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Technology Opportunities for Wind Energy

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2010 iNEMI Alternative Energy Workshop

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Turbine design evolution
- Wind Energy 101
- Technology Challenges
- Sandia Research Efforts
- Summary

Turbine Design Evolution

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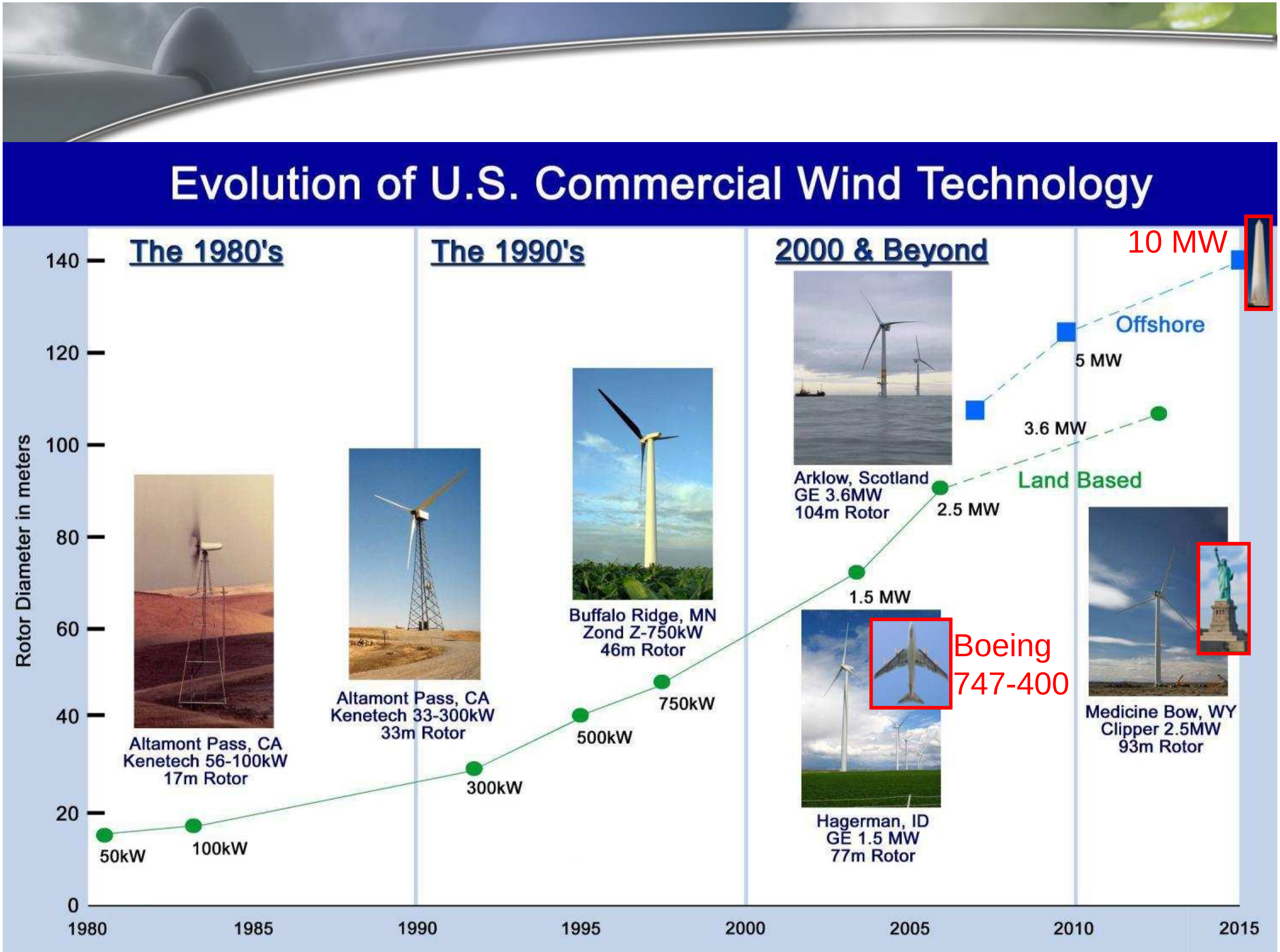

Evolution of U.S. Commercial Wind Technology
The 1980's
The 1990's
2000 & Beyond
10 MW
Offshore
5 MW
3.6 MW
Land Based
2.5 MW
1.5 MW
750kW
500kW
300kW
100kW
50kW
Altamont Pass, CA
Kenetech 56-100kW
17m Rotor
Altamont Pass, CA
Kenetech 33-300kW
33m Rotor
Buffalo Ridge, MN
Zond Z-750kW
46m Rotor
Arklow, Scotland
GE 3.6MW
104m Rotor
Hagerman, ID
GE 1.5 MW
77m Rotor
Boeing
747-400
Medicine Bow, WY
Clipper 2.5MW
93m Rotor
Rotor Diameter in meters
140
120
100
80
60
40
20
0
1980
1985
1990
1995
2000
2005
2010
2015

Example Small Wind Systems

Bergey Windpower

BWC XL.1
1 kW, 8.2 ft Dia.
Battery-Charging

Southwest Windpower

Skystream 3.7
1.8 kW
12 ft Dia.
Grid-Connect

Northern Power Systems

NorthWind 100/21
100 kW, 69 ft dia.
Grid-Connect

Endurance Wind Power Inc.

