Challenges in Offshore Wind Energy Aerodynamics: Floating Wind Turbines and Wind Farms

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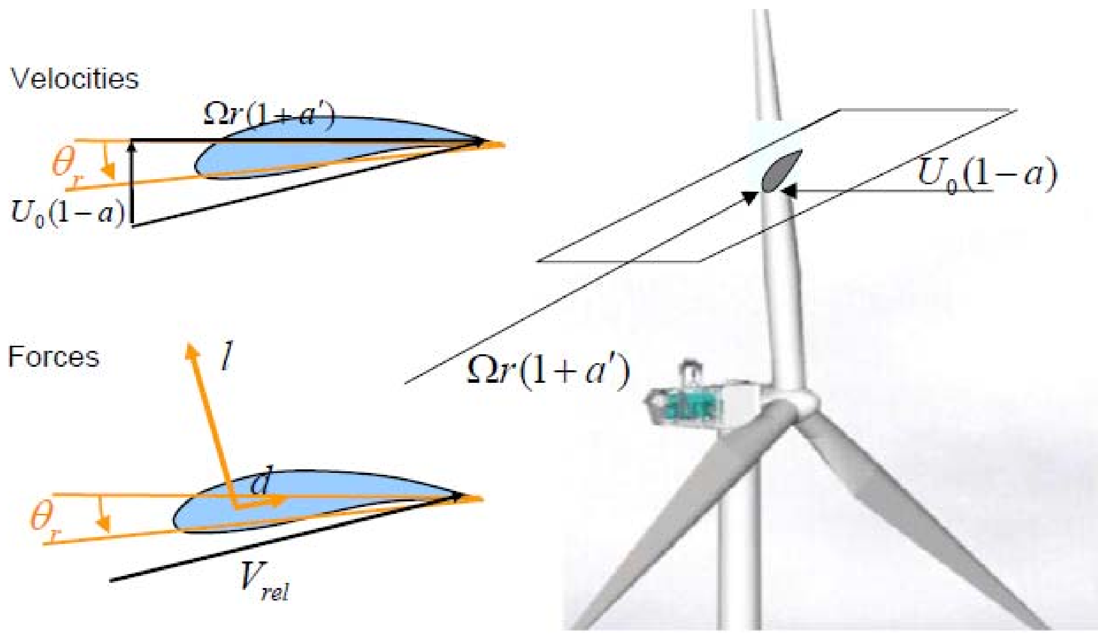
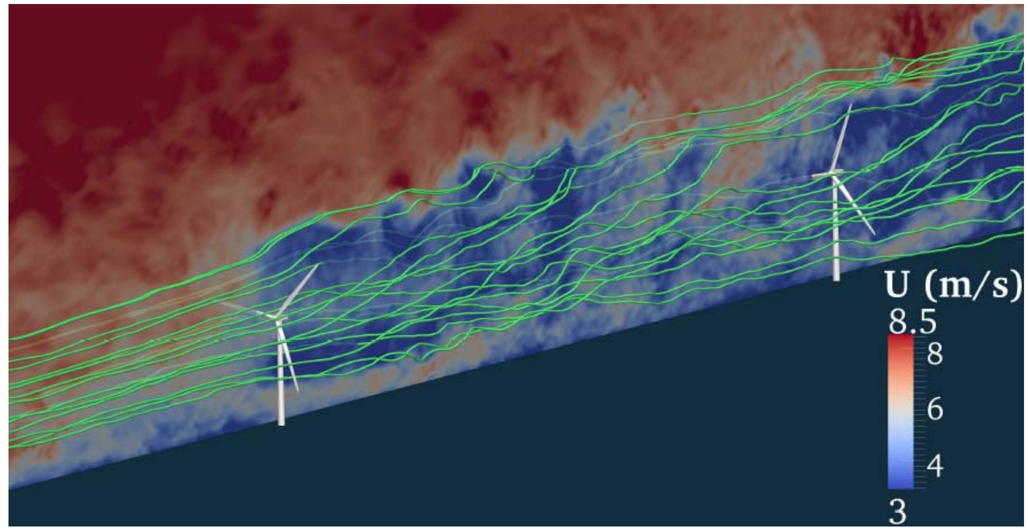
Why are Aerodynamics important?

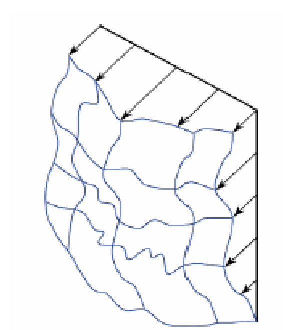
- Wind turbines convert kinetic energy in the wind into rotational energy of the rotor which then is extracted as electrical energy by the generator.
- Aerodynamic forces, i.e. lift, are responsible for this conversion.

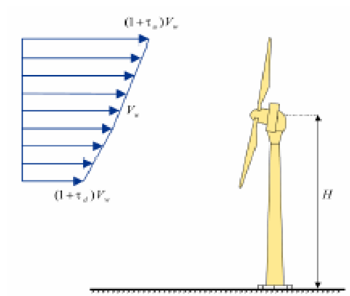


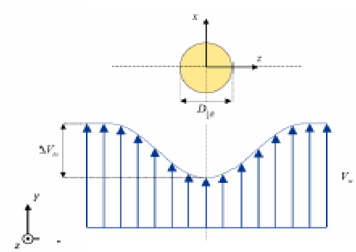
Complexity of Wind Turbine Aerodynamics

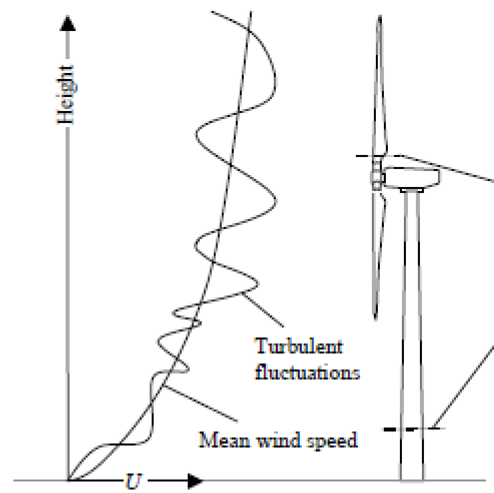
- Wind turbines operate in a complex external flow field.
  - Turbulence
  - Wind Shear
  - Tower shadow
  - Yaw
  - Upstream wakes
- Leads to complex flow over the blades and time varying, unsteady forces





