Wind Energy Aerodynamics – Rotor, Wake, and Wind Plant

Stanford Seminar for Faculty and Students
Stanford, CA

October 12, 2010

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NREL's National Wind Technology Center

NREL/PR-5000-49705

National Wind Technology Center

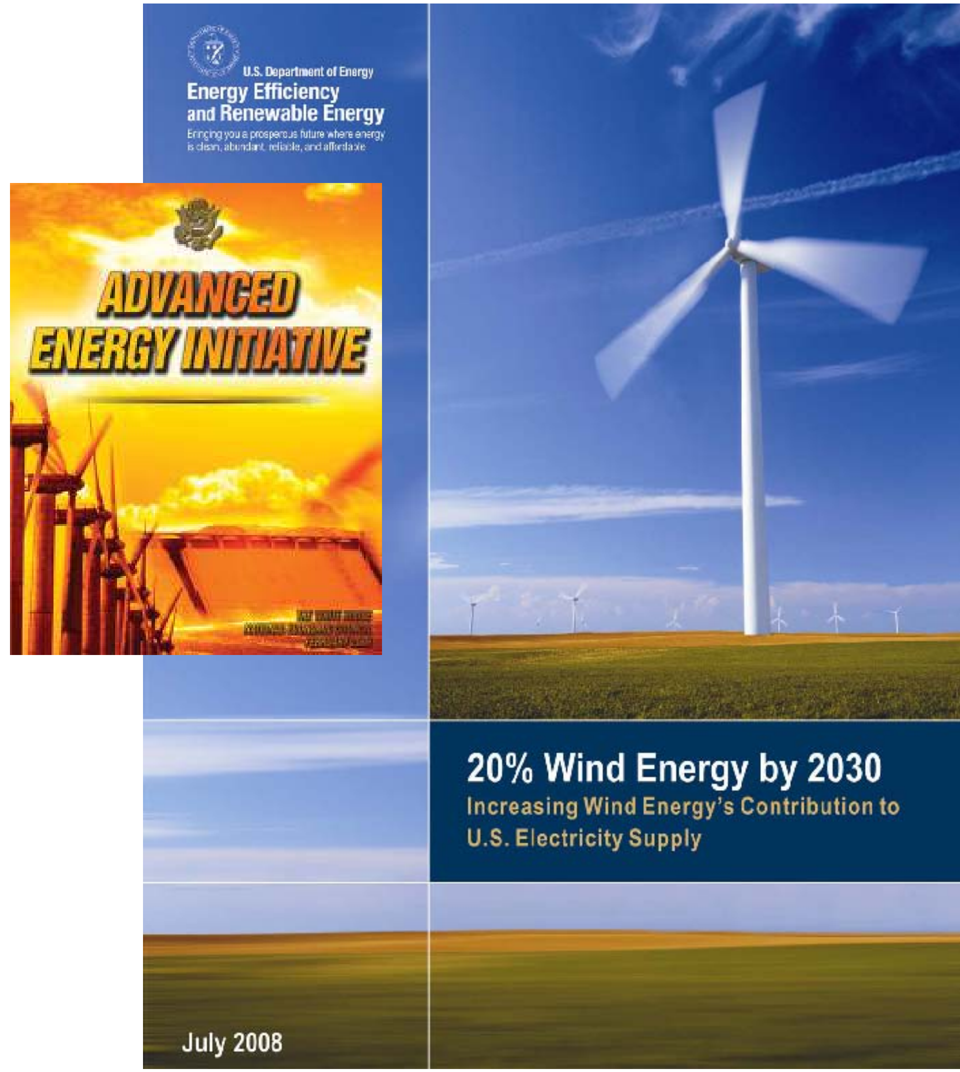
- Turbine technology since 1977 (SERI)
- Development of design and analysis codes
- Pioneers in component and field testing
- Unique test facilities
    - Blade Testing
    - Dynamometer
    - CART turbines
- Modern utility-scale turbines
- Approx. 160 staff on-site
- Budget approx. $35M
- Many CRADAs with industry
- Leadership roles for international standards

PIX #15847

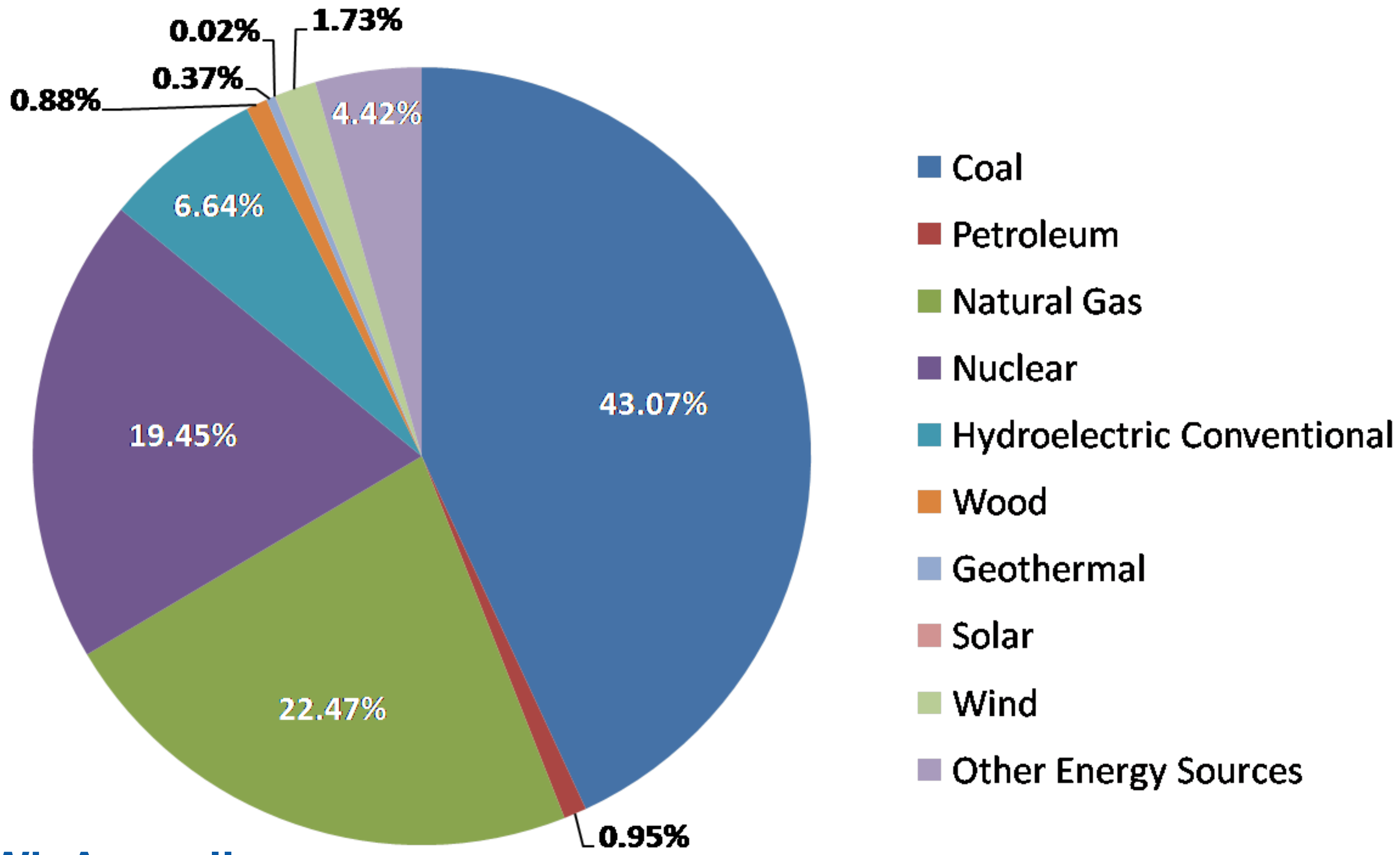
Critical Elements for 20% Scenario

300 GW by 2030

- 80% Land 20% Offshore
- Improved Performance
  - 10% reduction in capital cost
  - 15% increase in capacity factor
  - Address Wind Farm underperformance
- Mitigate Risk
  - Reduce O&M costs by 35%
  - Foster the confidence to support continued 20% per year growth in installation rates from now until 2018
- Enhanced Transmission System (AEP)
  - $60 billion cost estimate over 20 yrs
  - 19,000 mi of line
  - Supports 200-400 GW addition
- Policy, Communication & Outreach
- Infrastructure Development