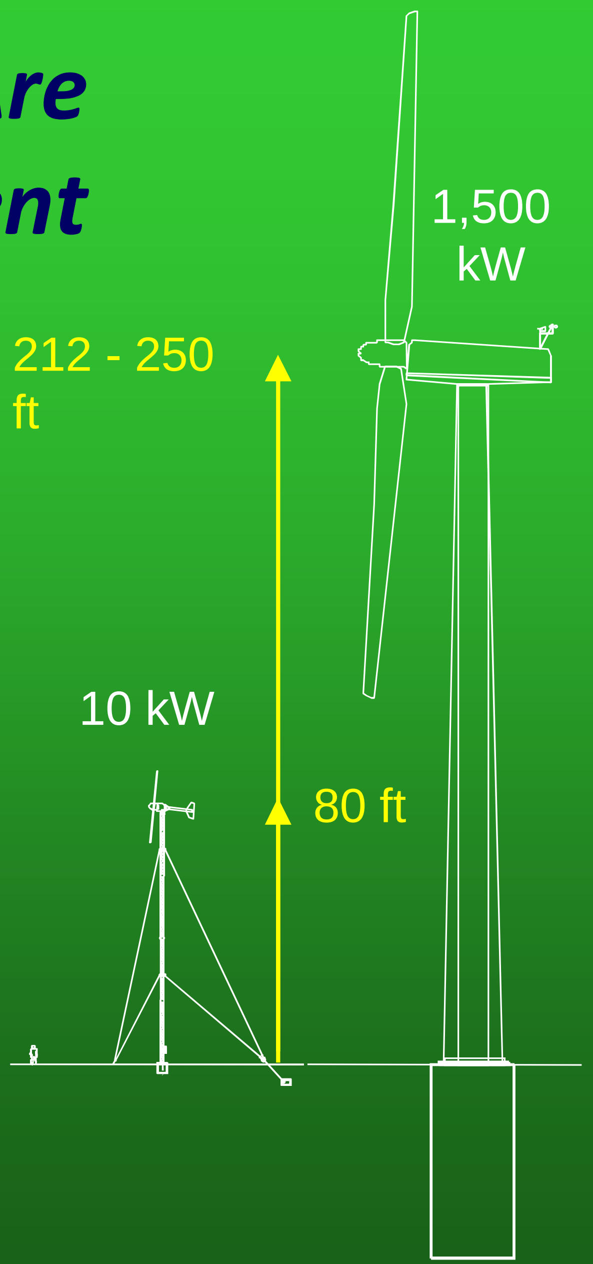
Endurance S-250
4.25 kW, 18 ft Dia.
Grid-Connect

Industry has Changed from Small Machines to Large Multi-Mega-Watt Machines

- **Above: Tehachapi, CA – 65kW, 900kW, and 3MW machines**
- **Left: Palm Springs, CA – field of 65kW with four larger machines in foreground (~750kW)**

Small Wind Turbines Are Different

- **Utility-Scale Wind Power**
  1,000-3,000 kW wind turbines
  - Installed on wind farms, 10–700 MW
  - Interconnected to transmission
  - Professional maintenance crews
  - Class 4-6 wind resource
- **Small Wind Power**
  up to 100 kW wind turbines
  - Installed at individual homes, farms,
    businesses, schools, etc.
  - Interconnected to distribution, on the "customer side" of the meter
  - Few moving parts, high reliability, low maintenance
  - Class 2-4 wind resource