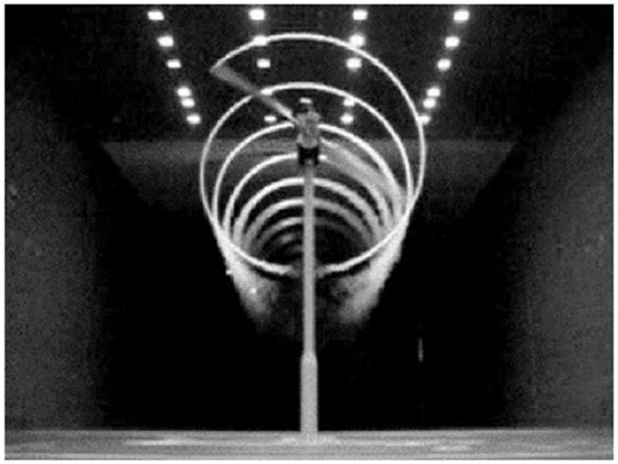


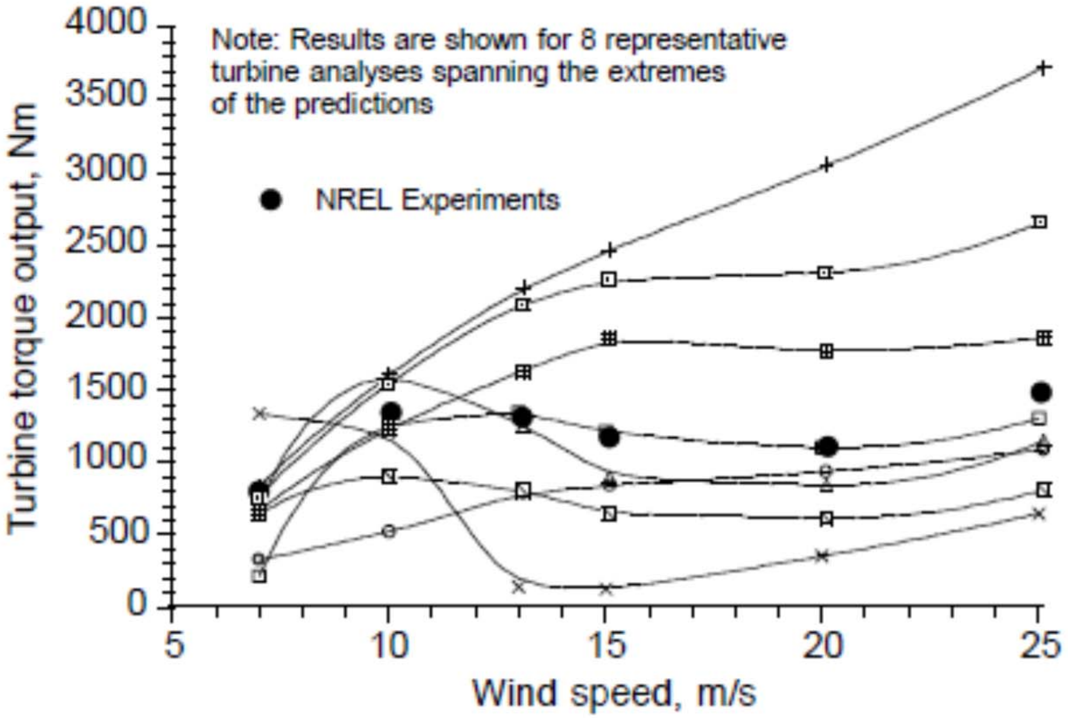




Modeling is hard!

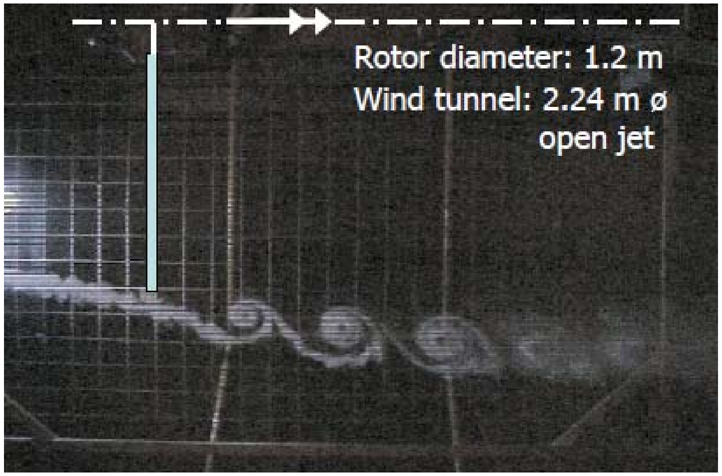
- NREL NASA AMES Unsteady Aerodynamics Experiement (UAE) in 2000.
  - 2 bladed turbine in controlled conditions.
  - 10 m diameter, 80' by 120' tunnel
  - Blind modeling comparison

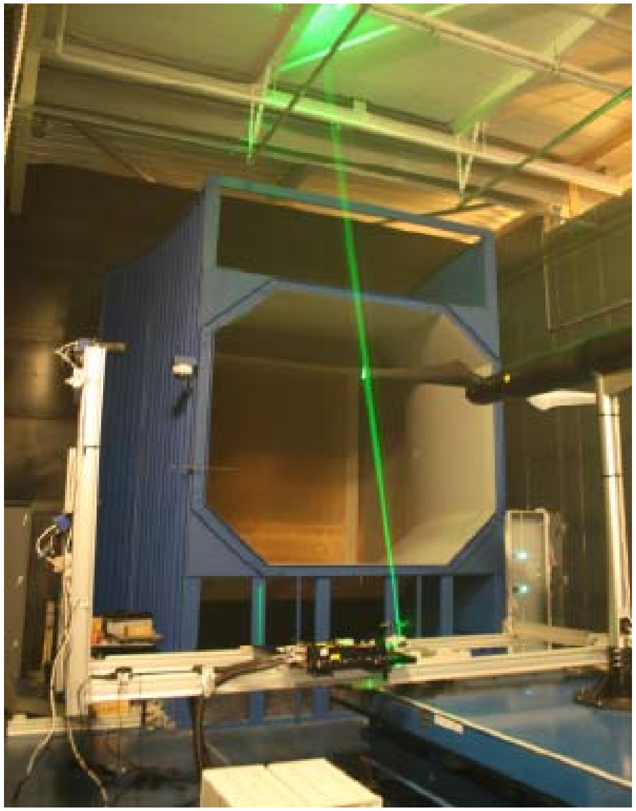


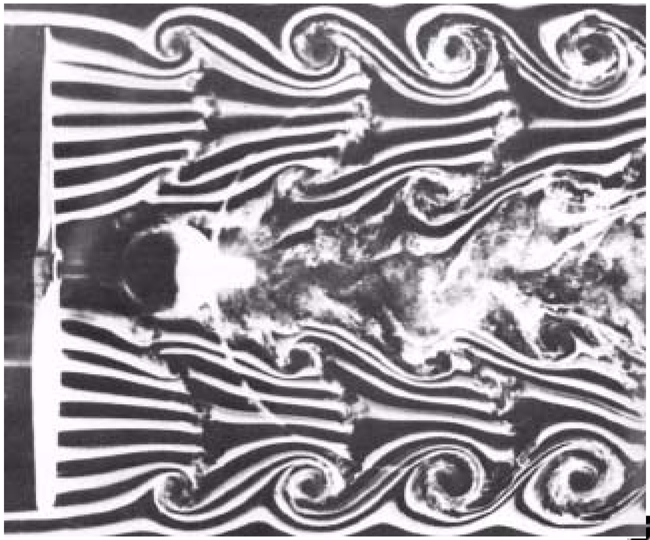


Measuring Performance

- Many techniques and experiments to generate data and better understand wind turbine aerodynamics
  - Smoke
  - PIV
  - Hot wire
  - etc

