The Importance of Turbulence in Wind Energy

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Outline

- **Background**
  - **Importance of understanding the interaction among turbines & Atmospheric Boundary Layers in Wakes Modeling**
  - **Importance of Turbulence on Wind Energy & Optimization Design**
- **Motivation & Objectives**
  - **Improve understanding of the vertical transport of momentum & K.E.**
  - **Use Experimental data for Analysis & Global Optimization of Wind Farms.**
  - Reduce the cost by layout optimization
- **Wind Tunnel Experiments**
- **Wind Farm Power Model: Optimization Design (Layout)**
- **Economic Model:** Cost of Energy Optimization
- **Conclusion**

Background

- Wind turbines well studied from a blade aerodynamics perspective.

- **Wind turbines within an array display power generation loss of up to 40%**, when compared to a freestanding wind turbine, Crespo et al. (1999).

- Wind Array: Important to understand such interactions **to optimize wind farm layout.**
  - **Analytical methods**, not CFD tools, commonly used to design wind farm layouts.

- Wind energy is planed to account for 20% of the U.S. electricity consumption by 2030.

- Efficient planning and resource management is the key to the success of an energy project.
  - Accurate (**flexible to local market changes**) cost models of wind projects would allow investors to better plan their projects.
  - Investors can provide valuable insight into the areas that require further development to improve the overall economics of wind energy.

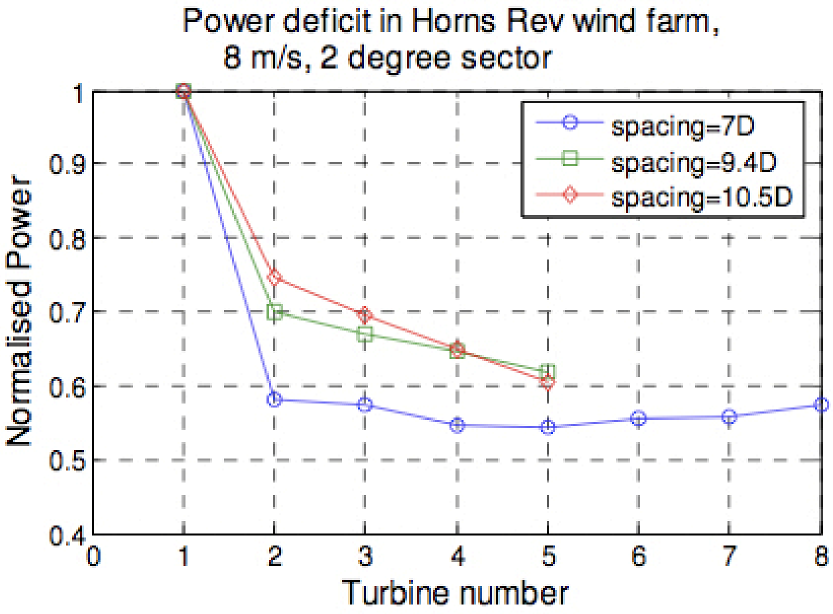
Background: Long Downstream Effect

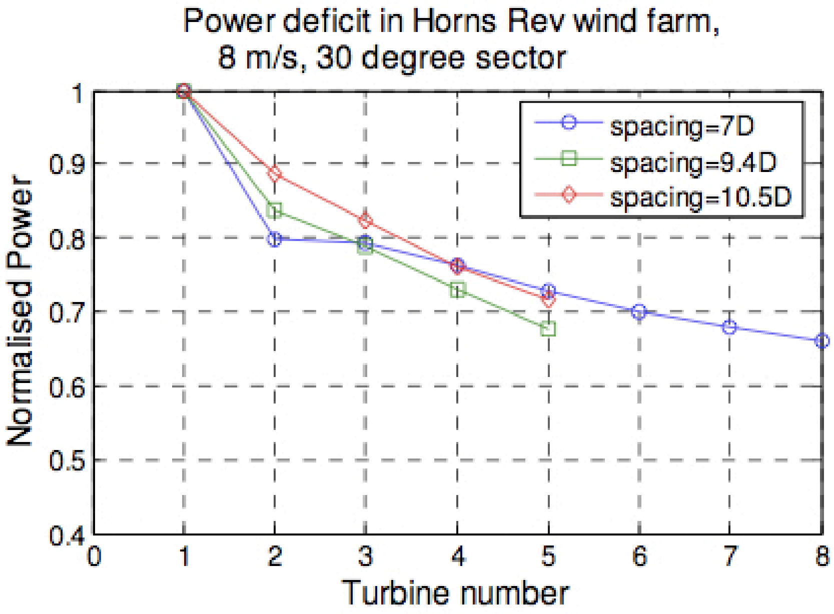
Modeling and measurements of wakes in large wind farms

Barthelemie, Rathmann, Frandsen, Hansen et al...