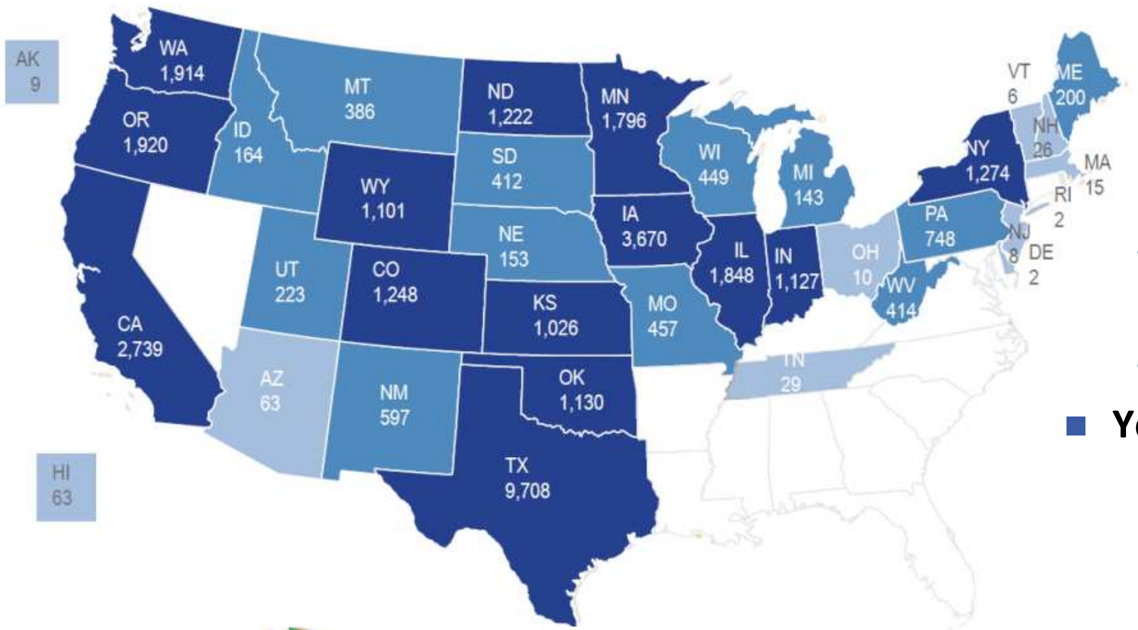


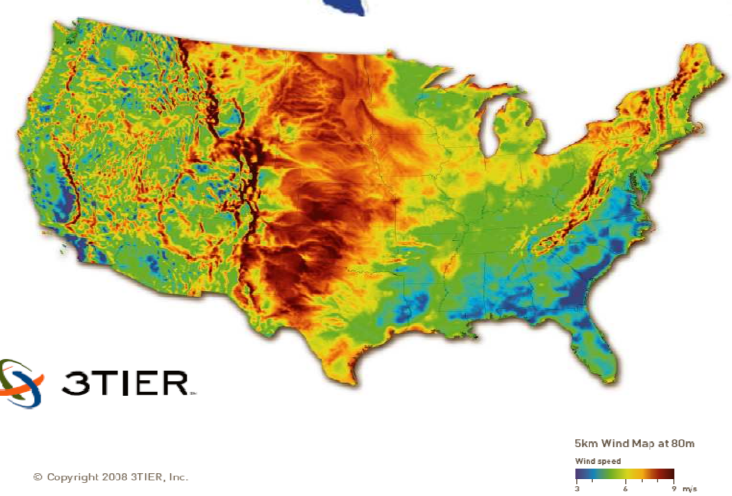
Courtesy Jim Green, NREL

Logistics become difficult as size increases

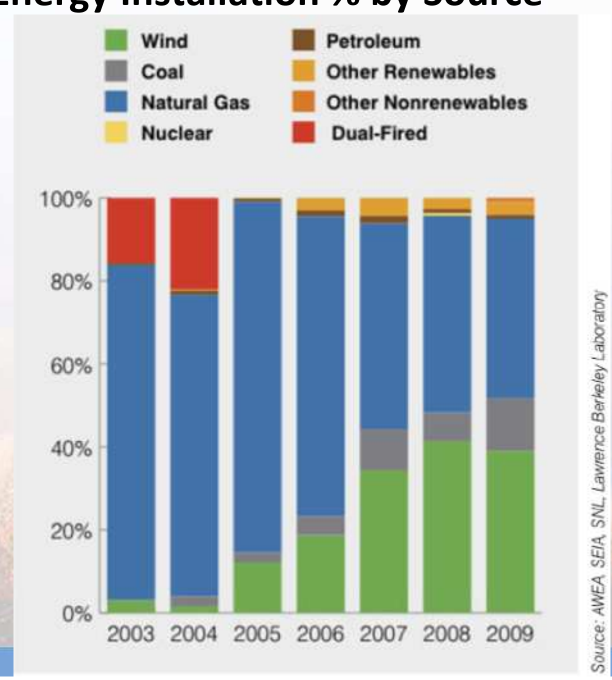
Current U.S. Installation

Almost 5.5 TW Available Resource
(Total U. S. Electric Capacity ≈ 1 TW in 2007)