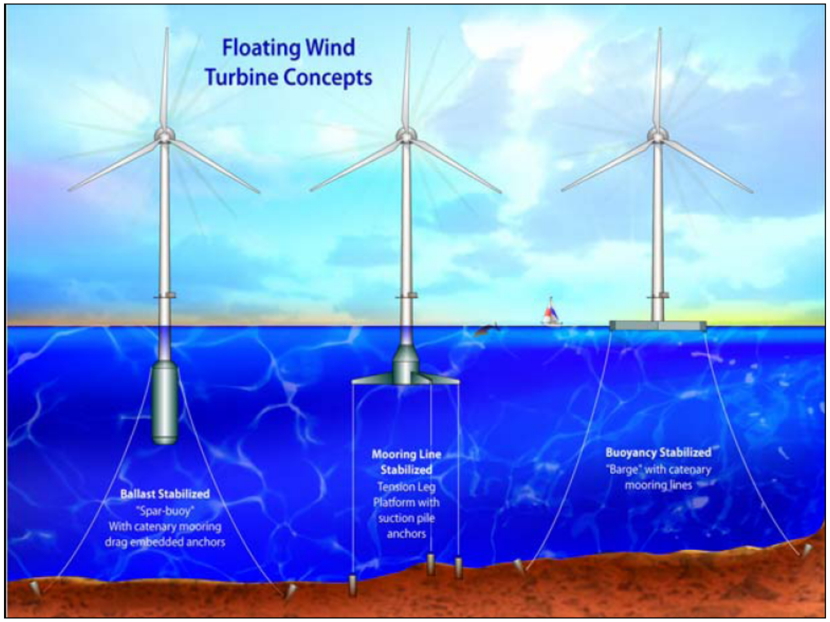


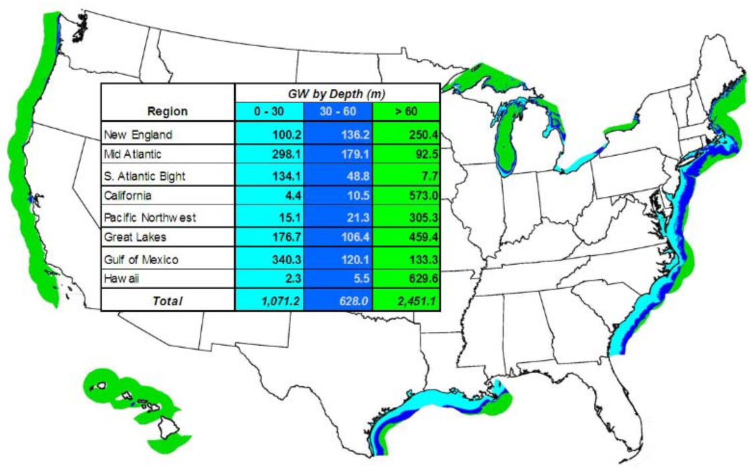




Floating Wind Turbines

- Significant promise and numerous advantages:
  - Access deeper water and higher winds
  - Relatively independent of sea floor
  - Potentially easier to install
- But also major challenges.
- Increased platform motion causes:
  - More complex aerodynamic operating environment.
  - Larger loading on structural components