J. Physics Conf. Series 75 (2007), 012049

Power extraction at Horns Rev wind farm:

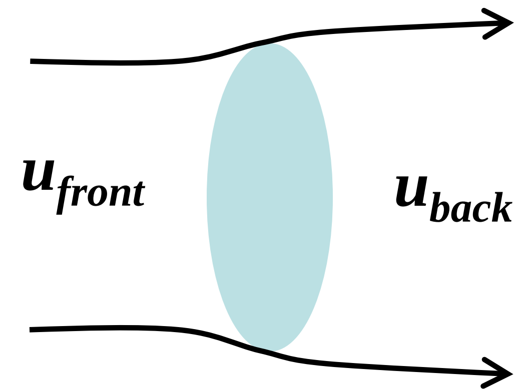




Wake model used for optimization by Elkinton et al.(2006).

Study showed the biggest uncertainty (~25%) in the cost estimation of a wind farm is due to the flawed wake modeling.

The Wake Profile: Layout Optimization and Energy Output



1. Induction factor for wind turbines

$$a = \frac{1}{2}\left(1 - \frac{u_{back}}{u_{front}}\right)$$

is used in wake models, e.g. for;

a. Output power prediction, and maximize energy extraction

b. Wind turbines placement (layouts) optimization

2. PARK model for wake velocity reduction (wake loss), Jensen (1983).

$$U(x) = U_0\left[1 - a\left(\frac{1}{1+\theta(x/D)}\right)^2\right]$$

Assumptions:

velocity inside wake ➔assumed to be axi-symmetric and uniform

free-stream velocity ➔assumed to be uniform

entrainment parameter, θ,➔empirical value assigned

Θand a both depend on turbulence structure and are input parameters!

The WTABL and the Kinetic Energy:

+ horizontal averaging for simple vertical structure (Frandsen 1992)
("Wind speed reduction..." J. Wind Eng &IndAppl**39**, 1992)

• Multiplying the momentum by the mean velocity leads to the mechanical energy describing the kinetic energy.

$$\langle \overline{u} \rangle \frac{\partial \frac{1}{2} \langle \overline{u} \rangle^2}{\partial x} + \langle \overline{v} \rangle \frac{\partial \frac{1}{2} \langle \overline{u} \rangle^2}{\partial y} =$$

$$-\frac{1}{\rho} \langle \overline{u} \rangle \frac{dp_\infty}{dx} - \frac{\partial}{\partial y} \left(\langle \overline{u'v'} \rangle \langle \overline{u} \rangle + \langle \overline{u}''\overline{v}'' \rangle \langle \overline{u} \rangle \right) + \langle \overline{u'v'} \rangle \frac{\partial \langle \overline{u} \rangle}{\partial y} + \langle \overline{u}''\overline{v}'' \rangle \frac{\partial \langle \overline{u} \rangle}{\partial y} - \mathcal{P}(y),$$