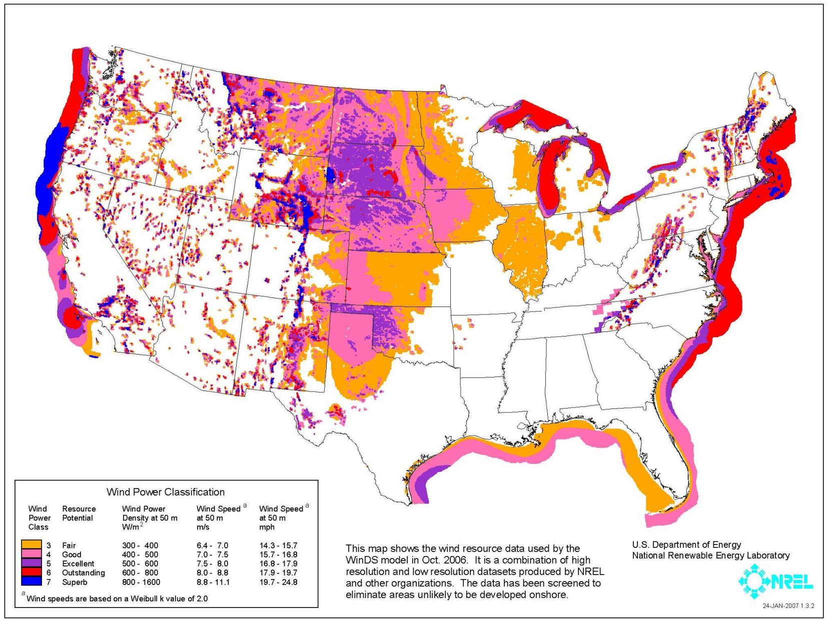


- **Wind Energy Today (Q2 2010)**
  - Total installed capacity: +36,000MW (37 States) - ~2% of U.S. energy consumption
    - **9,922 MW installed 2009**
      - **All time record**
      - **3,200MW under construction**
  - Approximately 19 billion dollars invested in 2009
  - Installed cost: ~5-8¢/kWh
- **Yearly Energy Installation % by Source**



Offshore Wind

- **Technical challenges, higher costs**
- **Close to load centers**
- **>2000 MW (end 2009) installed in worldwide**
  - No U.S.installations
- **Limited shallow depths in U.S.**
- **Several Proposals in U.S.**
  - Cape Cod (Cape Wind)
  - Long Island (LIPA)



Wind Energy 101

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Wind Power Basics

Air Density → ρ; Rotor Area → A; Wind Speed → V_∞

$$WindPower = \frac{1}{2}\rho A C_P V_\infty^3$$

Wind Power output is proportional to wind speed cubed.