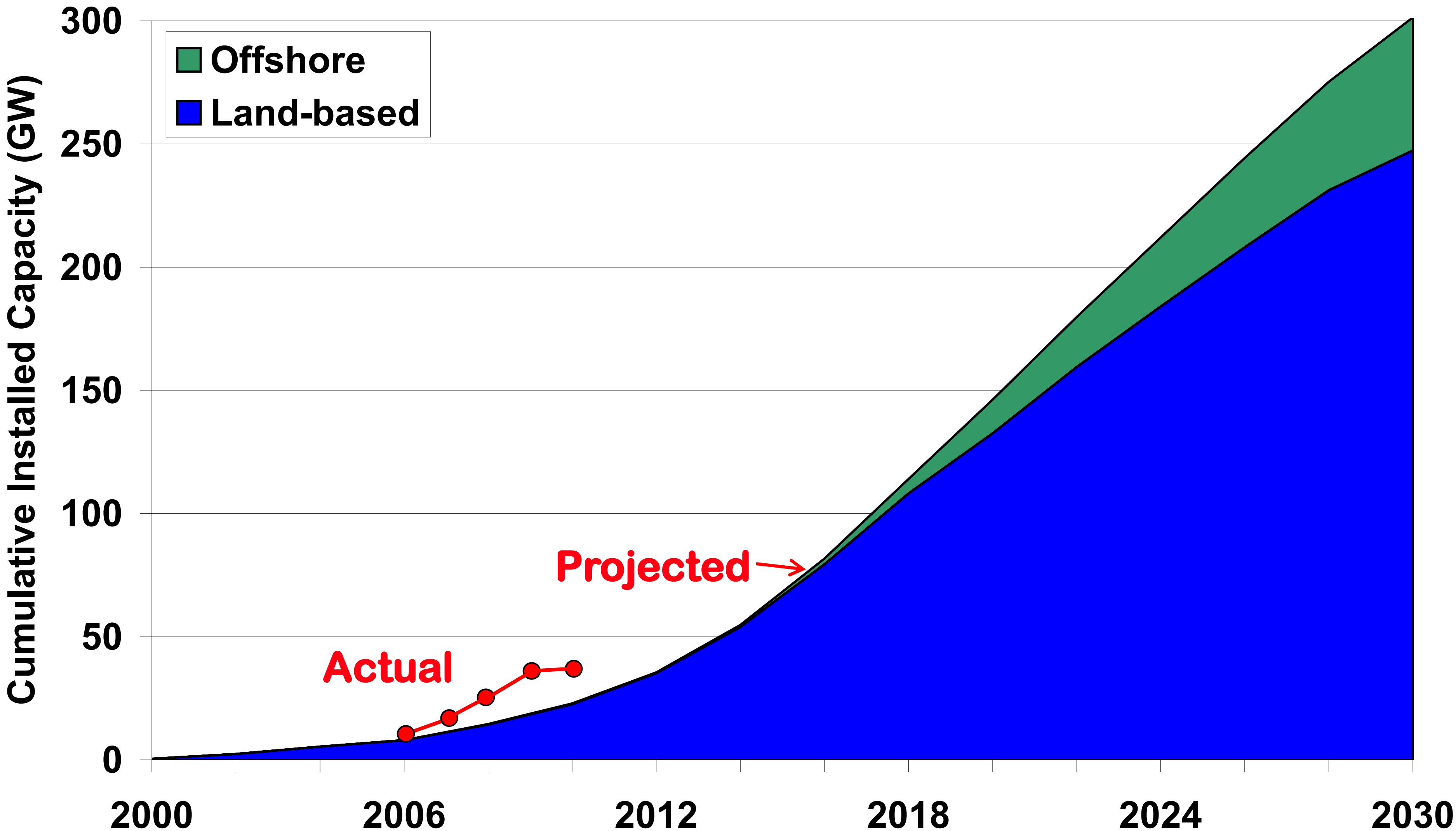
Electrical Power Generation by Source



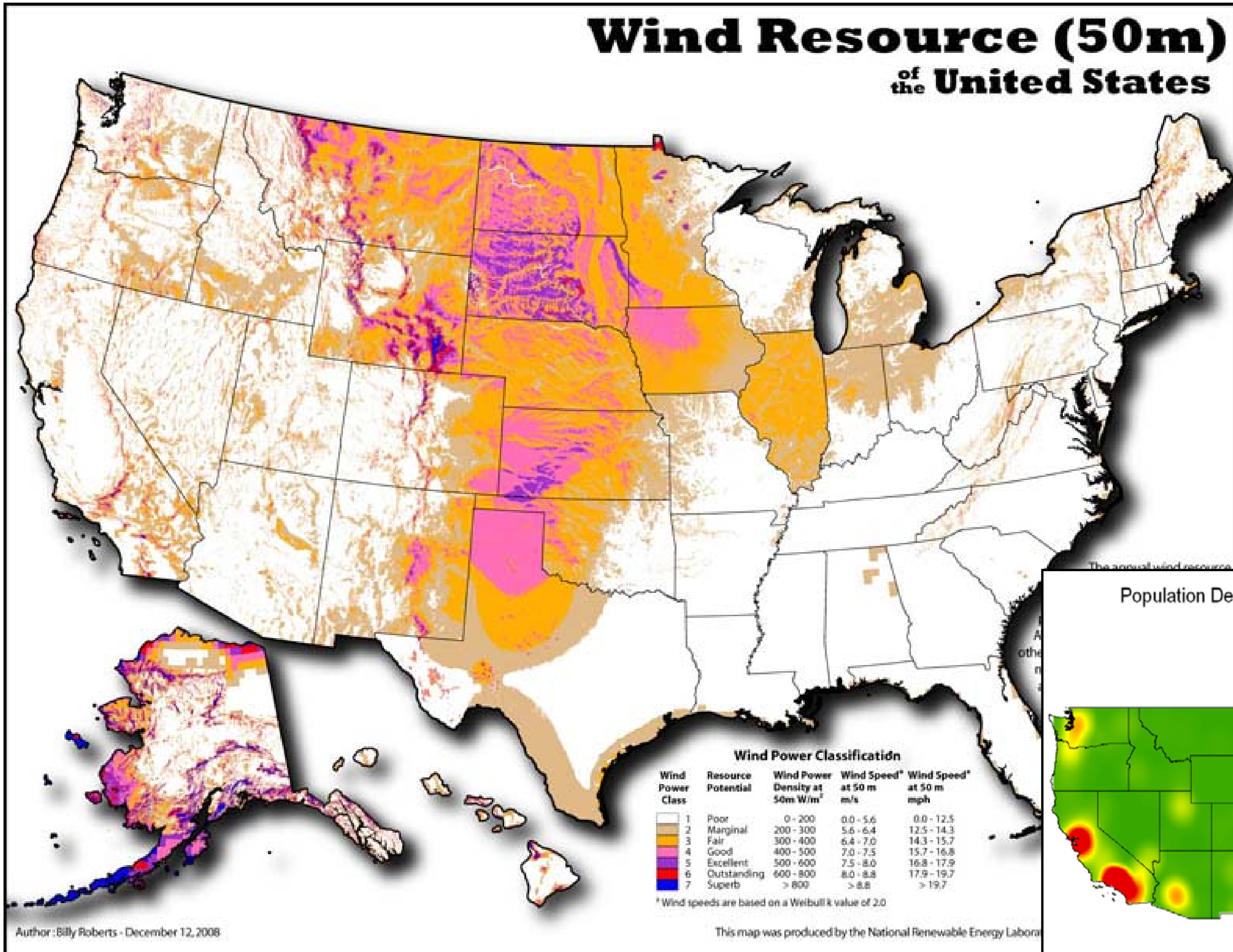
3700 TWh Annually
(0.42 TW Continuous energy use)

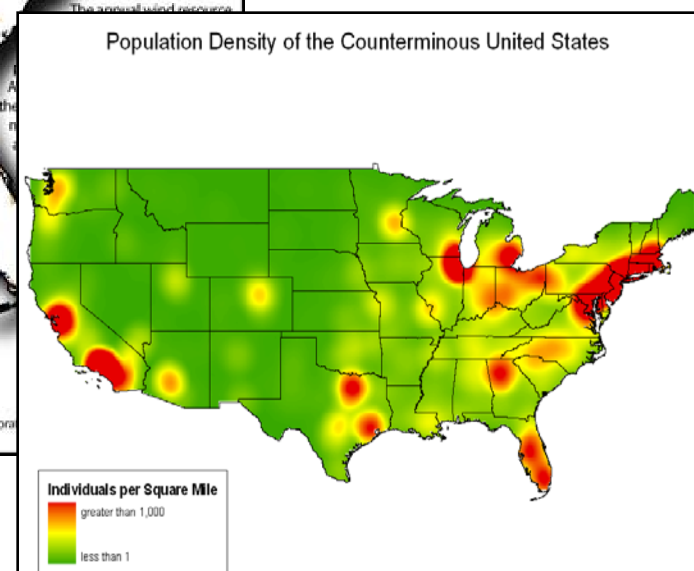
Source: *Electric Power Monthly*, March 15, 2010
http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html

20% Requires 300 GW - Land & Offshore

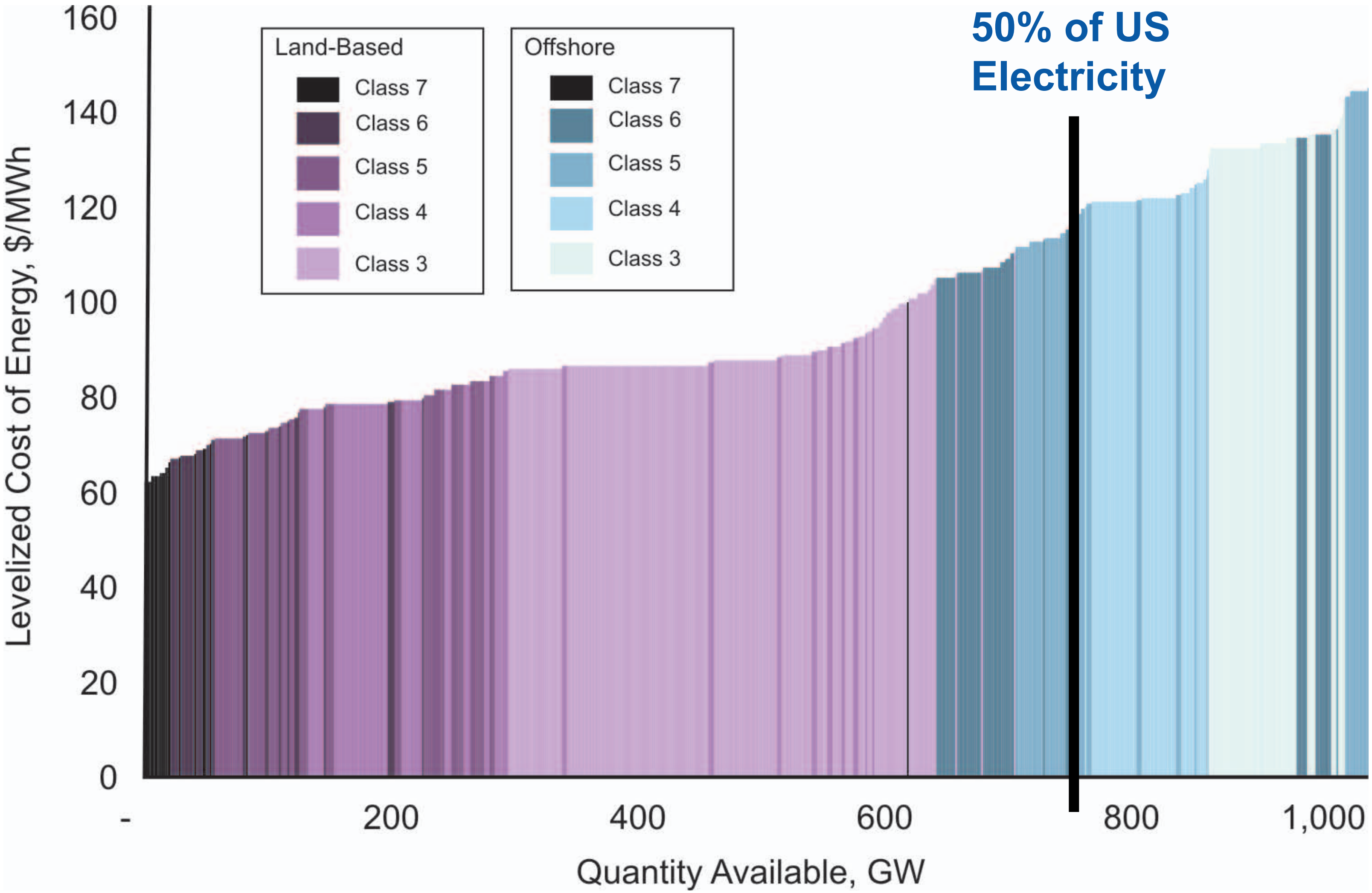


Wind Resource Distribution





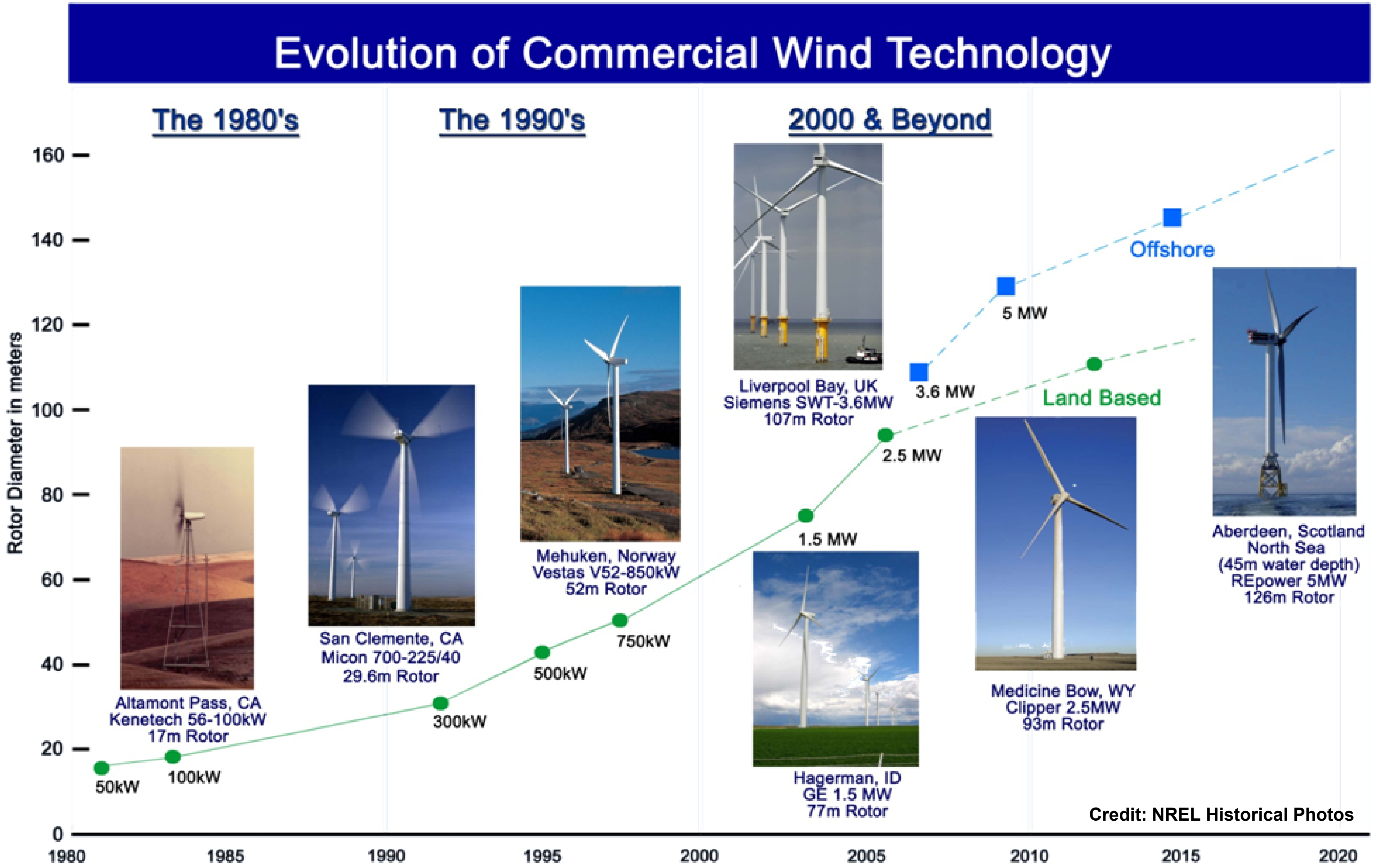
How Much Wind is Available … Really?