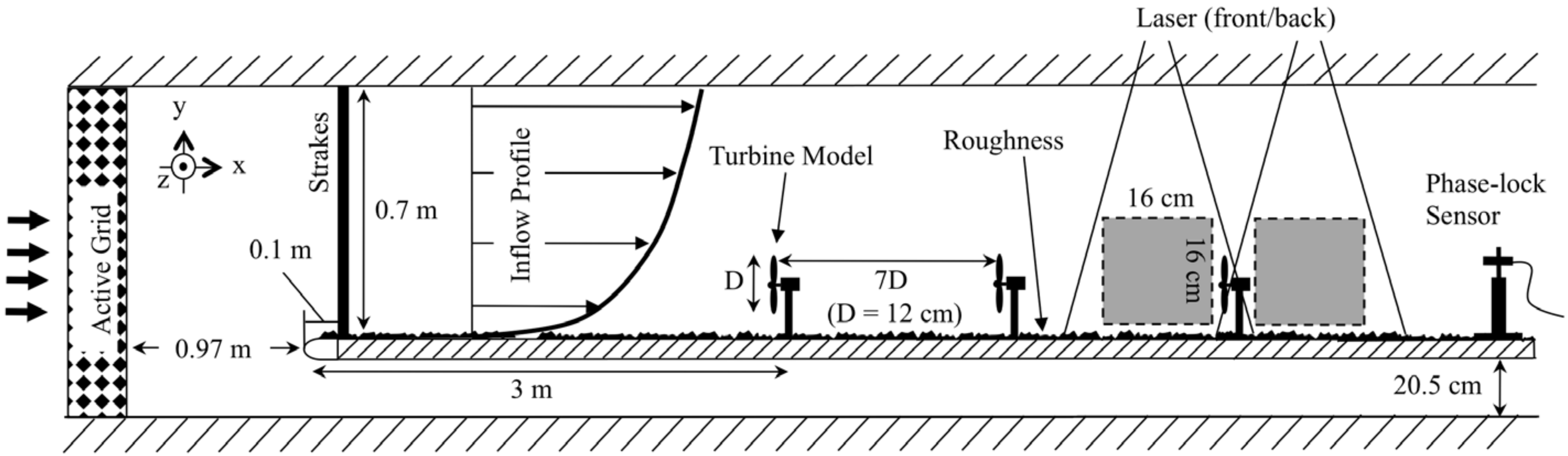
• In the inner region, the following terms are dominant:

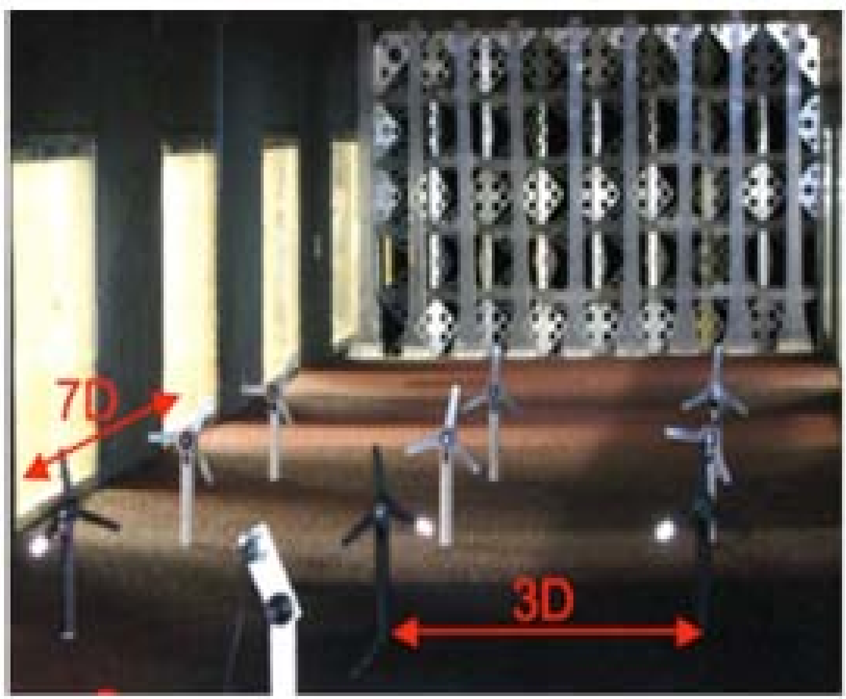
$$-\frac{\partial}{\partial y} \left(\langle \overline{u'v'} \rangle \langle \overline{u} \rangle + \langle \overline{u}''\overline{v}'' \rangle \langle \overline{u} \rangle \right) + \langle \overline{u'v'} \rangle \frac{\partial \langle \overline{u} \rangle}{\partial y} + \langle \overline{u}''\overline{v}'' \rangle \frac{\partial \langle \overline{u} \rangle}{\partial y} - \mathcal{P}(y) \approx 0$$

- Kinetic energy flux
- Dispersive flux due to spatial average
- Turbulent dissipation dispersive dissipations
- Product of the spatially averaged velocity and the averaged thrust force

What is the role of turbulent momentum & KE flux in energy?