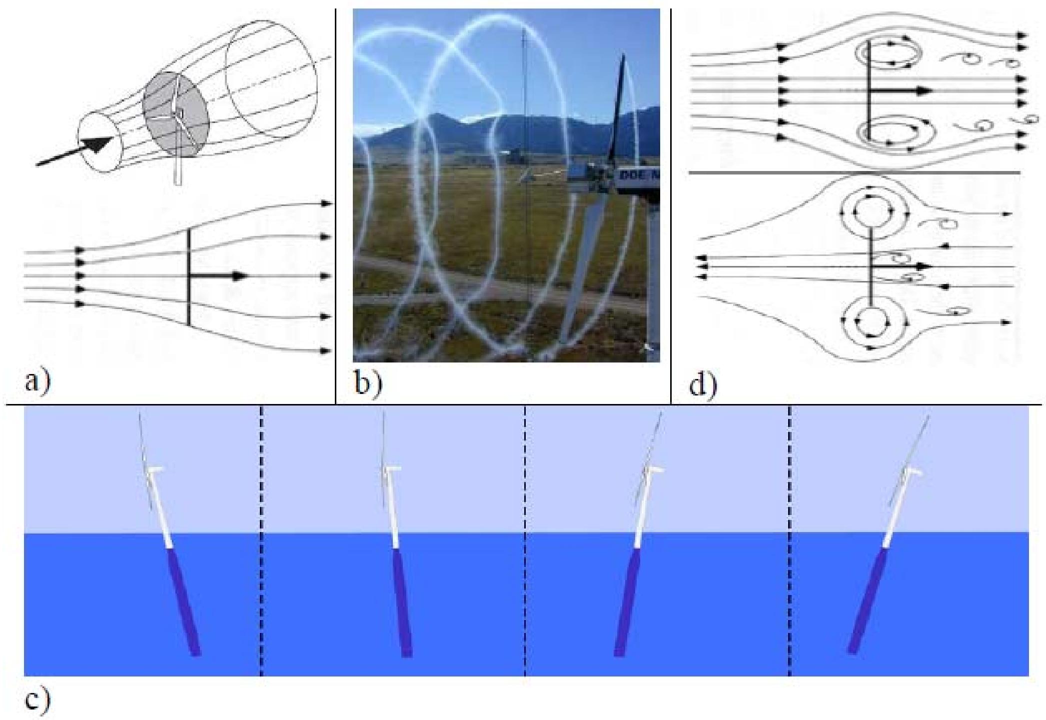


Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

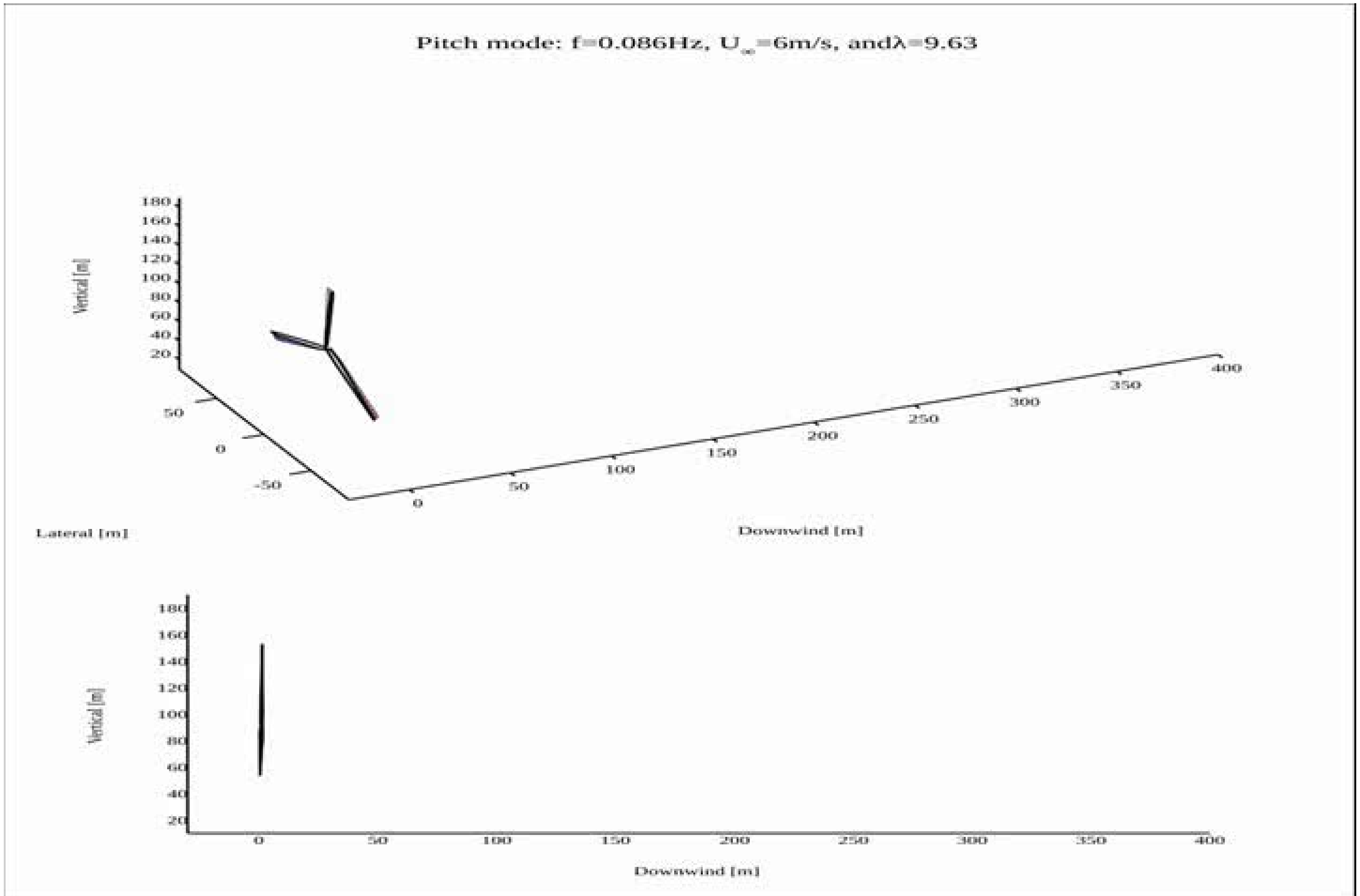
UMASS

Unsteady Aerodynamics of Floating Turbines due to Platform Motions

- Standard wind turbine has rotor that is relatively stationary.
- Platform motion for floating turbine causes effective wind contributions.
- Possible transient flowfield due to periodic shifting between windmill and propeller state.
- Potentially much more complex flowfield for floating turbines.
- Question: how to understand and model flowfield of a floating wind turbine?



Wake Structure Generated Using WInDS



Analysis of Floating Turbine Aerodynamics

- Flowfield of floating turbines is significantly more complex and unsteady than monopiles
  - Ad-hoc corrections are less valid
  - Table shows unsteady energy for floating turbines relative to a monopile

	ITI Energy barge	OC3/Hywind spar-buoy	MIT/NREL TLP
Below-rated	14.1	2.1	1.1
Rated	4.1	3.7	1.1
Above-rated	3.2	6.3	1.0

- Higher fidelity models are needed.
  - Standard methods fail for this situation
- Floating wind turbines present an important and interesting aerodynamic modeling challenge.

Summary

- Floating wind turbines have tremendous promise but much more complex aerodynamics.
- Optimal design of monopile rotor may not be optimal for floating turbine.
- Aerodynamics are directly related to the support structure design, and impact the blade structural design and the overall turbine reliability.
  - Possible interdisciplinary research opportunities in engineering.
- Floating turbines require different infrastructure and installation approaches.
  - Possible interdisciplinary research opportunities in planning and economic development.

Wind Farm Aerodynamics

- Offshore wind turbines likely to be organized into wind farms with 10's or 100's of turbines.
- Wakes of upstream turbines impact downstream turbines with lower wind speeds and higher turbulence.
  - Typical spacing between turbines is 4-10 rotor diameters
- 10-15% energy loss possible in large wind farms.
- Loads are larger due to the increased turbulence in the wakes (increase up to 100% in partial wake).

Measurements and Models

- Upstream turbines see unaffected free stream flow.
- Big power drop for second turbine
- Then smaller drop to later turbines
- Models do “OK”

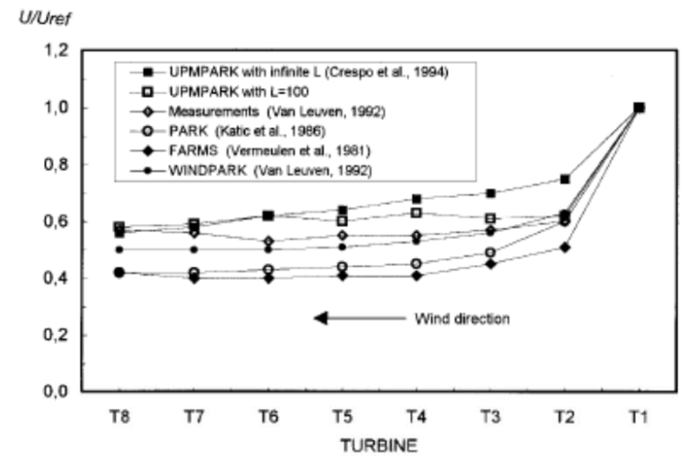


Figure 5. Velocity distribution in wake region of seven turbines forming a row. Comparison of measurements and results of several wind farm codes. Measurements and configuration correspond to the Zeebrugge wind farm.[93,94] U_{ref} is the unperturbed upstream velocity at hub height. The UPMPARK calculations have been performed for two stability situations: neutral atmosphere (Monin–Obukhov length, $L = \infty$) and stable atmosphere ($L = 100\,m$, hub height $31\,m$)