Excludes PTC, includes transmission costs to access 10% existing electric transmission capacity within 500 miles of wind resource.

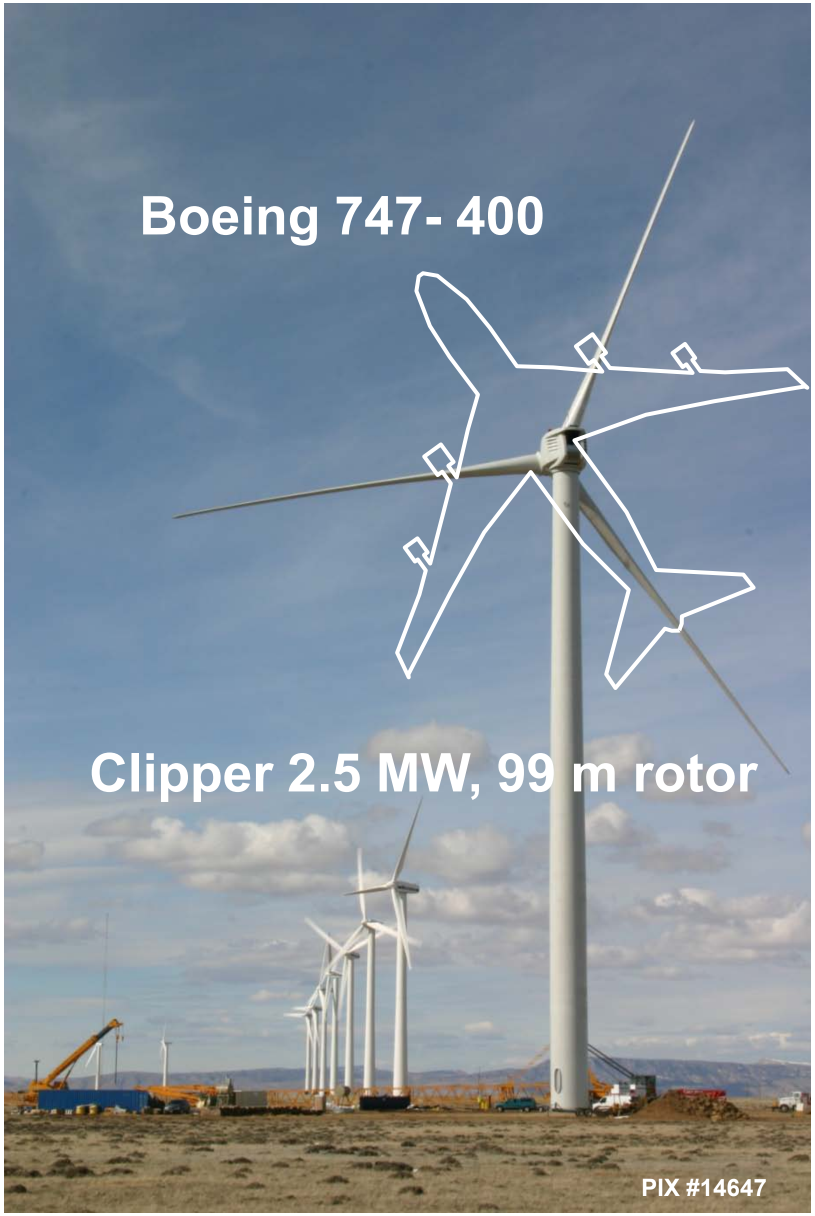
Source: Black & Veatch/NREL

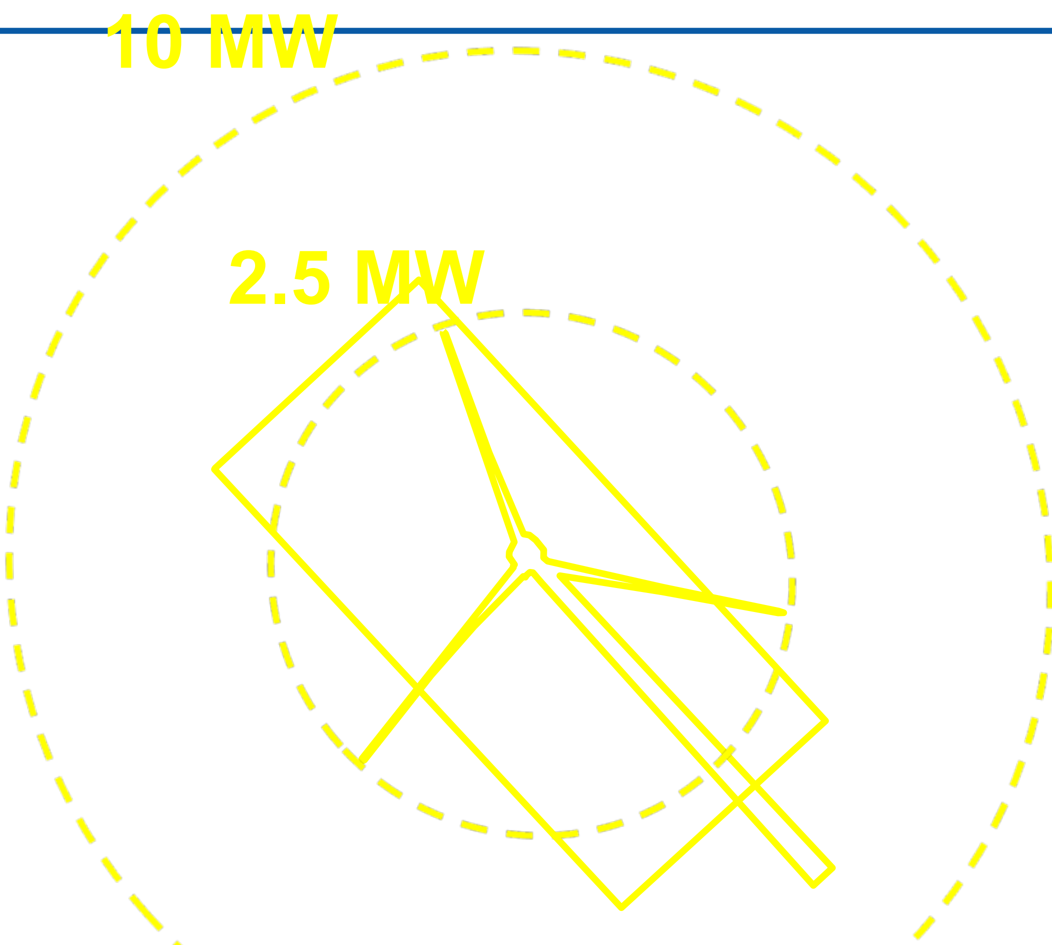
Technology Evolution



Wind Turbine Scale – Present and Future

- 2.5 MW - typical commercial turbine Installation
- 5.0 MW prototypes being installed for testing in Europe
- Clipper Wind Power developing an 8.5 MW turbine
- Most manufacturers have a 10 MW machine in design
- Large turbine development programs targeting offshore markets
- Development Outpacing Test & Validation Capability

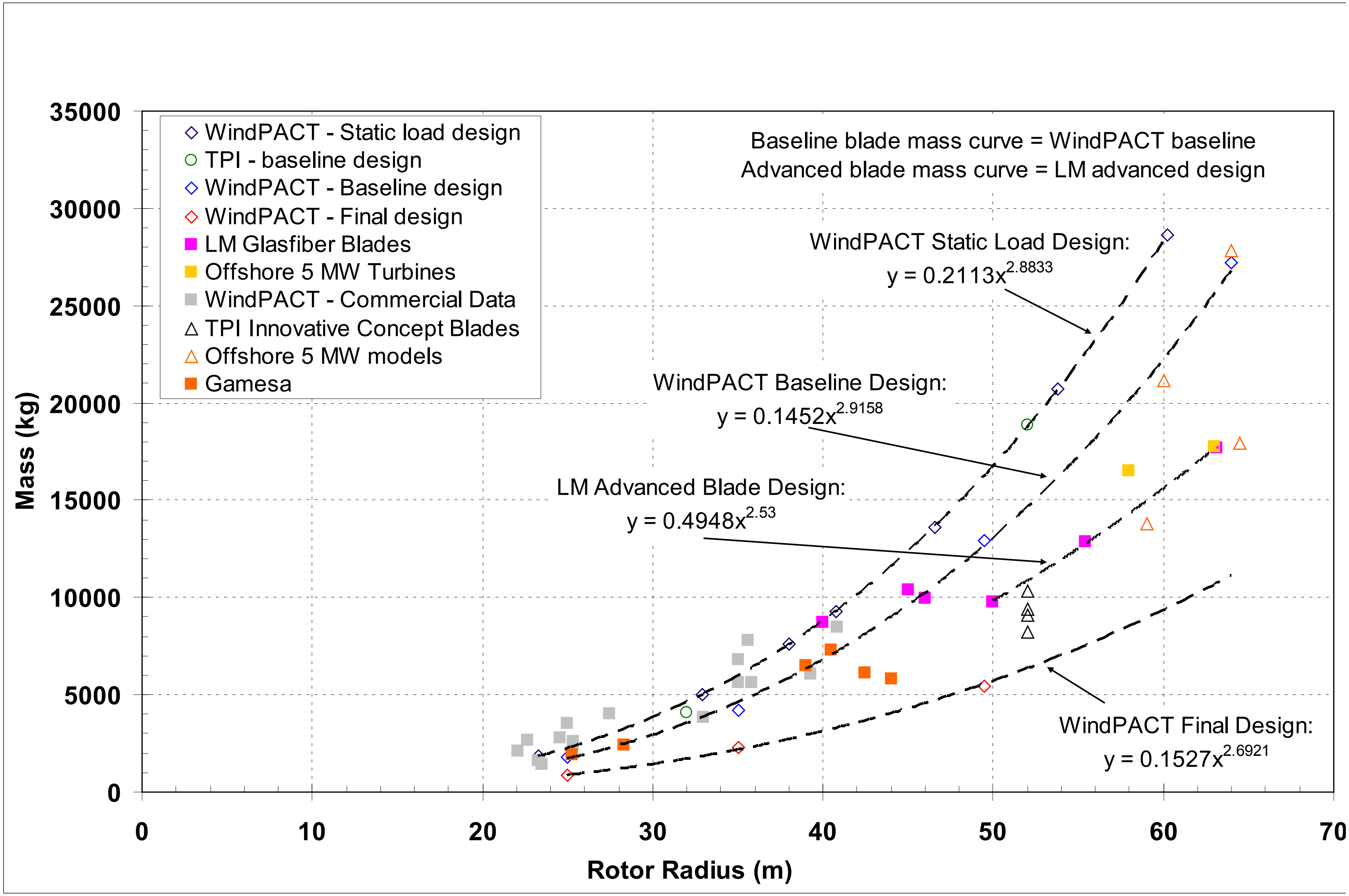




Stanford stadium overhead image from web address below. Use rectangle above to scale.

http://msrmaps.com/image.aspx?T=4&S=10&Z=10&X=2871&Y=20716&W=1&qs=Nelson+Road%7cStanford%7cCA&Addr=Nelson+Rd%2c+Stanford%2c+CA+94305&ALon=-122.1601053&ALat=37.4320765