Wind-tunnel experiment set up





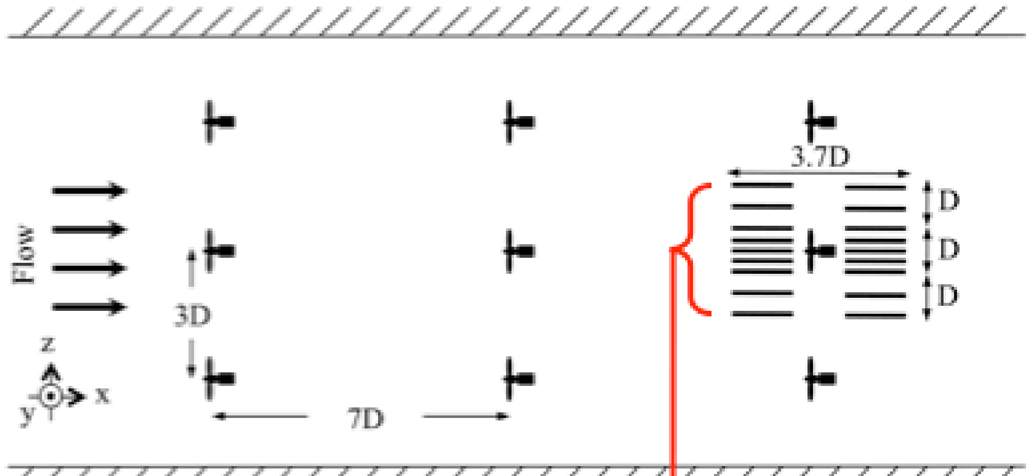
Photograph from the downstream area of the wind tunnel experiment, looking towards upstream direction.
Cal et al. 2010.

S-PIV: Contours of the Mean Steamwise Velocity

Time-averaged mean velocity for 18 planes surrounding the target wind turbine.

9 planes in front

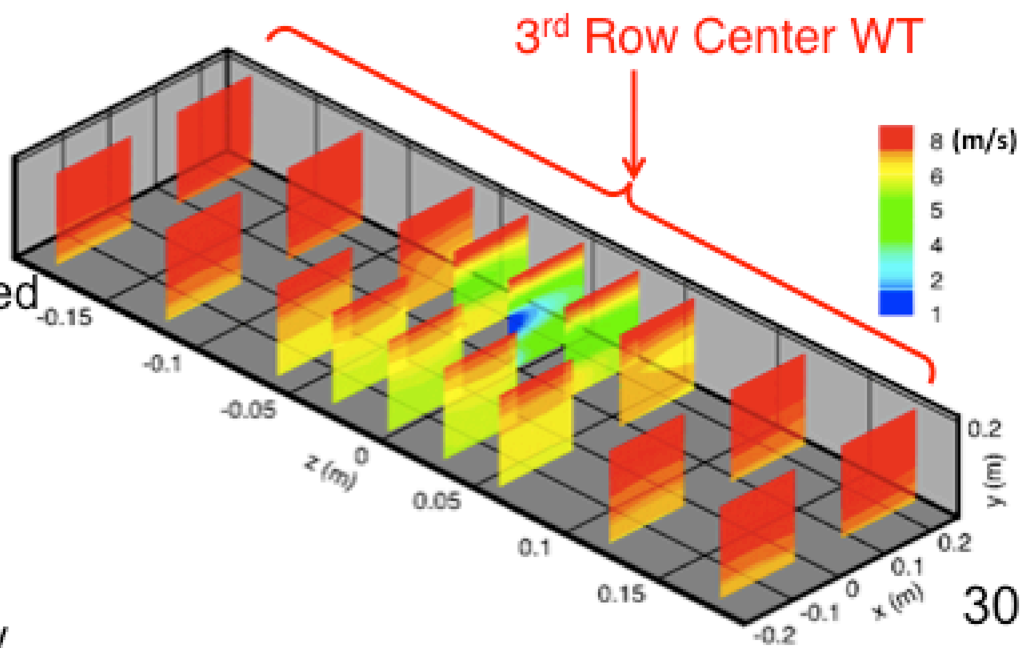
9 planes in back



The wake of the preceding wind turbine is clearly visible as an overall lower velocity in the spanwise locations downstream of the turbines in the middle column.