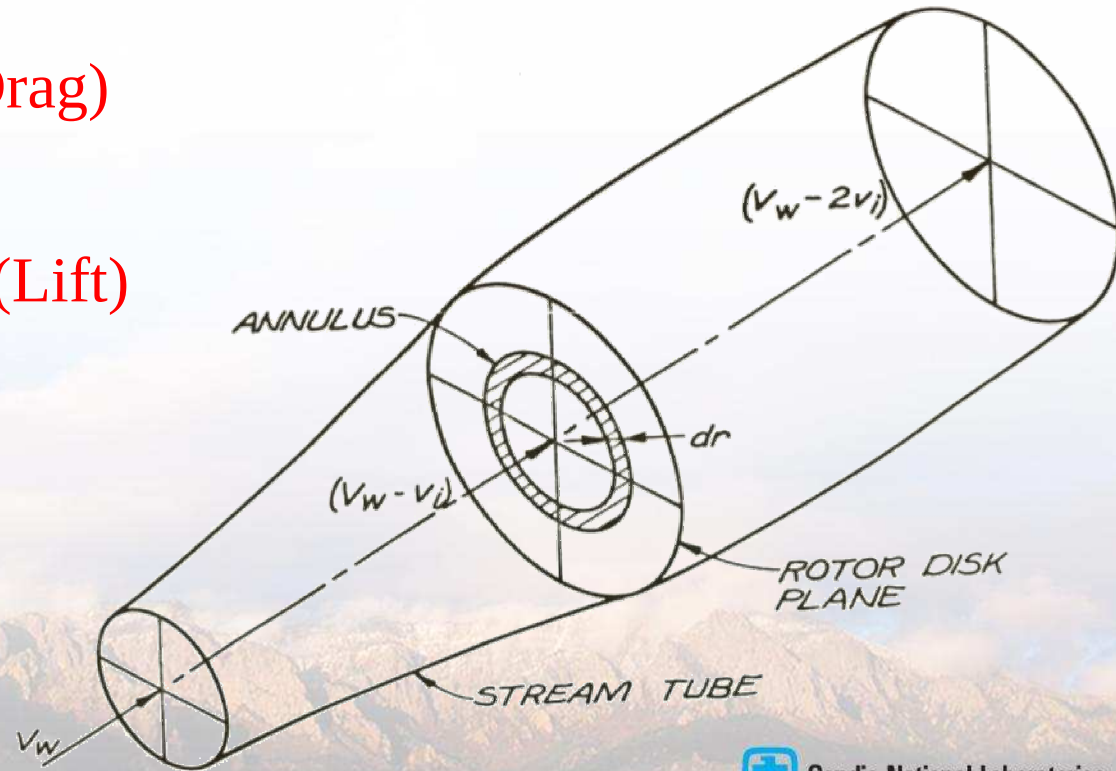
$$C_{P\max} \cong 0.3 \text{ (Drag)}$$

$$C_{P\max} \cong 0.59 \text{ (Lift)}$$

The Betz Limit

$$V_i = \frac{1}{3} V_w$$

$$P = \frac{16}{27}\left(\frac{1}{2}\rho A V_w^3\right)$$



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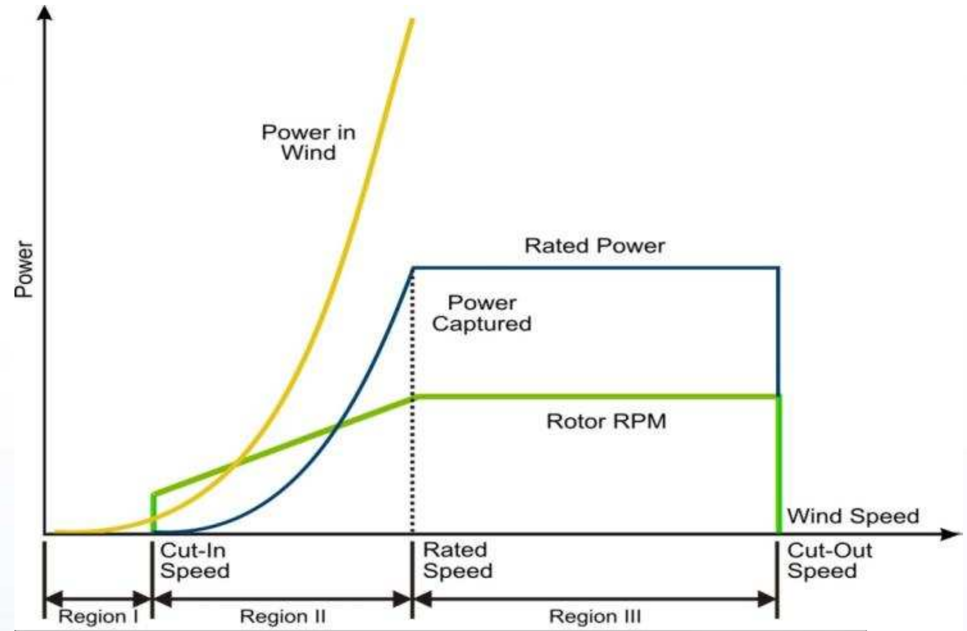
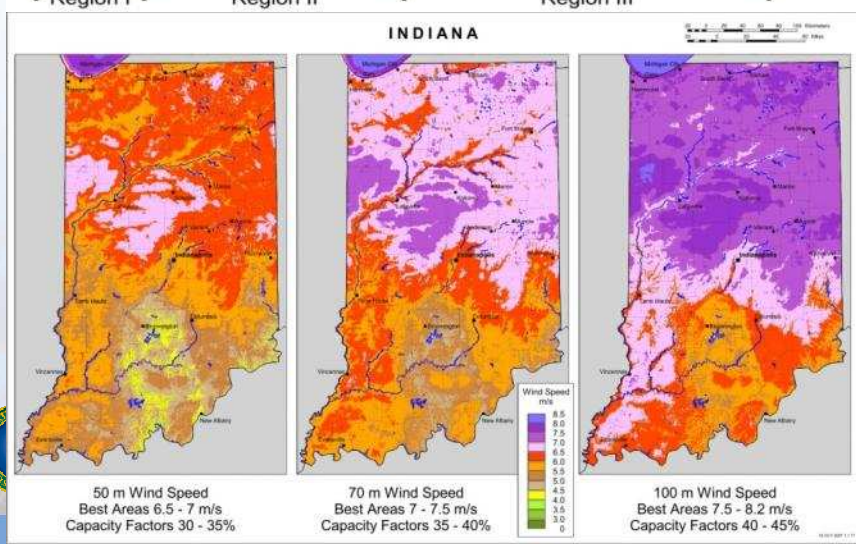
The Physics of the Power Curve Drives Technology Development





Facts about Wind Technology

- **Power in the wind is proportional to wind speed cubed**
- **At best, we can capture 59% (the Betz limit)**
- **“Rated Power” governs the size and cost of the entire turbine infrastructure**
- **Energy is power multiplied by the amount of time spent at that power level**
- **Capacity Factor is the ratio of total output to what would have been generated if always operating at Rated Power – Meaningful metric**
- **Wind shear puts higher winds at greater elevation**