Structure Size and Weight – Implications



Technology Challenges Remain

- Wind plant energy production
  - Example
    - 200 wind turbines @ 2 MW
    - 36% cap factor$\rightarrow$1.26x10^9 kWh/yr
    - 5 ¢/kWh, 1% AEP underproduction
    - $630K/year = $12.6M/plant lifetime
  - 1% - 10% underproduction common
- Turbine O&M cost prediction
  - Blade delamination, cracking
  - Gear, bearing failures
  - Unanticipated fatigue loading

Wind Turbines vs. Aircraft

- Overall cost
  - Aircraft: 600 USD/lb
  - Wind turbine: <6 USD/lb
- Wing/blade cost
  - Aircraft: >600 USD/lb
  - Wind turbine: <9 USD/lb
- Lifetime fatigue cycles
  - Aircraft: 10^6
  - Wind turbine: 10^8
- Inspection/maintenance
  - Aircraft: Daily/weekly
  - Wind turbine: Six months/one year

Fundamental Challenges

Current engineering approach

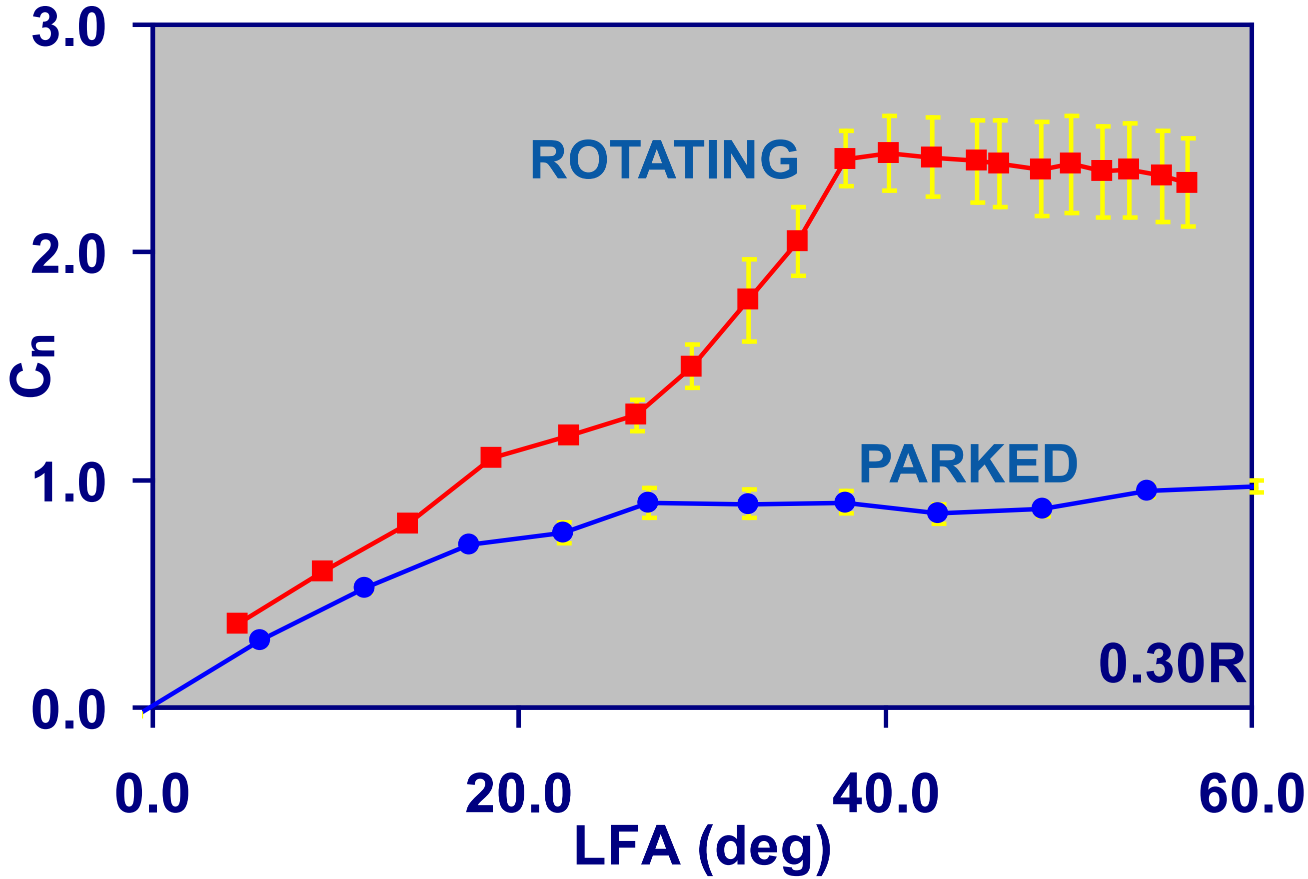
- Linearized and reduced order
- Partitioned for tractability
- Limited scale range and interaction

Physics and numerics

- Coupled and nonlinear
- Broad scale range
- Multiple physics

NREL UAE Phase VI Turbine in NASA Ames 80’x120’

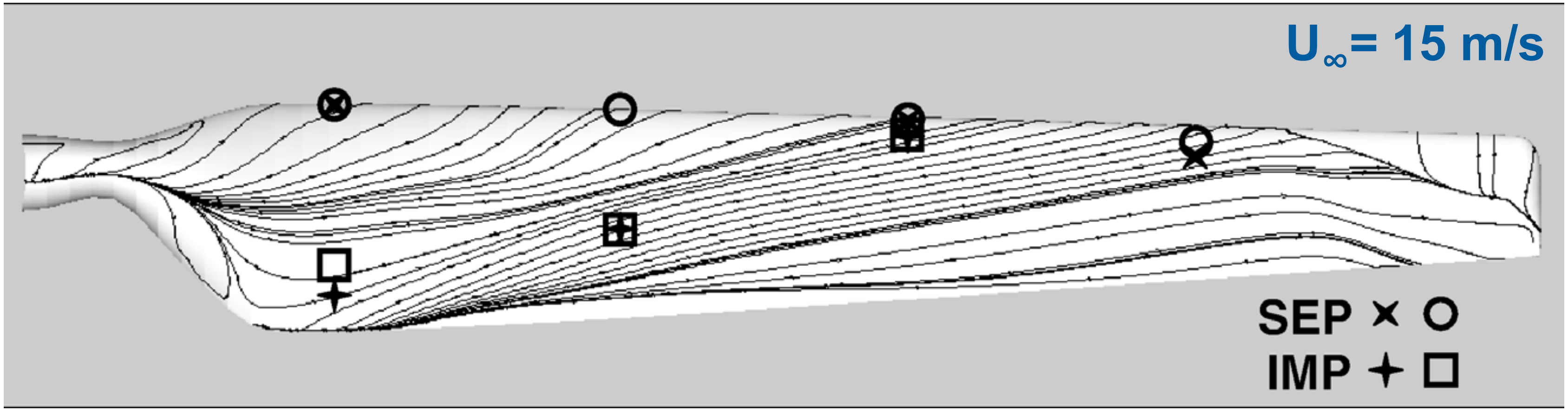
Zero Yaw – Rotational Augmentation



Max rotational augmentation of 3X parked

Deviation same as 15 – 20 % TI, ~10 Hz

Flow Field Topology

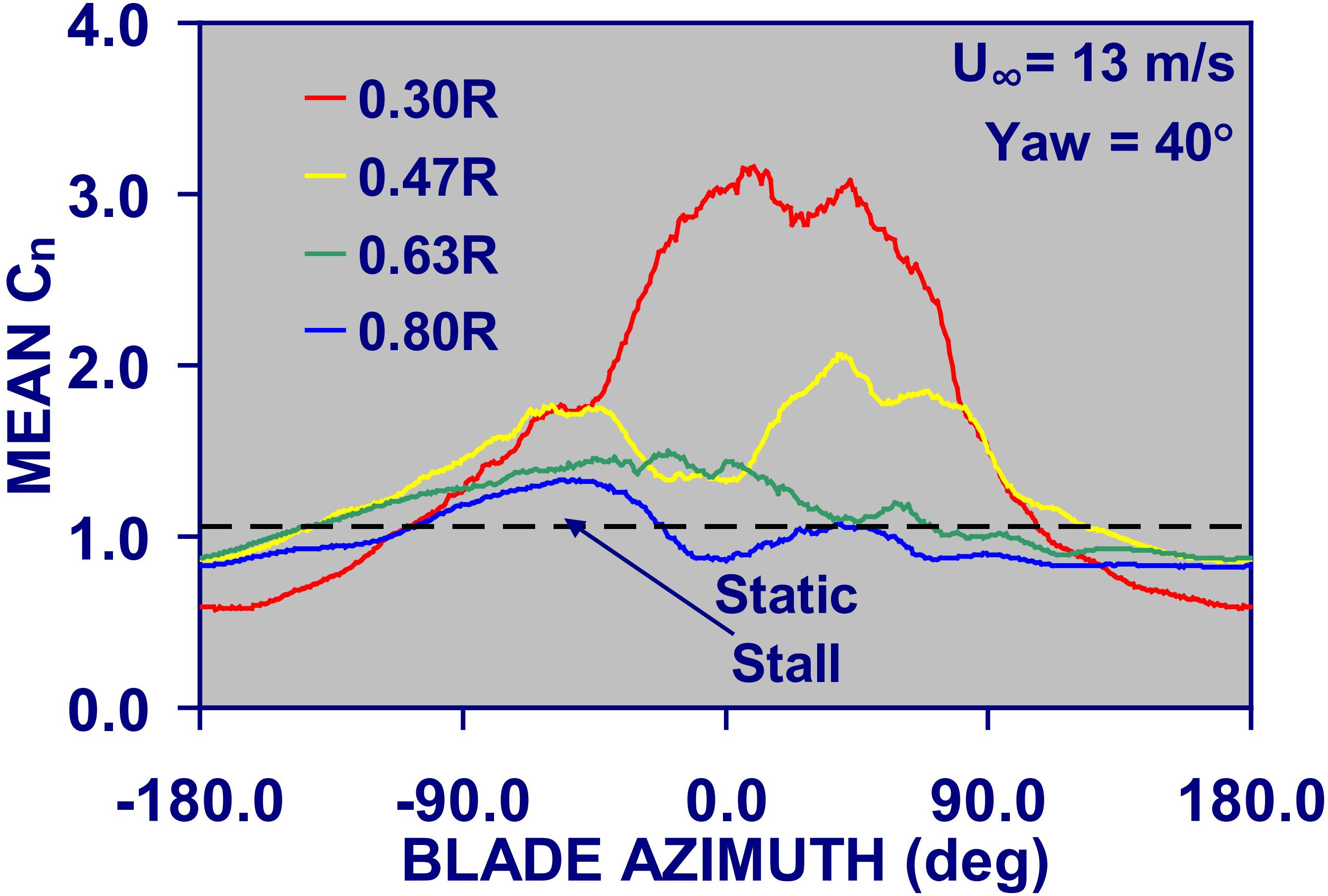


(CFD courtesy of N. Sørensen, Risø National Laboratory)