This confirms that there will be **considerable wake losses** in the modeled wind farm.

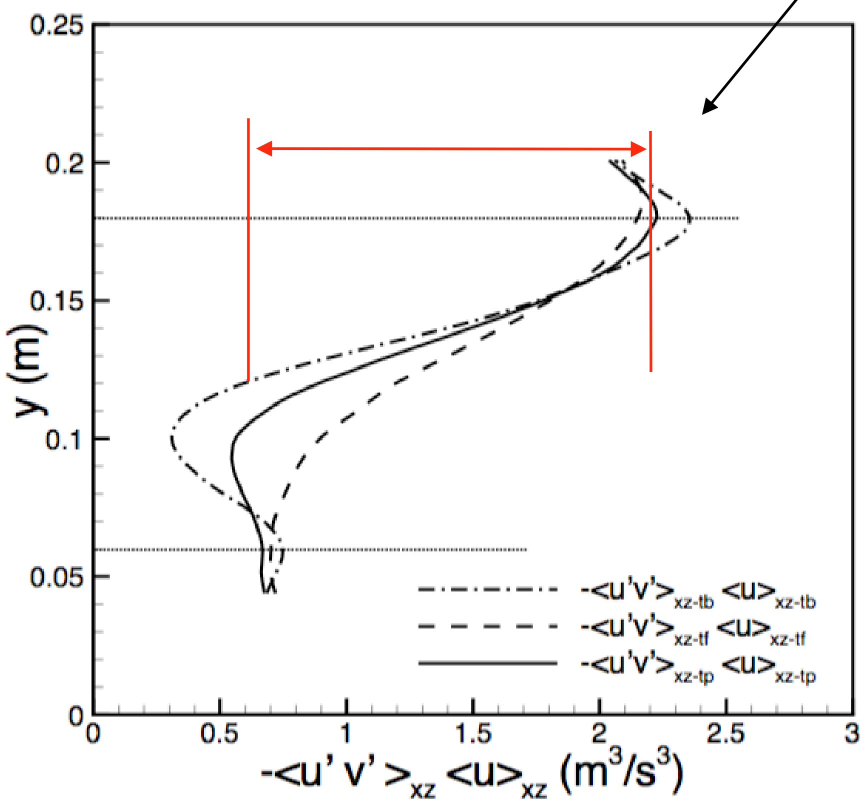
It can be observed that the **flow slows down upstream as it approaches the wind turbine rotor** in qualitative agreement with classic streamtube theory.



Horizontally averaged profiles - kinetic energy terms:

Kinetic energy flux due to turbulent transport

$$\frac{d\frac{1}{2}\langle u\rangle_{xz}^2}{dt} = -\varepsilon_{turb} - \varepsilon_{canop} - \frac{d}{dy}\left(\langle\overline{u'v'}\rangle_{xz}\langle u\rangle_{xz} + \langle\overline{u}''\overline{v}''\rangle_{xz}\langle u\rangle_{xz}\right) - \langle u\rangle_{xz}\frac{1}{\rho}\frac{dp_\infty}{dx} - P_T(y)$$



Integrate kinetic energy dissipation across rotor.

$$P_{loss} = \rho\, s_x s_z D^2 \int_{y_h-D/2}^{y_h+D/2} -\langle\overline{u'v'}\rangle_{xz}\frac{\partial\langle\overline{u}\rangle_{xz}}{\partial y}\, dy \approx 0.094 \text{ W.}$$

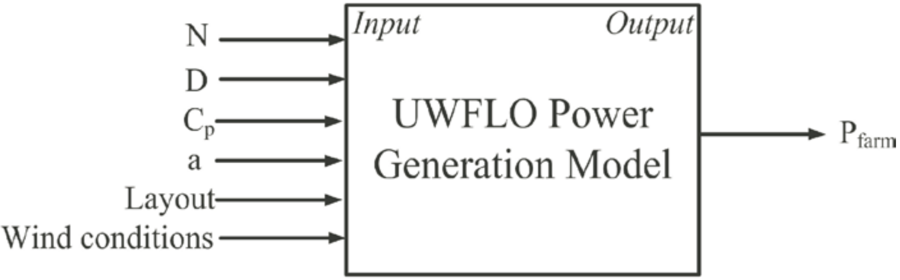
Analysis consistent with view that kinetic energy extracted by turbine (0.34W) is delivered vertically by turbulence fluxes (0.45W)**

**Mechanical power measured independently Kang et al. (2009).

Cal *et al.* JRSE Vol. 2, 013106, (2010).