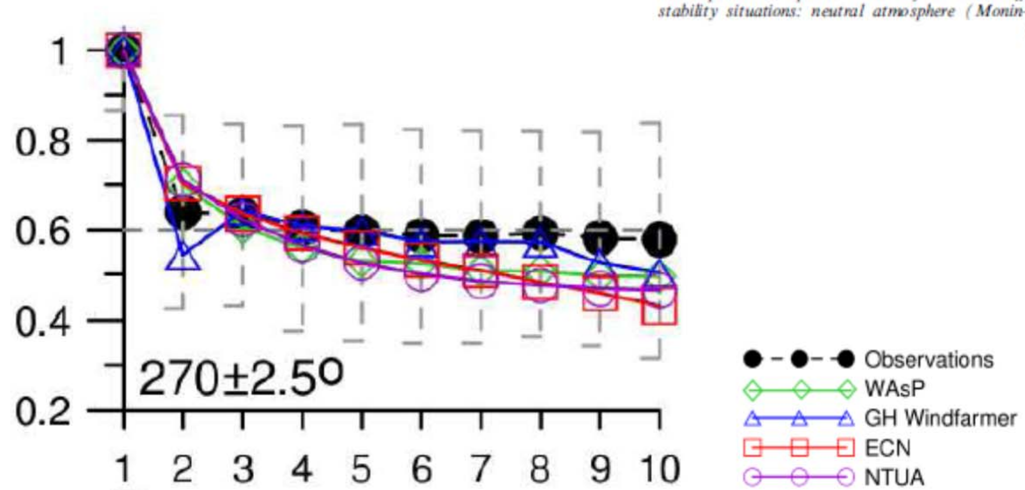
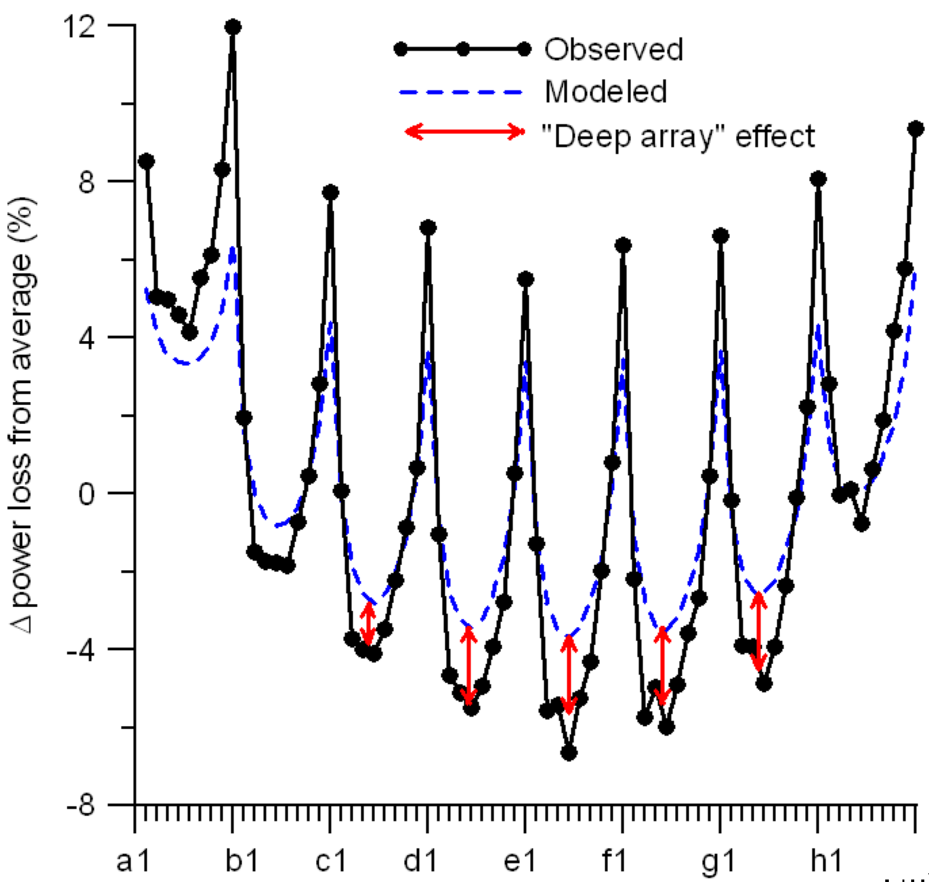


Figure 8: Power (normalised) as function of turbine number in a wind farm at a wind speed of 8 m/s; different models compared to measurements [4].

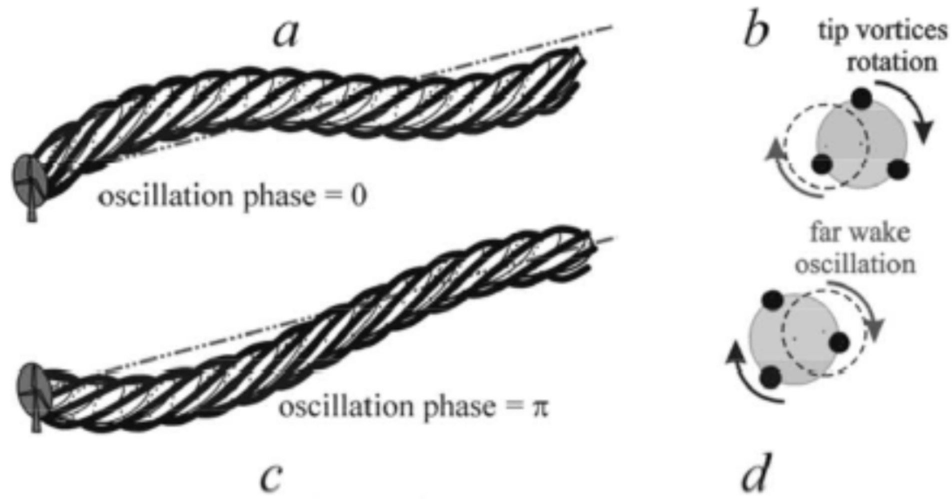
Hard to Model

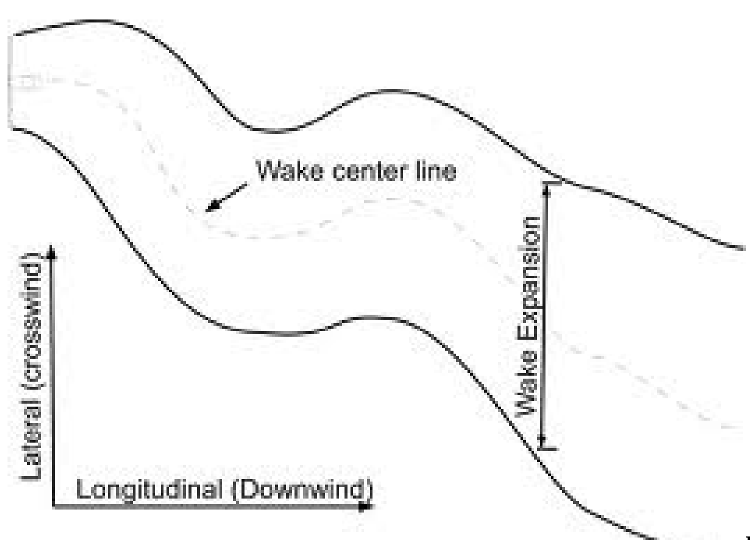
- Turbine output deep in array is especially hard to model



Meandering!