Off-surface structures 3-D and complex

Topology responsive to operating condition

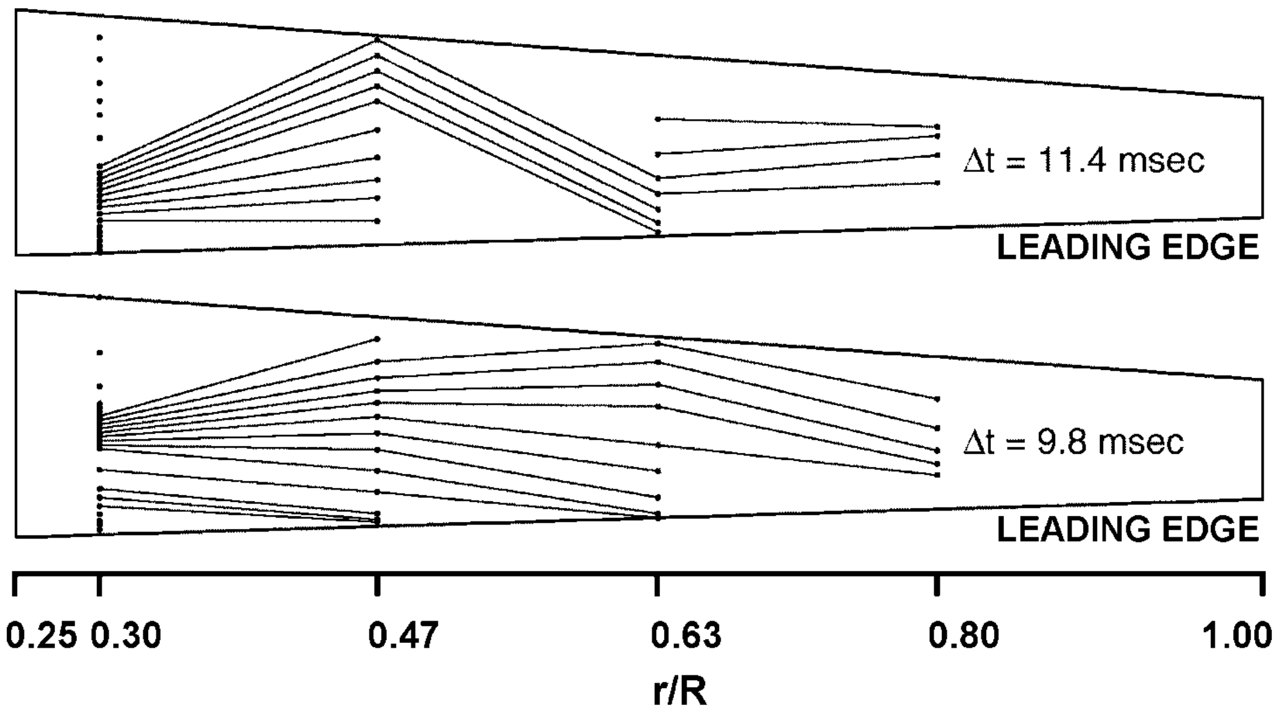
Nonzero Yaw – Dynamic Stall



Mean C_n maxima = 1.5X - 3X static stall levels

Rise times = 0.1 - 0.2 sec (1/8 - 1/4 cycle)

Flow Field Topology



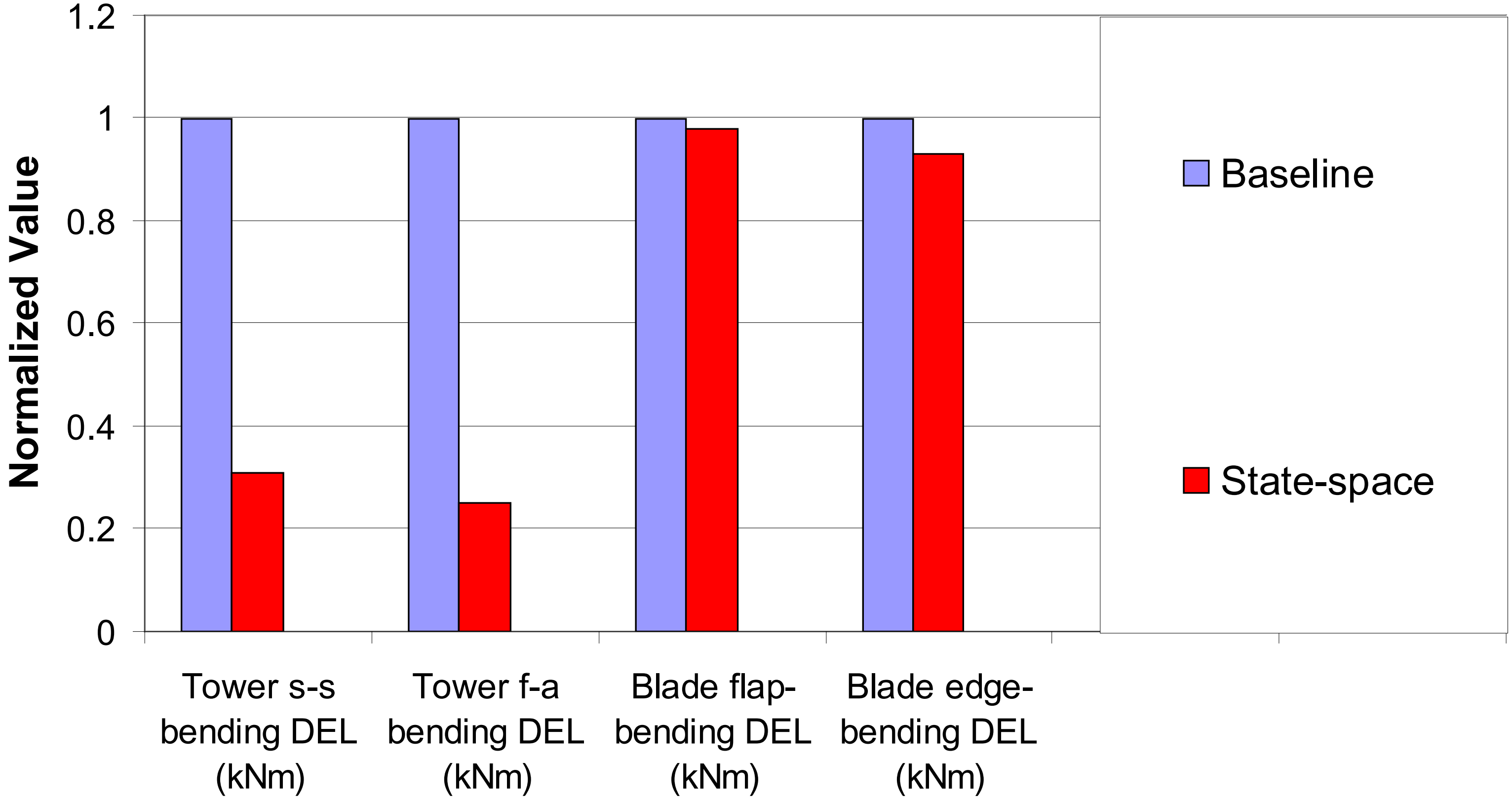
U_∞= 13 m/s
Yaw = 30°

U_∞= 15 m/s
Yaw = 40°

Vortex convection not radially uniform

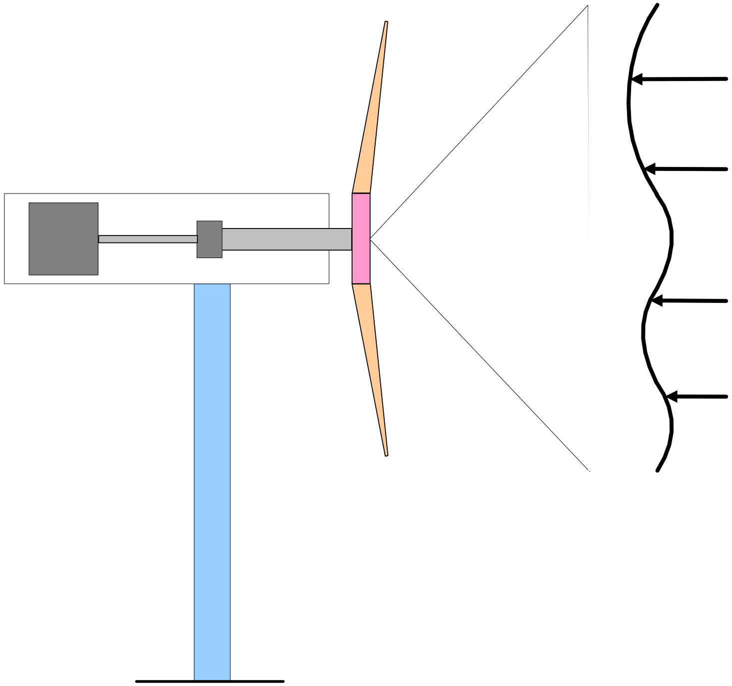
Operating condition drives 3-D deformation

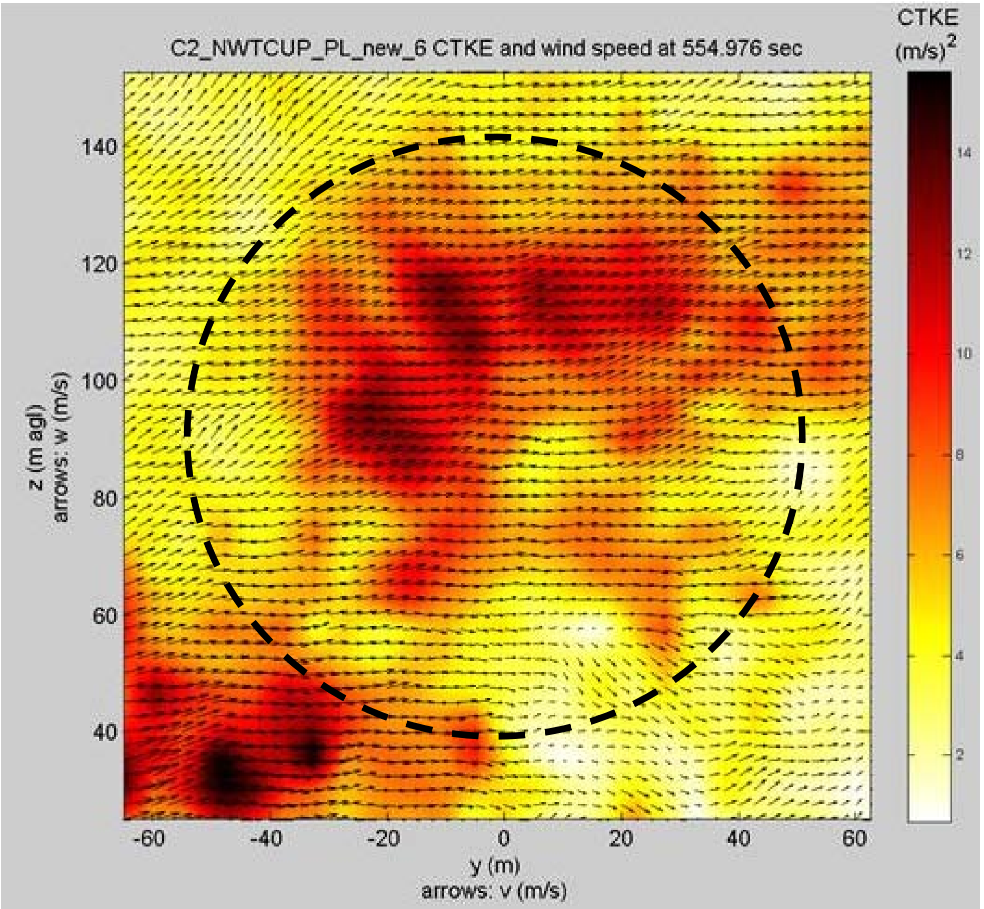
Control Effectiveness



- Test results for advanced MIMO control
- Integrated blade pitch-generator torque control