Power Generation Model

- The Unrestricted Wind Farm Layout Optimization (UWFLO) Power Generation Model



Optimizing Cost of Energy (COE)

- COE is measured by *Levelized Production Cost* (LPC)

$$COE = \frac{C_t \times P_0 \times N \times 1000}{AEP_{net}}$$

- AEP_{net}: *Net Annual Energy Production*

$$AEP_{net} = 365 \times 24 \times P_{farm}$$

C_p: power coefficient curve, a: induction factor curve

Wind Farm Optimization Problem Formulation

Optimization Problem

$$\min_{V} : f = \frac{C_t \times P_0 \times N \times 1000}{AEP_{net}(V)}$$

$$V = \{x_1, x_2, \ldots, x_N, y_1, y_2, \ldots, y_N\}$$

subject to

$$g_1(V) \leq 0$$

$$g_2(V) \leq 0$$

$$0 \leq x_i \leq x_{farm}$$

$$0 \leq y_i \leq y_{farm}$$

Constraints

Minimum clearance

$$g_1(V) = \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} max\left(\left(D_i + D_j + \Delta_{min} - d_{ij}\right), 0\right)$$

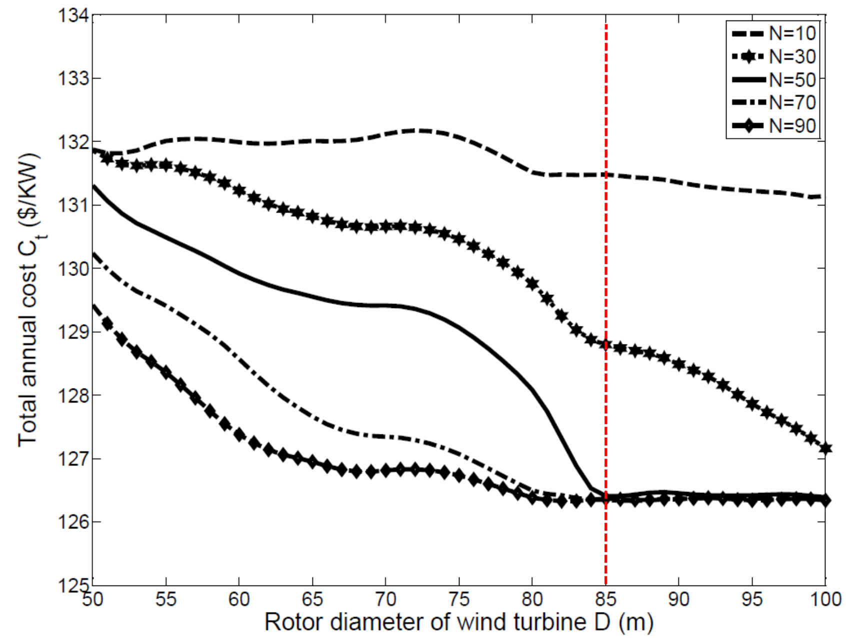
$$d_{ij} = \sqrt{\Delta x_{ij}^2 + \Delta y_{ij}^2}$$

Ensure the location of wind turbines within the fixed size

$$g_2(V) = \frac{1}{2N}\{\frac{1}{x_{farm}} \sum_{i=1}^{N} max(-x_i, x_i - x_{farm}, 0) + \frac{1}{y_{farm}} \sum_{i=1}^{N} max(-y_i, y_i - y_{farm}, 0)\}$$