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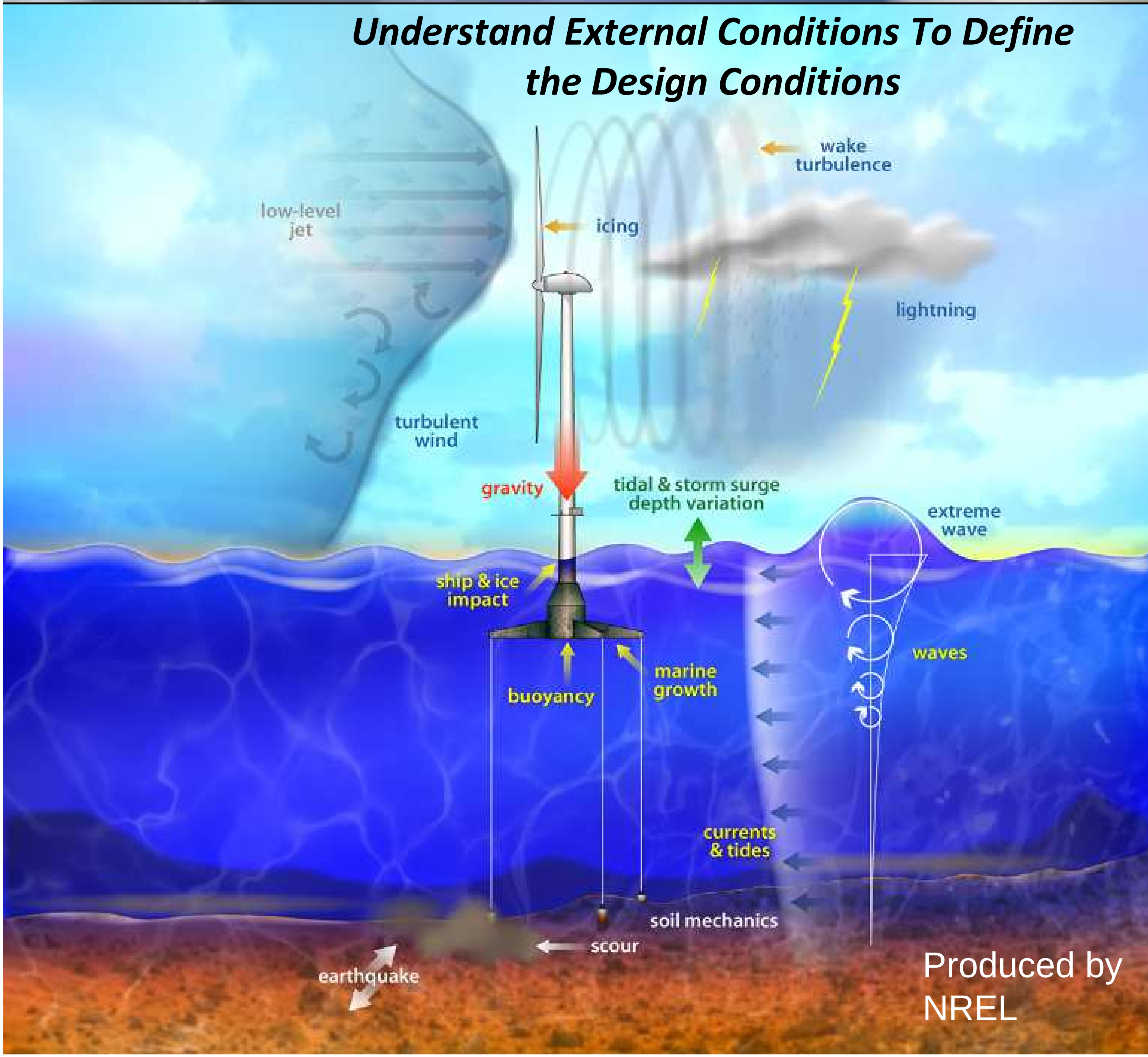
Understand External Conditions To Define the Design Conditions