Advanced Control – Sensors/Actuators





- Real-time sensing of inflow velocity field
- Independent blade pitch actuation

Implications of Blade Flow Physics

Blade flow fields

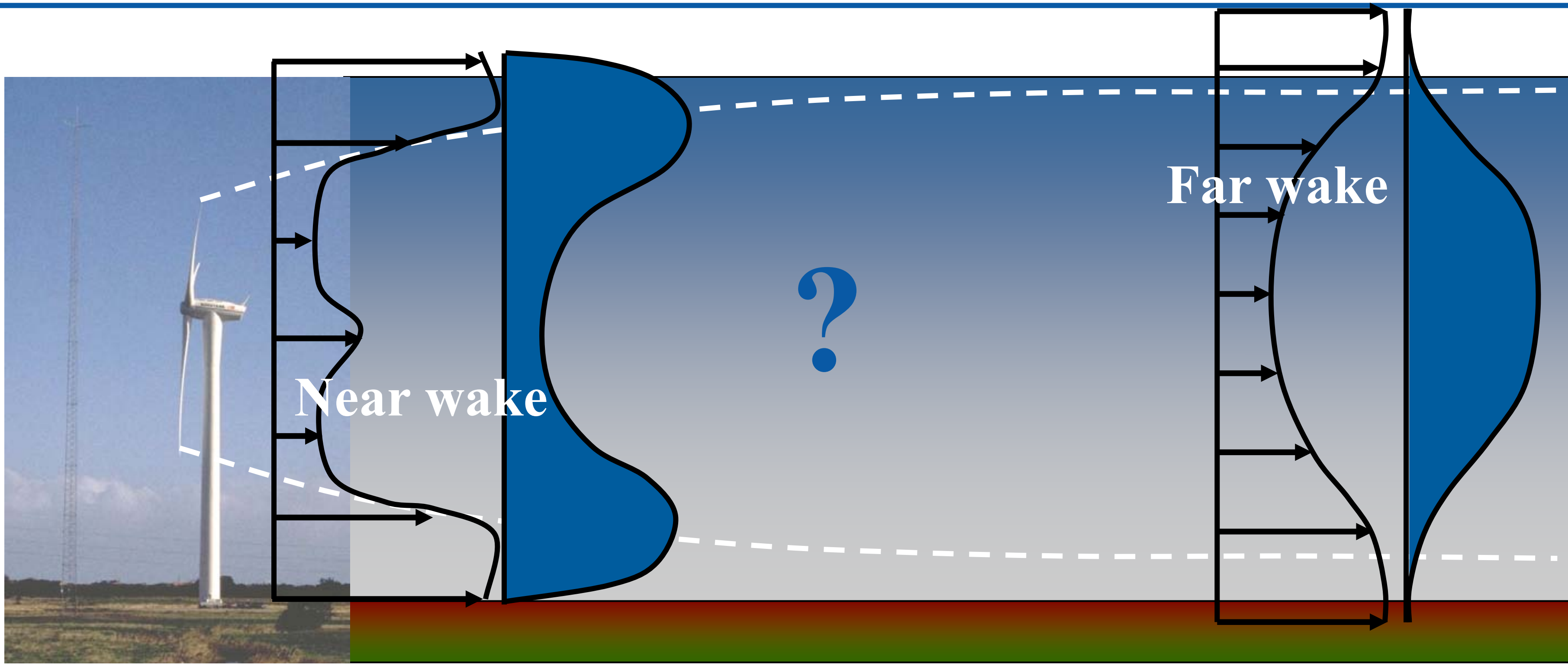
- Amplified loads
- Highly unsteady
- Large bandwidth
- Energetic vortices
- 3-D flow fields
- Commonly occur

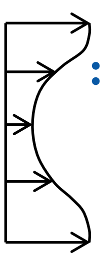
Control impacts

- Bandwidth
- Nonlinearity
- Sensors/actuators
- State identification
- Actuator authority
- Feasibility