Total Annual Cost *vs.* The Input Factors

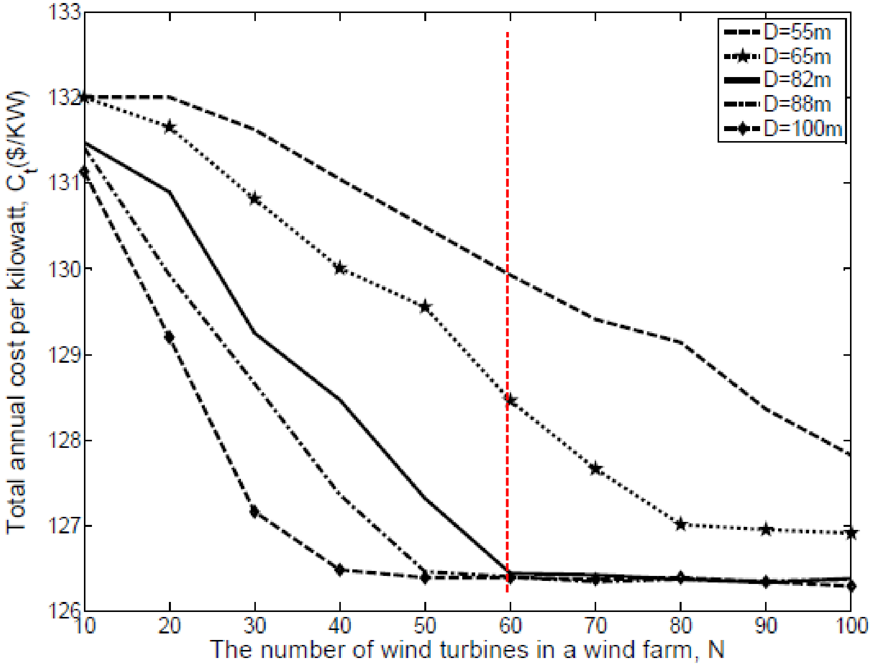
- The total annual cost deceases from \$131.3/KW to \$126.4/KW (approximately 3.73%) when the rotor diameter of a wind turbine increases from 50m to 100m.
- The total annual cost decreases slowly when the rotor diameter is less than 70m.
- The total annual cost begins to decrease sharply when the rotor diameter changes from 70m to 85m.
- If the rotor diameter continues to increase beyond 85m, the change in the total annual cost is particularly limited.



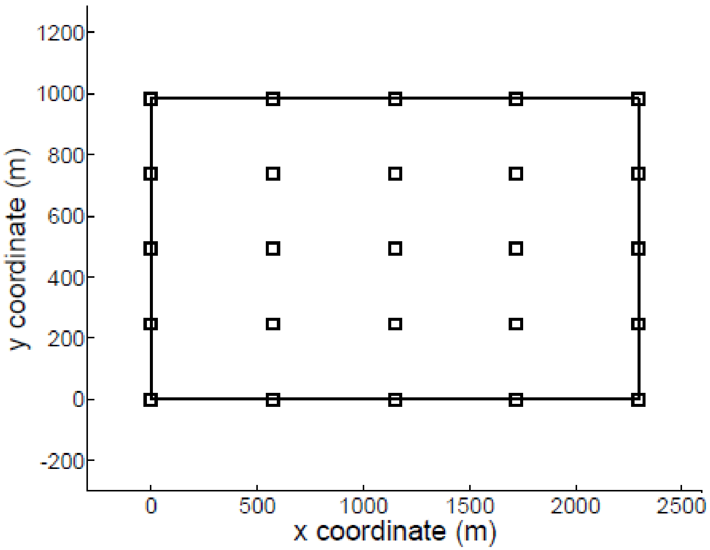
The total annual cost based on the rotor diameter of a wind turbine

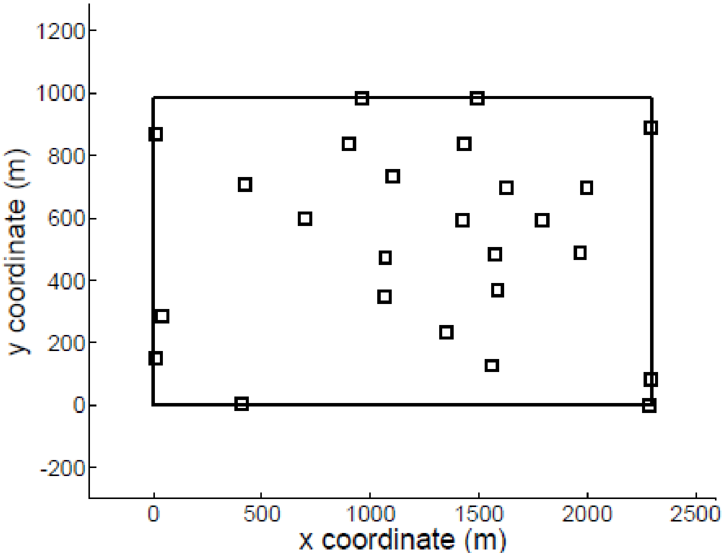
Total Annual Cost *vs.* The Input Factors

- The total annual cost decreases from $131.48/KW to $126.38/KW (approximately 3.88%) while the number of wind turbines increases from 10 to 100.
- The total annual cost does not change significantly when the number of wind turbines increases beyond 60.