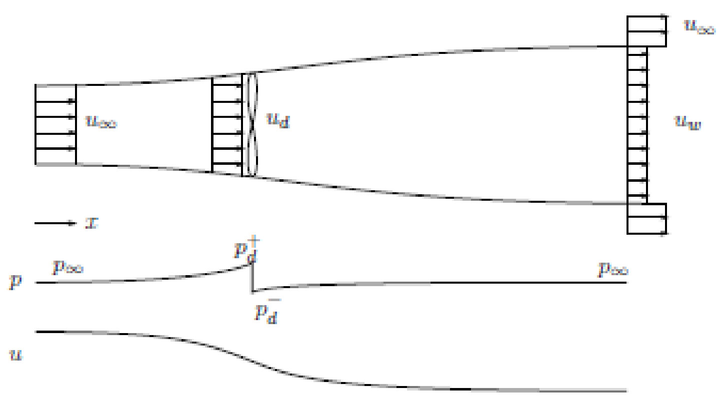
- Wakes meander i.e. they oscillate in their downstream trajectory
- Due to large scale turbulence in the atmosphere with scales on the order of the rotor diameter.
- Meandering can cause wakes to impact and then move away from downstream turbines dynamically
  - Large increases in fluctuating forces

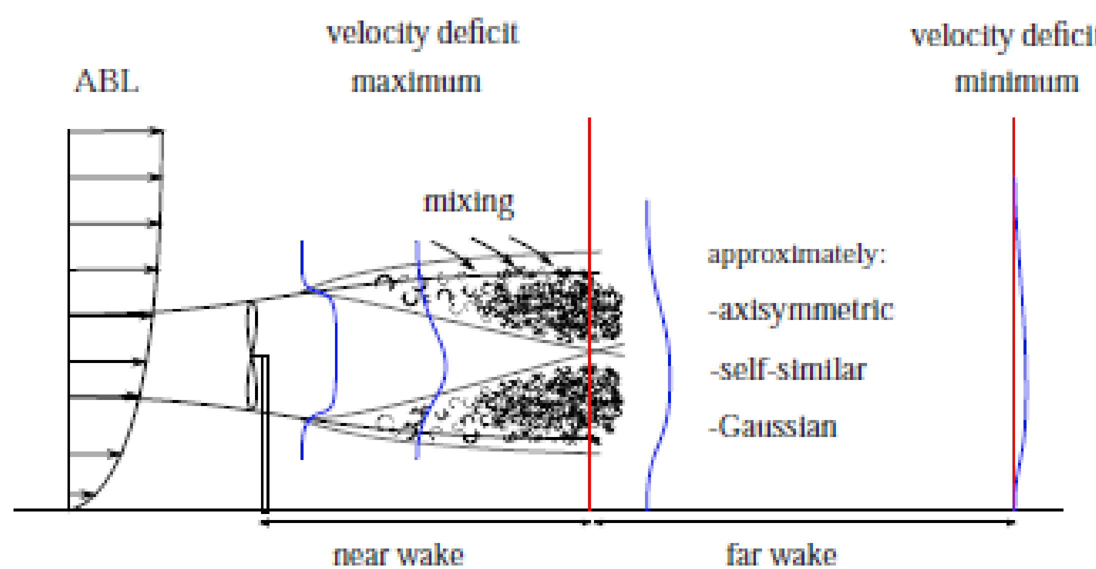




Physics

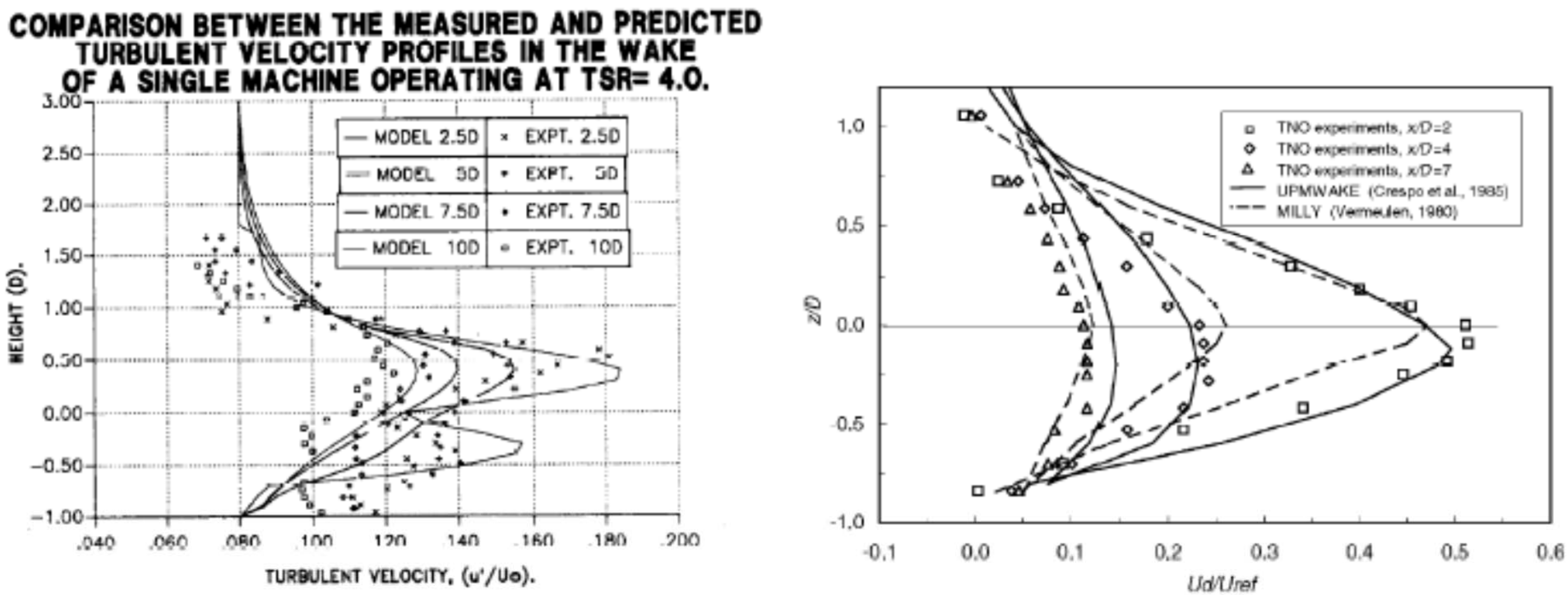
- The wake forms a cylindrical shear layer that separates the freestream flow from the slow moving wake flow.
- The shear layer produces turbulence – a thin velocity gradient between the freestream flow and the slow wake flow causes viscous shear and turbulent eddies are formed.
  - Turbulence created in the shear layer causes mixing between the freestream flow and the wake flow and causes the shear layer to become thicker





Experimental Wake Data

- Turbulent diffusion causes the wake velocity to gradually increase and the turbulence levels to decrease as the wake mixes with the freestream flow.
- Velocity deficit becomes negligible after approximately 10D.
- Turbulence in wake persists longer and is noticeable after 15D.