Difficult to understand & predict
Challenging to control
Drive COE

Wake Structure Development





: Axial velocity

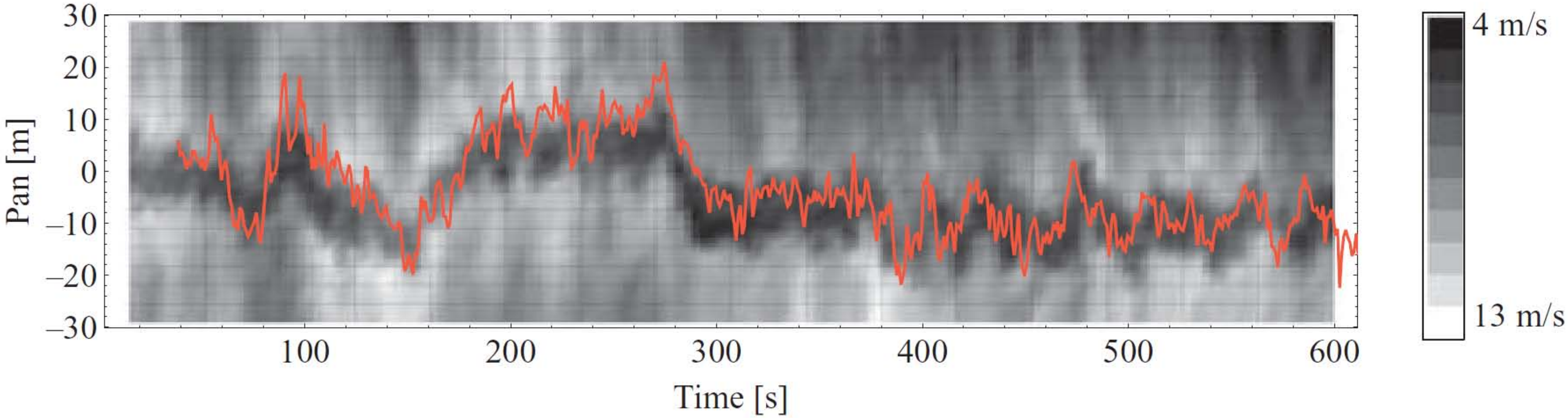
: Turbulence intensity

Sørensen, EWEC 2007

DTU

Danmarks Tekniske Universitet

Wake Dynamics – Meandering

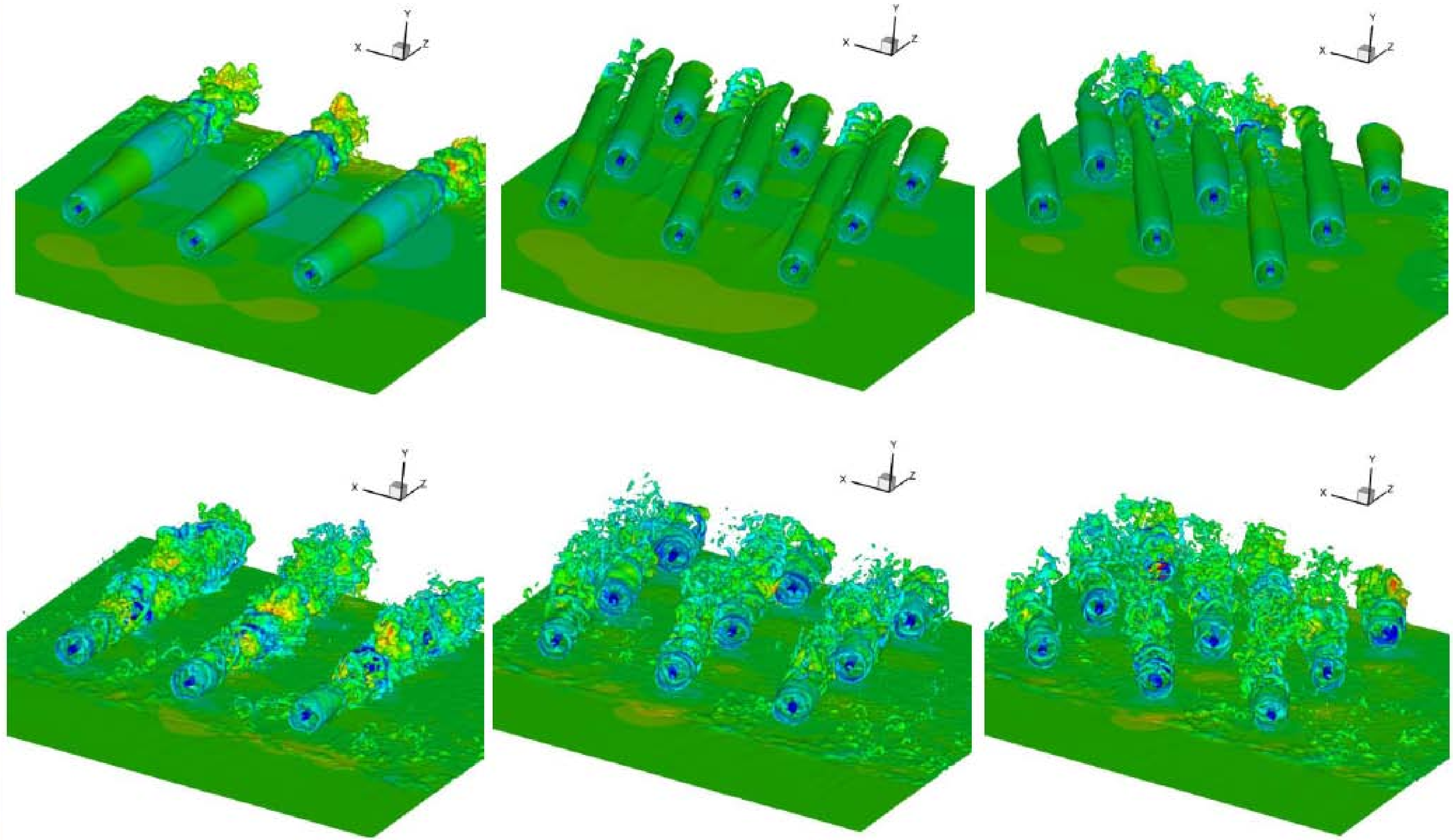


LIDAR (gray scale) tracks wake velocity

Model (red) assumes passive transport

Graphic courtesy of J. Mann, Risoe-DTU

9 turbine park simulation



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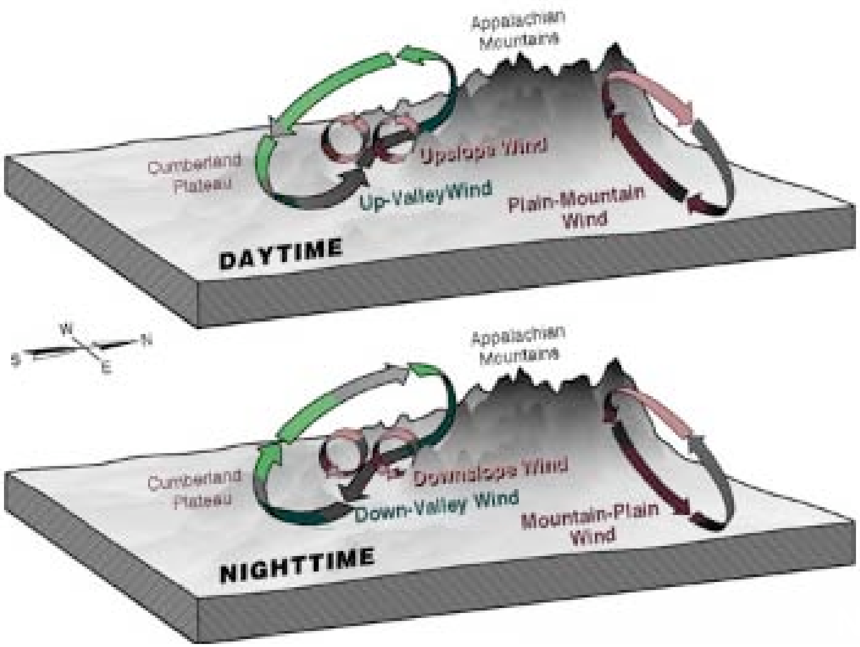
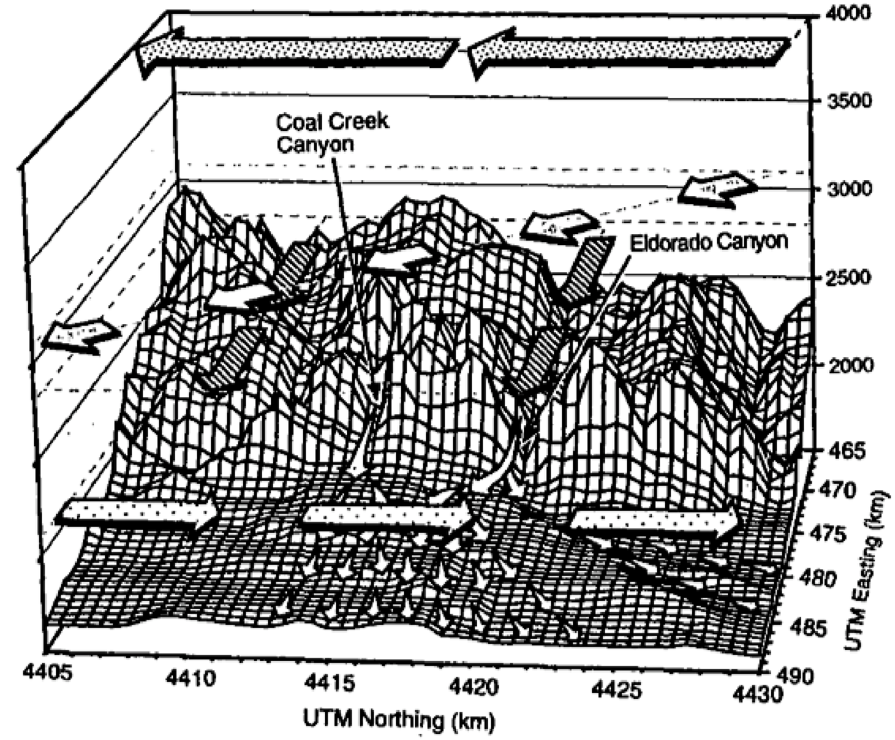
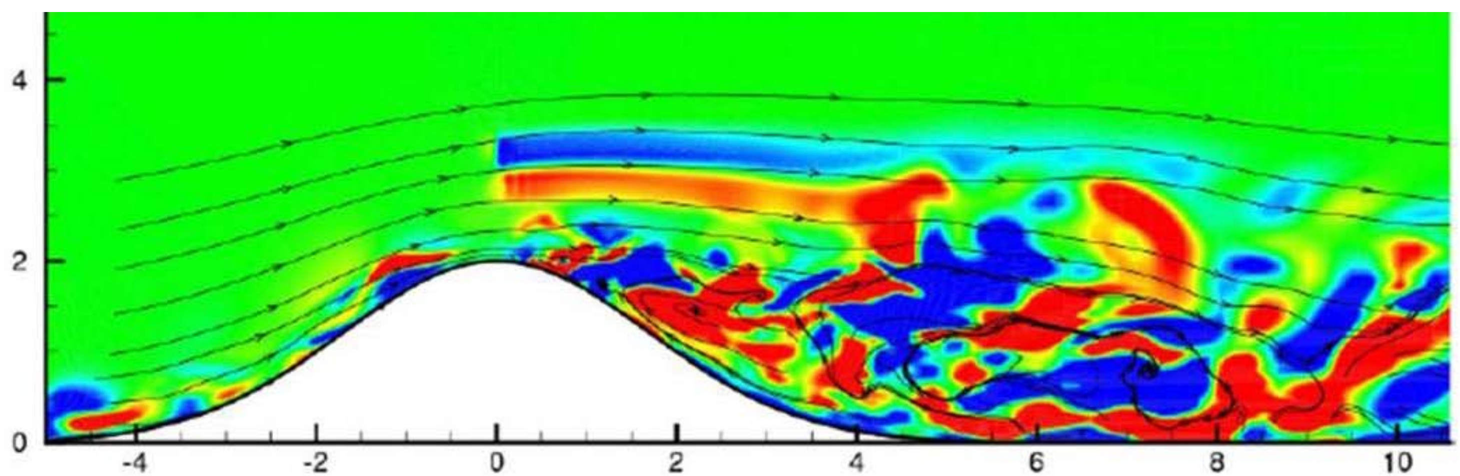
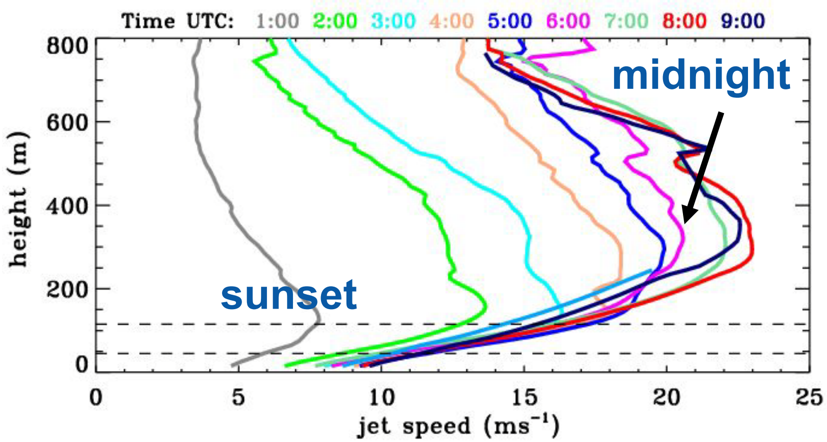
Complex Topography Effects

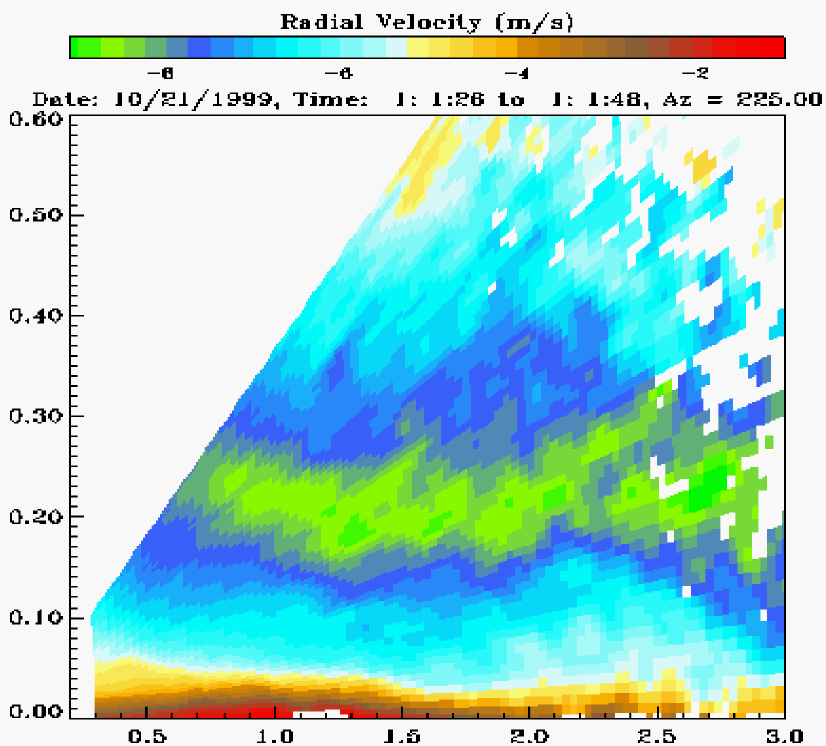






Planetary Boundary Layer (PBL)



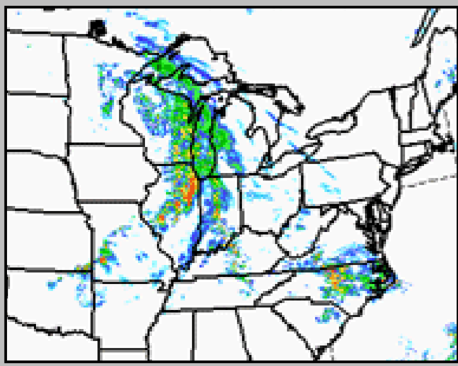


- Turbine, wind farm, PBL; similar dimensional scales
- Farm / inflow interactions not quantified
- Characterization & prediction remain an issue
- Detailed inflow information required for turbine design and optimized control
- Diurnal variation
- Growing concerns include:
  - Quality of the downwind resource
  - Microclimatology changes
  - Agriculture impacts
  - Permitting

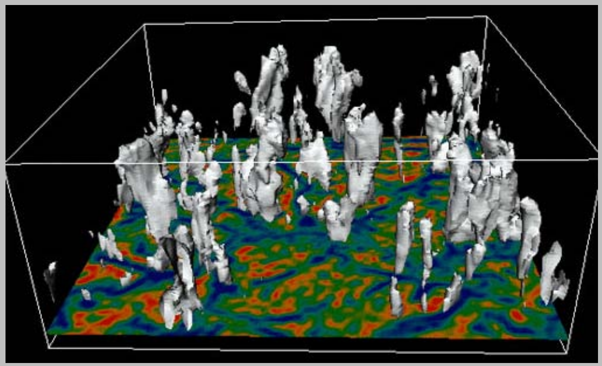
Unification Across Models & Scales

Treating Multi-Scale Flow Interactions Among Models

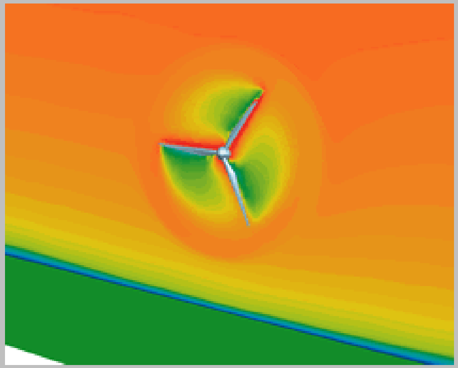
Mesoscale Models



LES Models



CFD Models

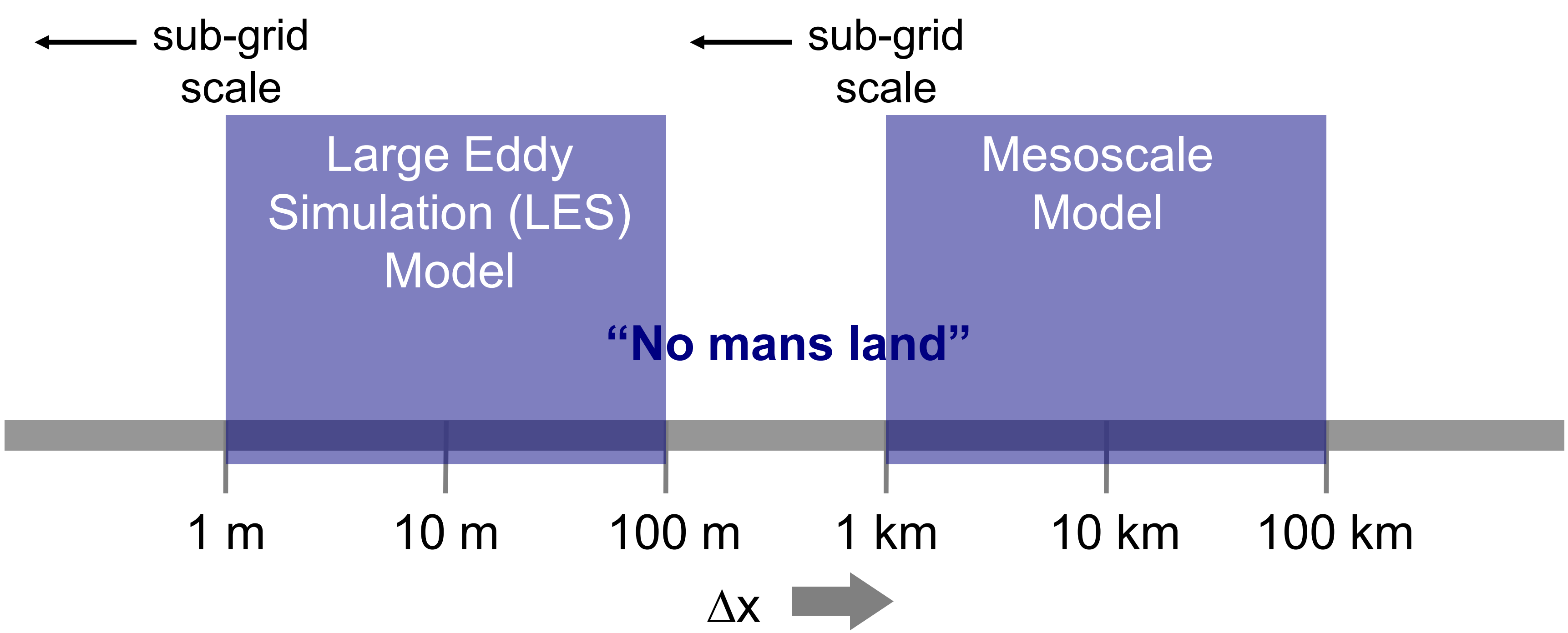


temporal and spatially varying BCs →

← parameterizations

- Mesoscale, LES and CFD models normally run separately
- LES and CFD models use constant or periodic boundary conditions
- Some work already underway in linking these types of models
- Include terrain and variable land-use into LES models