The total annual cost based on the number of wind turbines

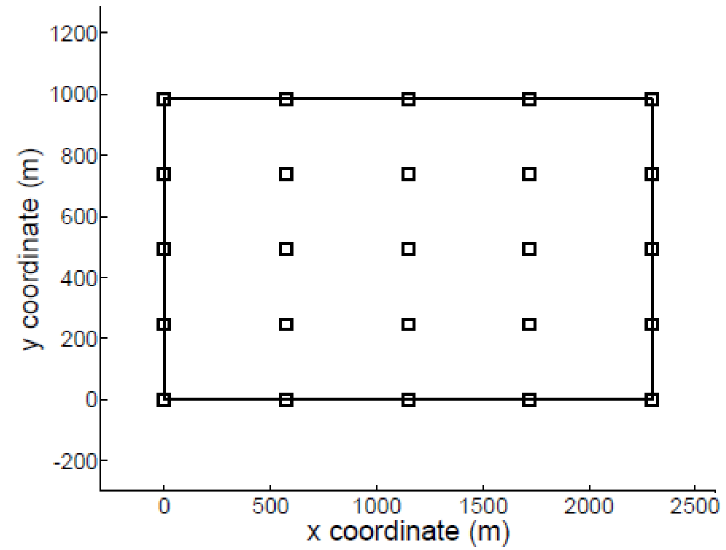


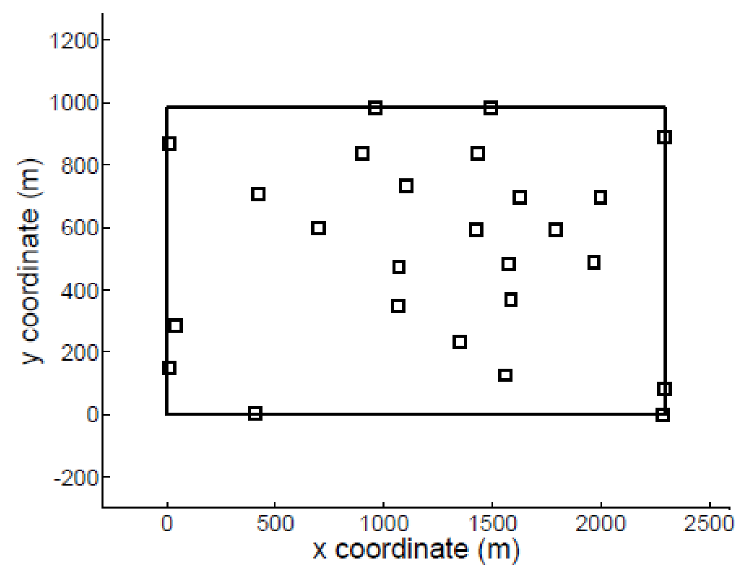


Case Study

Wind farm parameters

Parameter	Value
Number of wind turbines	25
Type of wind turbines	ENERCON E-82
Length of the wind farm	28D
Breadth of the wind farm	12D
Rated power (P_0)	2MW
Rotor diameter (D)	82m
Hub height (H)	85m
Cut-in wind speed	2m/s
Cut-out wind speed	28m/s
Rated wind speed	13m/s





Summary:

- How much momentum transfer is caused by mean velocity dispersive stresses?
  - small compared with Reynolds shear stresses
  - although in the near-wake region they may contribute to wake recovery

- **The vertical fluxes of mean kinetic energy** associated with the streamwise velocity due to Reynolds shear stresses are of the **same order of magnitude as the power extracted by the wind turbines.**
  - -This becomes the dominant mechanism providing kinetic energy to the turbines.

- **The Cost of Energy (COE) was minimized to improve the overall economics of wind energy project.**

- **The preliminary cost map shows wide variation in wind farm cost in the U.S.**

- **The resulting cost model could be a useful tool for wind farm planning.**