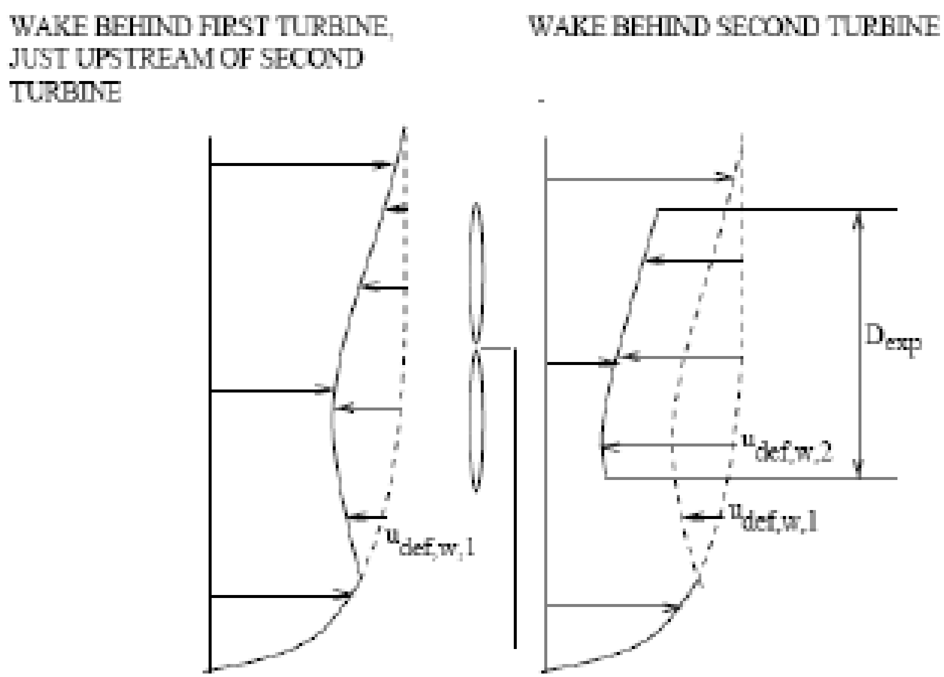
(a) Turbulent velocity [64]

(b) Velocity deficit [81]

Figure 7: Turbulence and velocity deficit in the wake at various downstream distances.

Downstream Impacts

- When wind turbines are organized in a farm, wakes from upstream turbines impact downstream turbines.
- Net result is lost power and increased loading.
- Partial wake is largest increase in loading.



Simulation: CFD

- Computational fluid dynamics is not practical in most cases and engineering or field models are used in practice.
- Recently some simulations of full wind farms have been performed
  - Model the wind turbine as a disk, not the details of each blade.

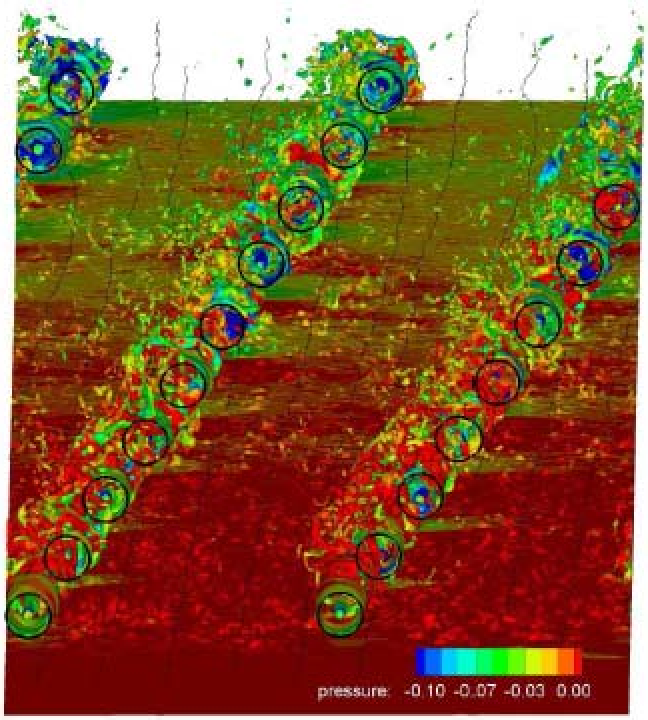


Figure 16: CFD simulation with EllipSys3D of Horns Rev [29].