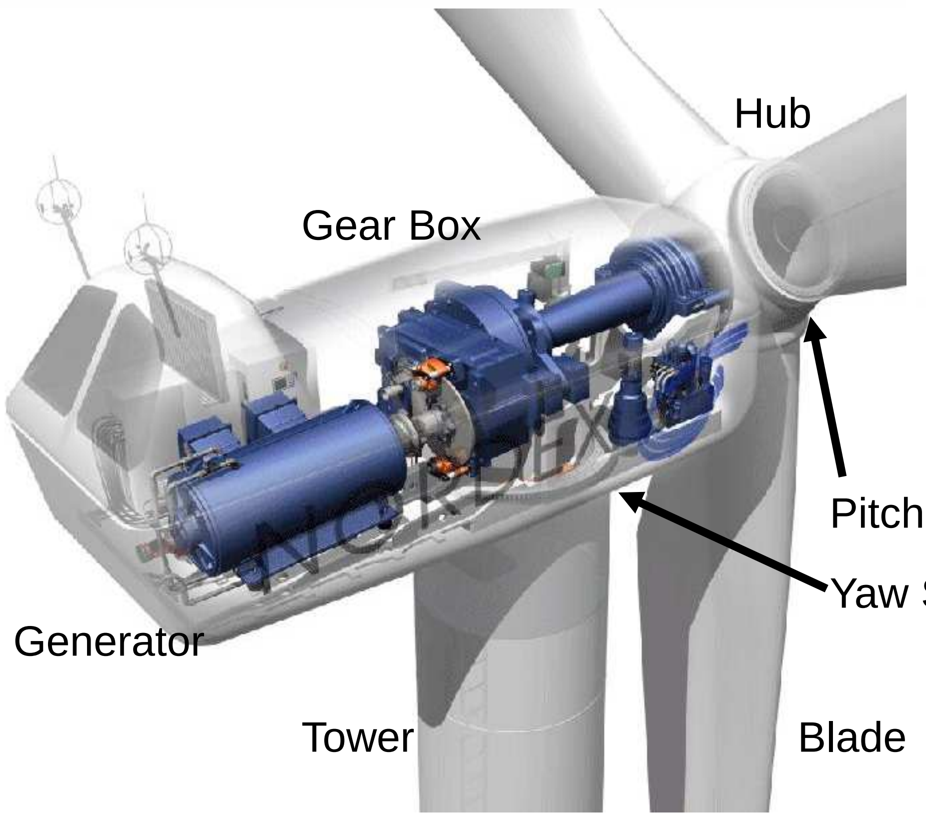


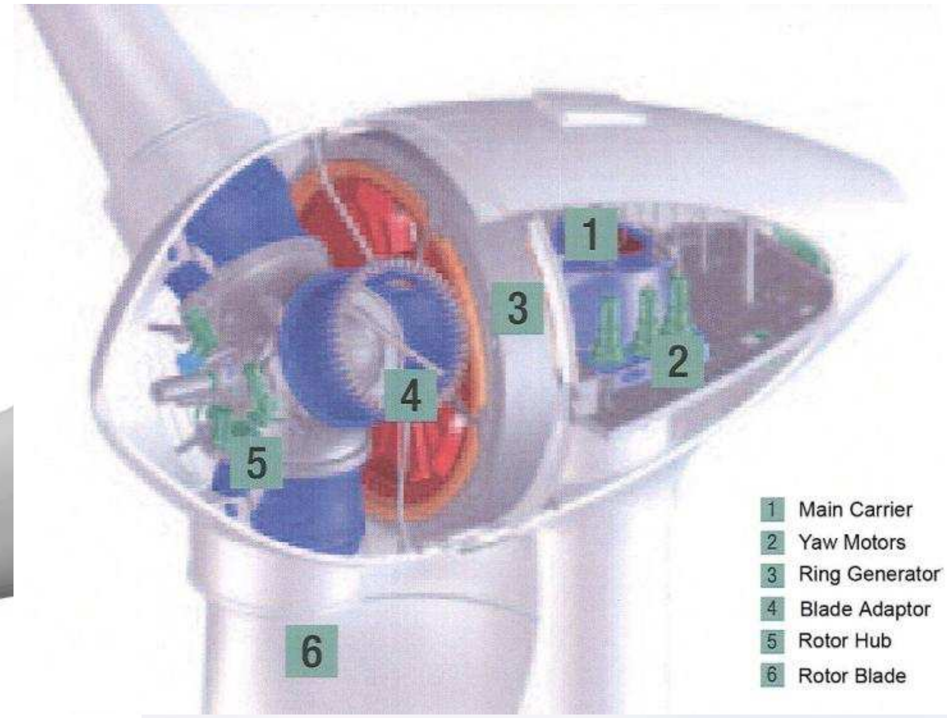
Land-Based Turbine

Offshore Turbine

Typical Wind Turbine Configurations

Conventional Drive Train





Direct Drive System

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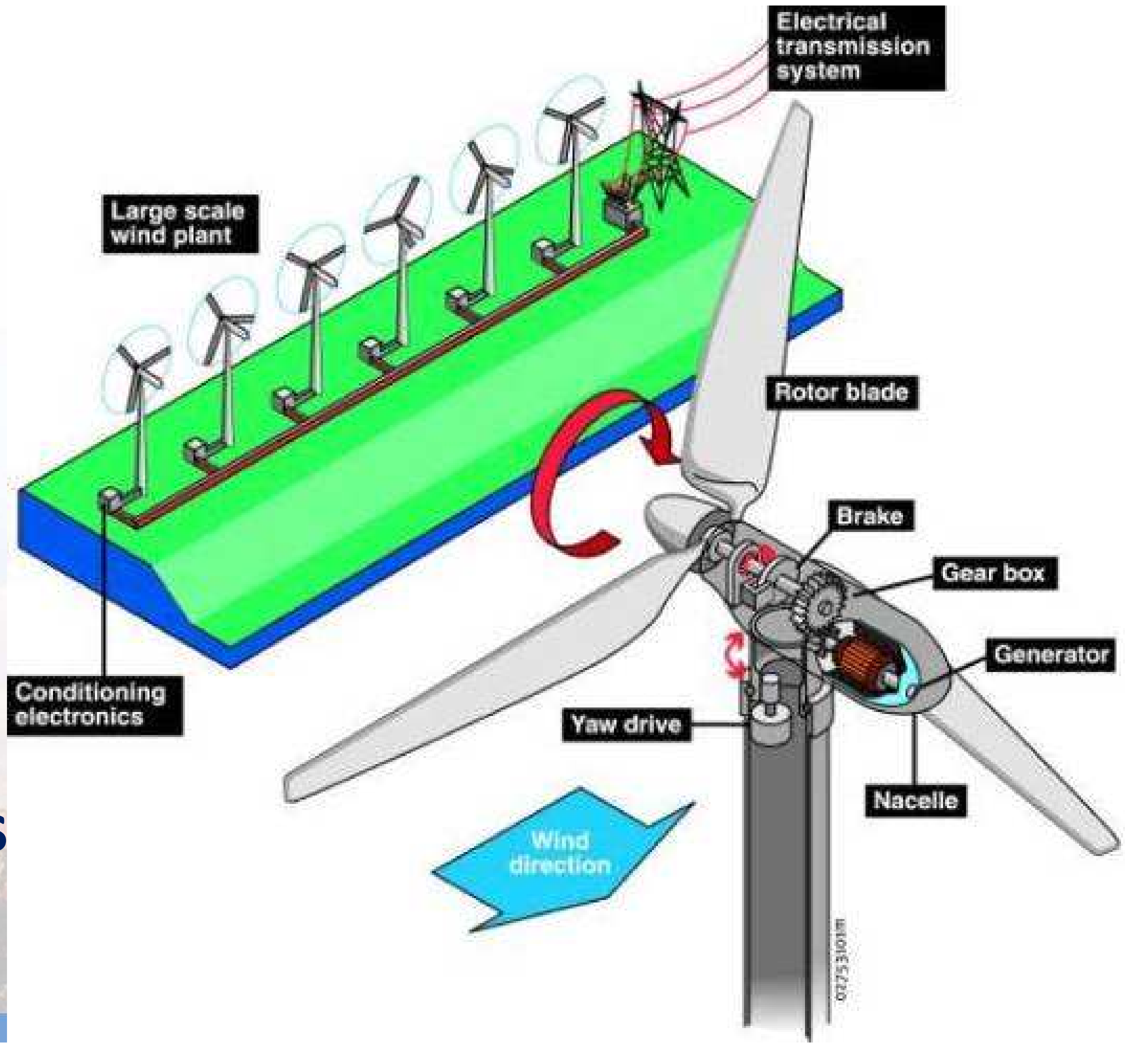
Typical Wind Farm Components