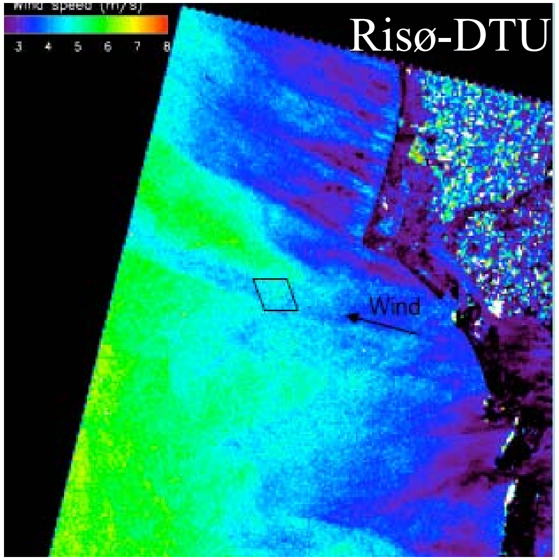
PBL Parameterizations

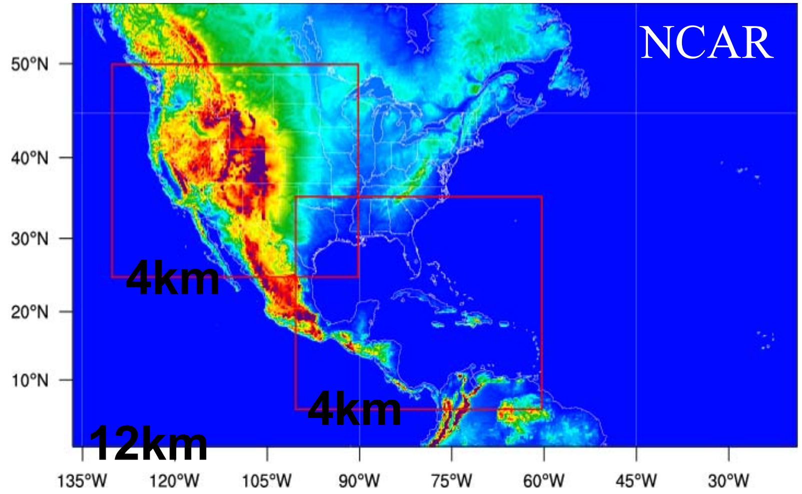


Models cover multiple spatial scales, but not all encompassing

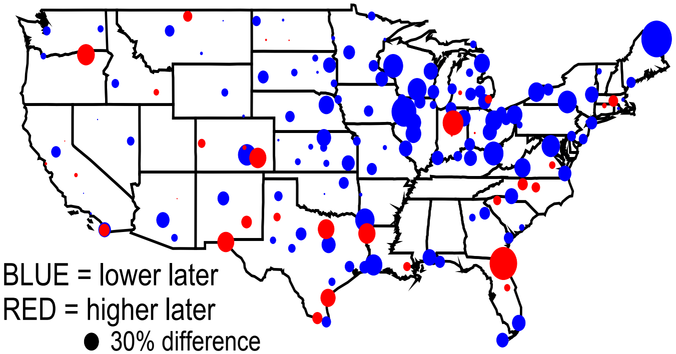
For Δx < 1 km, but problems exist – e.g., "double booking" turbulence

Climate Effects





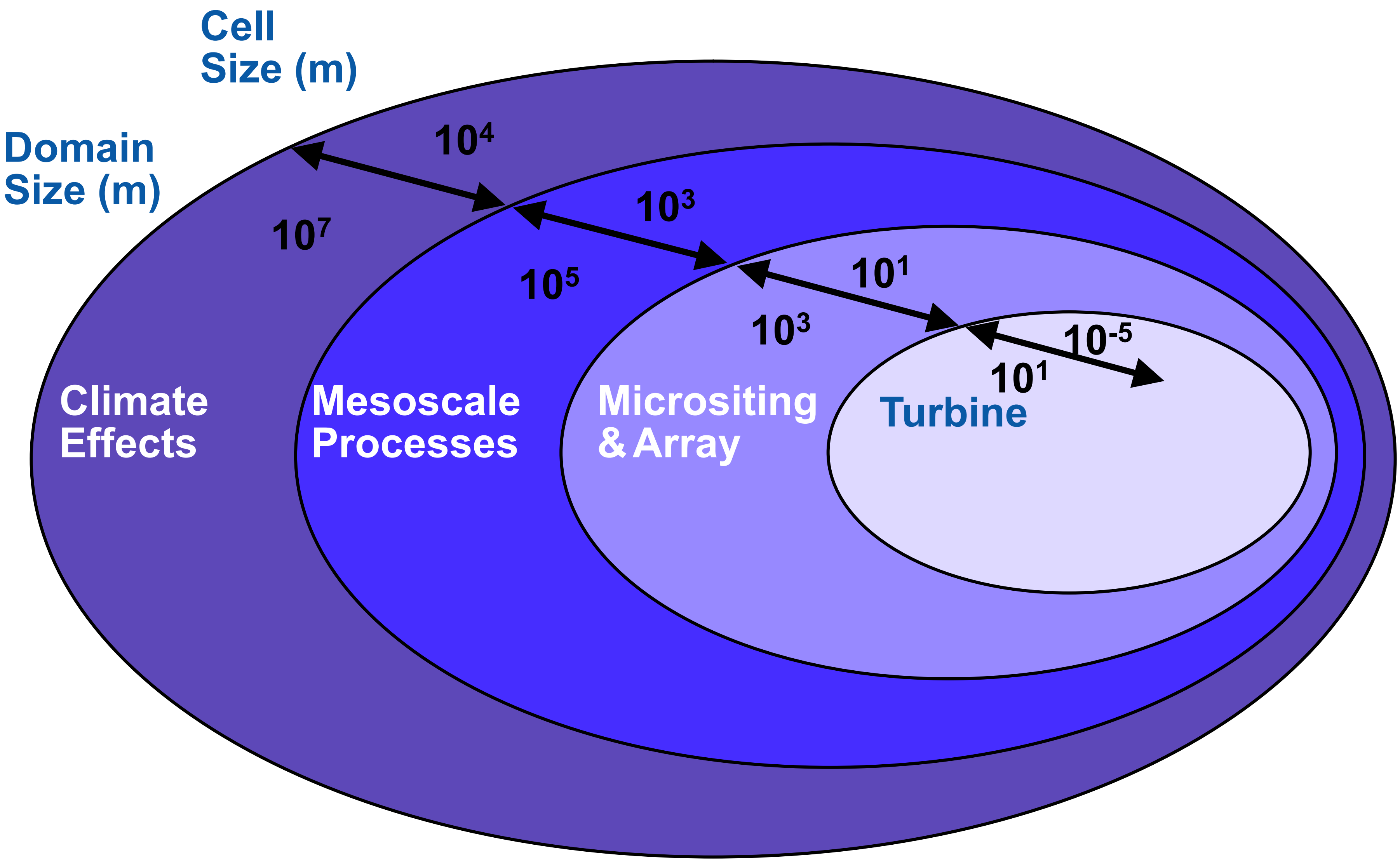
Energy Density Δ (91-05)–(73-87)



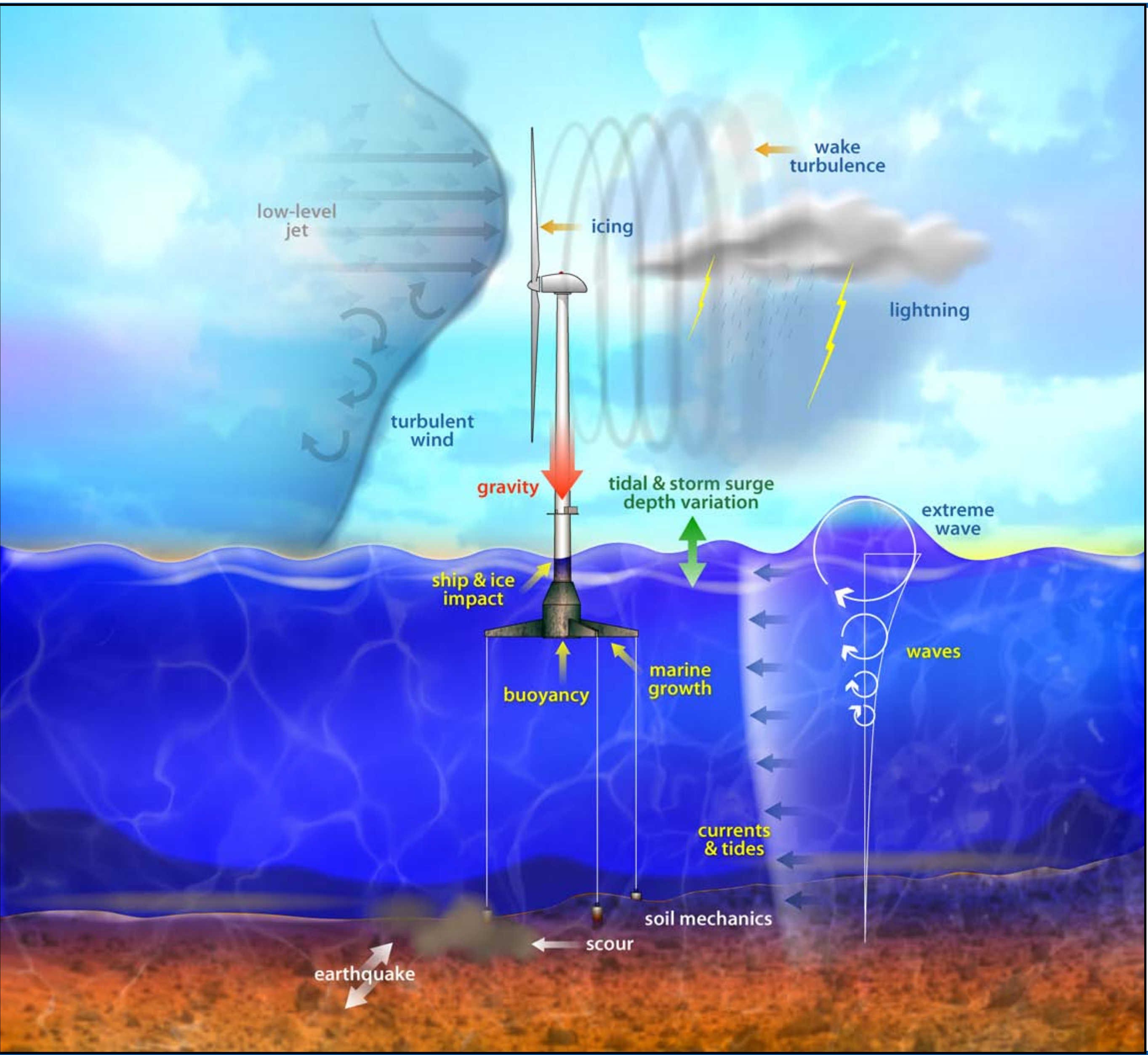
Climate effects

– Understand and predict wind resource variability
– Wind plant and local/regional/global climate

Computational Modeling Scales



Deep Water Modeling Requirements



Fully coupled aero-hydro-servo-elastic interaction

Wind-Inflow:
- discrete events
- turbulence

Waves:
- regular
- irregular

Aerodynamics:
- induction
- rotational augmentation
- skewed wake
- dynamic stall

Hydrodynamics:
- scattering
- radiation
- hydrostatics

Structural dynamics:
- gravity / inertia
- elasticity
- foundations / moorings

Control system:
- yaw, torque, pitch

Large Facility Requirements

New Large Blade Test Facilities:

- Boston, MA with Massachusetts Technology Collaborative
- Corpus Christy, TX with University of Houston

DOE NOI for 5-15 MW Dynamometer

A 45-meter wind turbine blade undergoing fatigue testing at the NWTC, July 2004.

Multi-MW Turbines at NWTC

DOE 1.5 MW GE Turbine:

- Model: GE 1.5SLE
- Tower Height: 80 m
- Rotor Diameter: 77 m
- DOE owned; used for research and education

Siemens 2.3 MW Turbine:

- Model: SWT-2.3-101
- Tower Height: 80 m
- Rotor Diameter: 101 m
- Siemens owned and operated
- Multi-year R&D CRADA; aerodynamics and rotor performance

Questions?

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