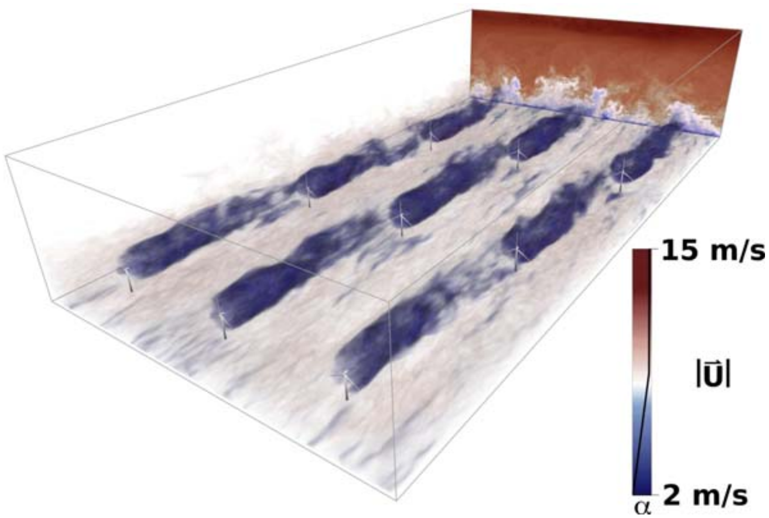
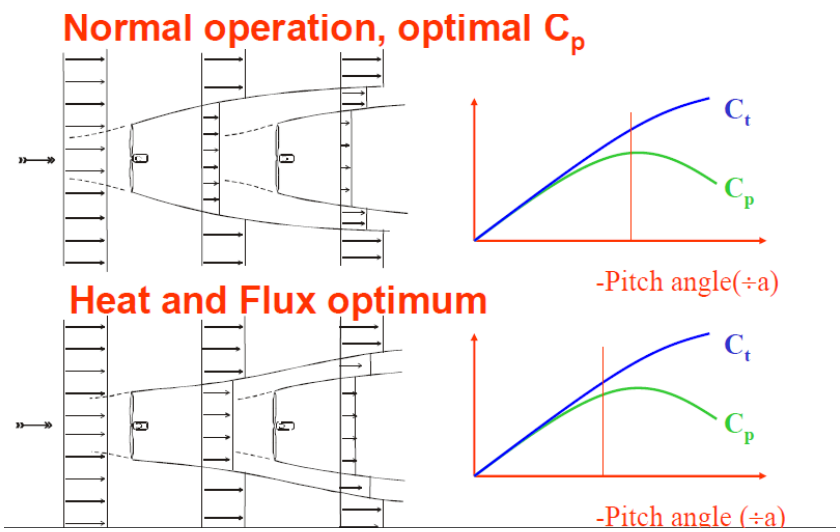
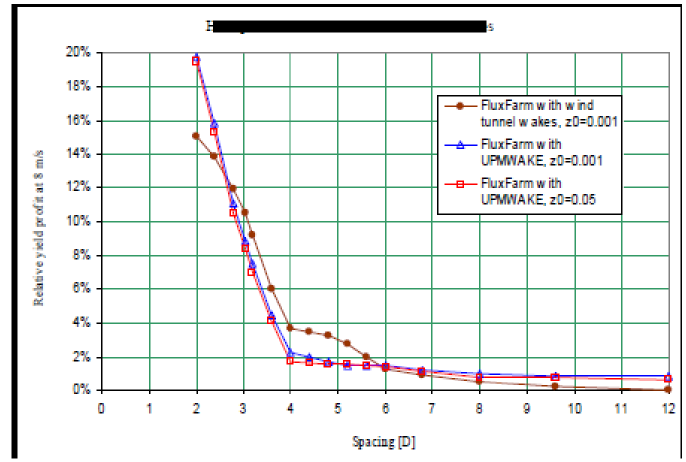
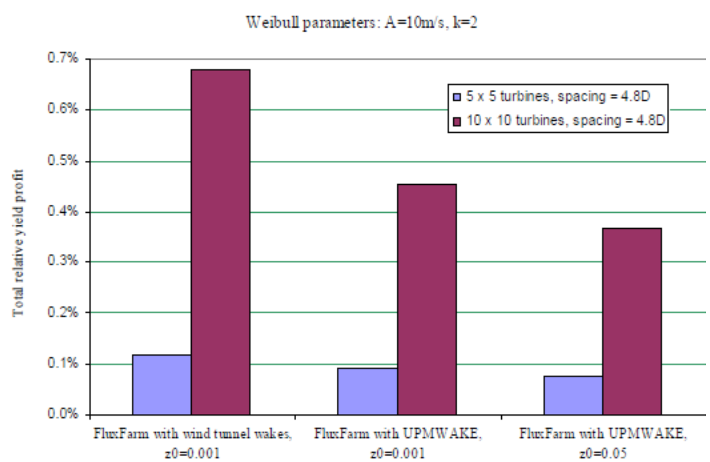
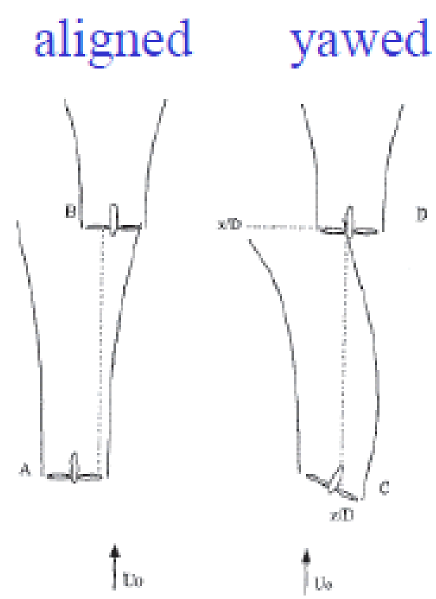


Figure 12 - Reducing wake losses



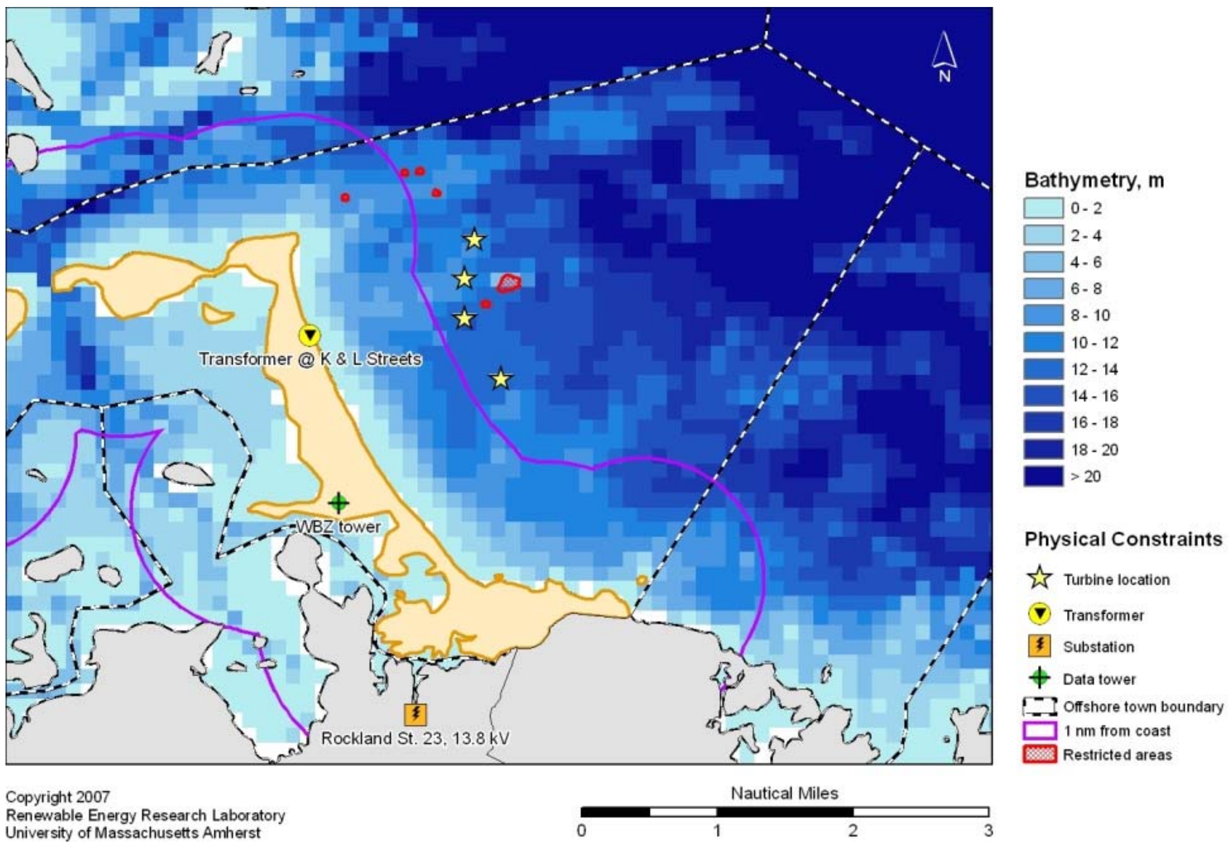






Optimization

- Wind farm layout optimization must take wake effects into account.



Summary

- Wind farm aerodynamics are complex and difficult to model
- Wakes have a huge impact on energy production and reliability of turbines
- Layout of the wind farm determines production and economic success.
- Interdisciplinary issues related to taking environmental issues and public preferences into account.