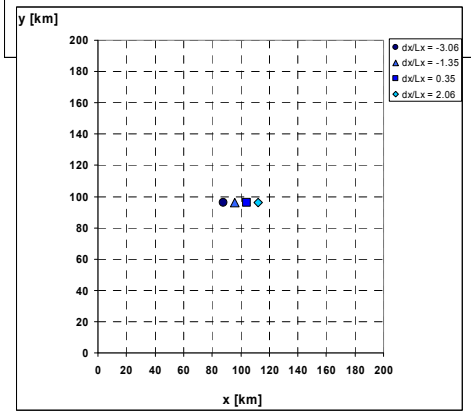
Velocity profile without a wind farm

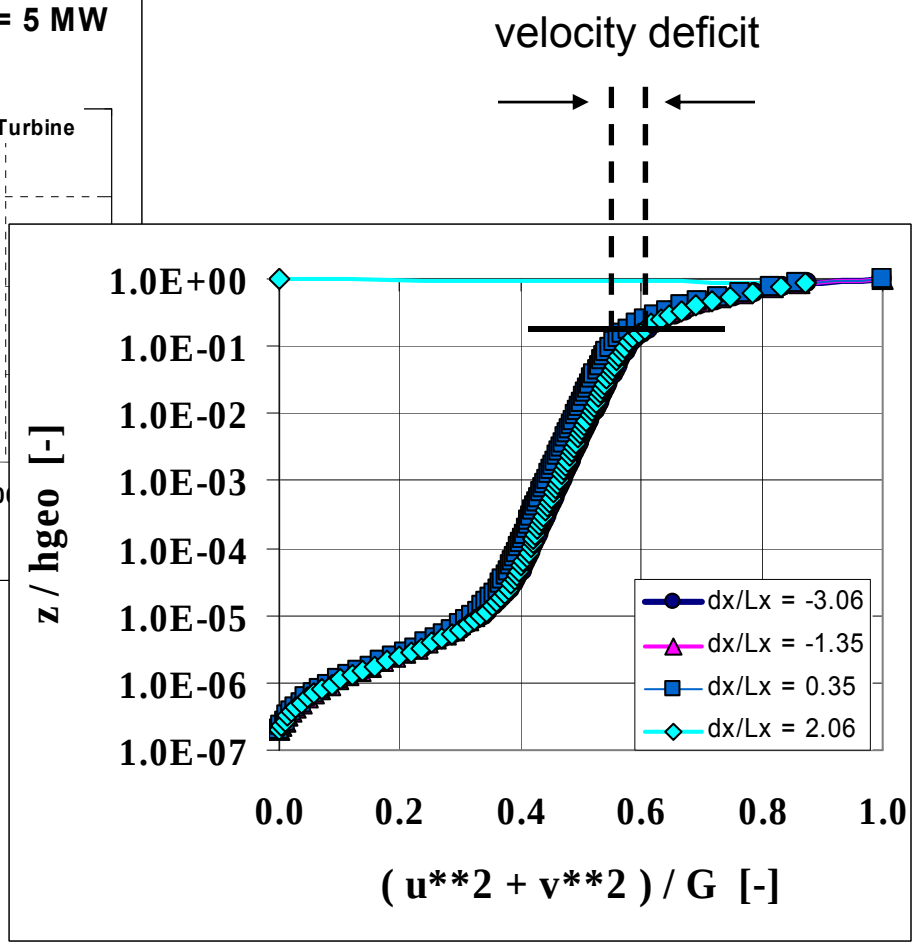




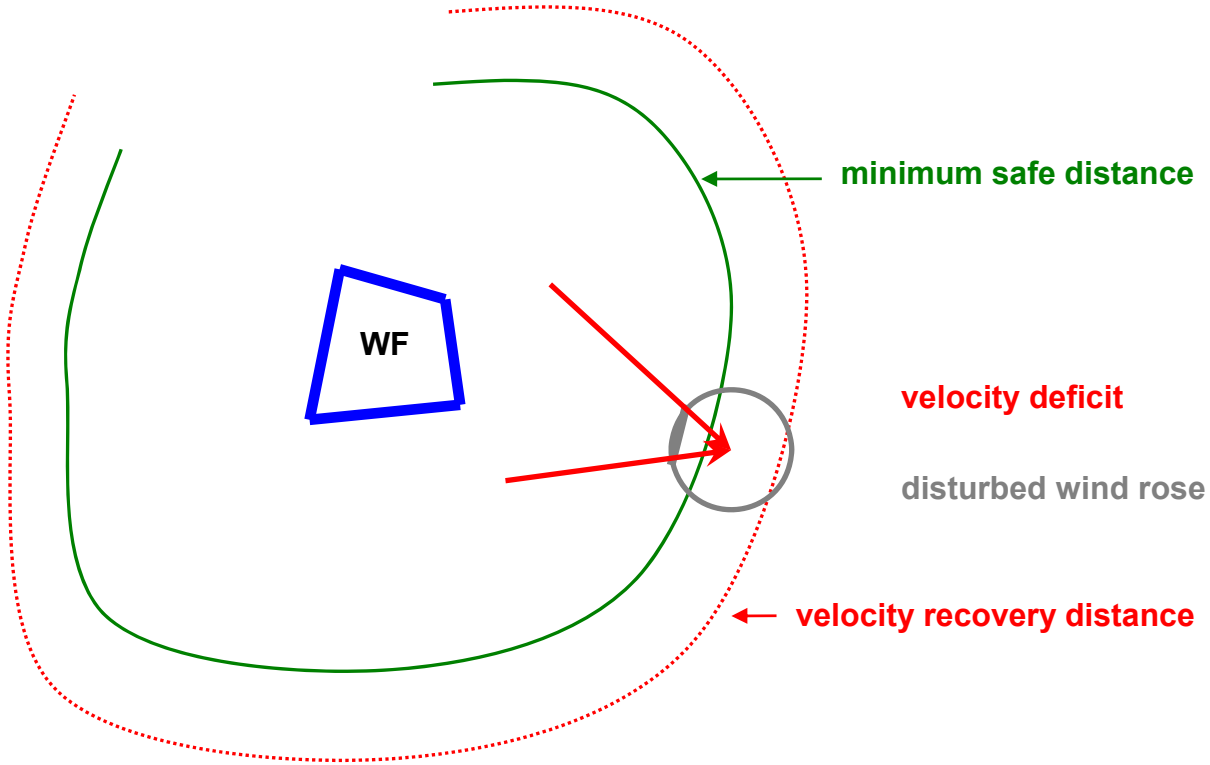
Velocity profile near a hypothetical wind farm







Conclusion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Extra

Momentum equations …

- Discretisation
- Representation
- Solution procedure
- Formal order of method
- Numerical stability
- Conservation of mass and energy

Other aspects

- Lagrange-multiplier approach
- Turbulence parameterization
- Wind turbine parameterization
- Initial and boundary conditions
- Discretization error estimation

Predictions

Impact of nominal power density on initial velocity deficit

Predictions

Impact of nominal power density on velocity recovery distance

Summary