- Turbine
- Foundations
- Electrical collection system
- Power quality conditioning
- Substation
- SCADA
- Roads
- Maintenance facilities



Technology Opportunities

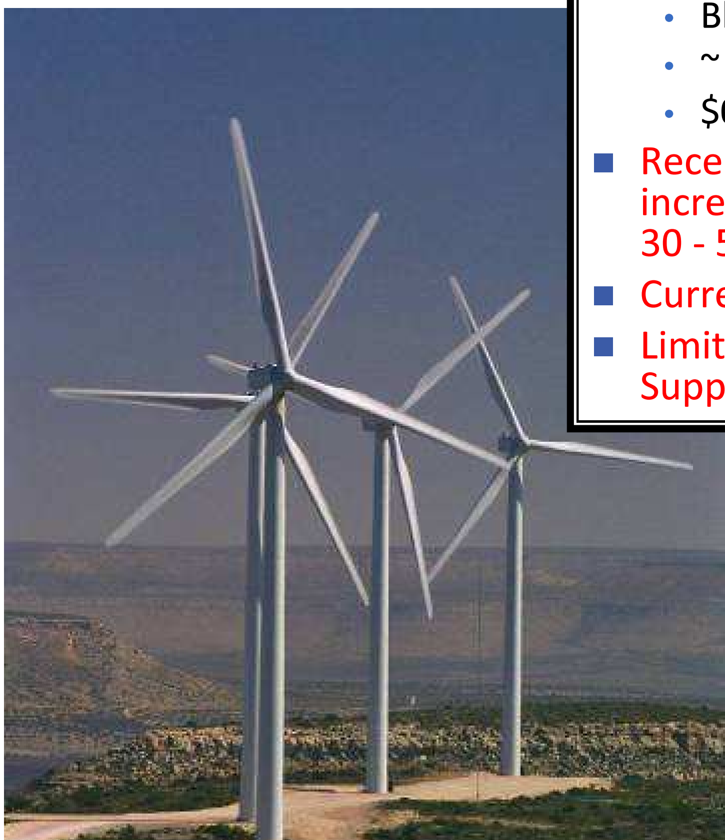
Wind Industry Trends & Challenges

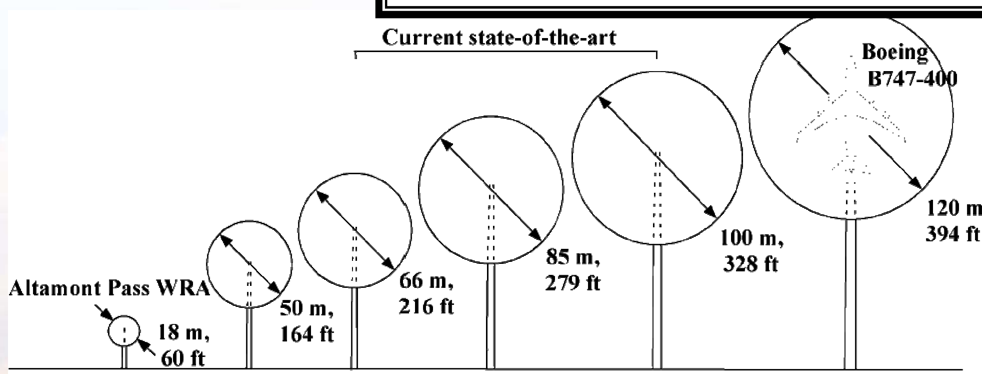
- **Costs (traditional)**
  - System ~ $3/lb
  - Blades ~ $6/lb
  - ~ $1.00/Watt (2002)
  - $0.04-$0.06/kWh (2002)
- Recent cost of steel & copper increases have increased cost by 30 - 50%
- Currency exchange rate
- Limited Manufacturers & Suppliers

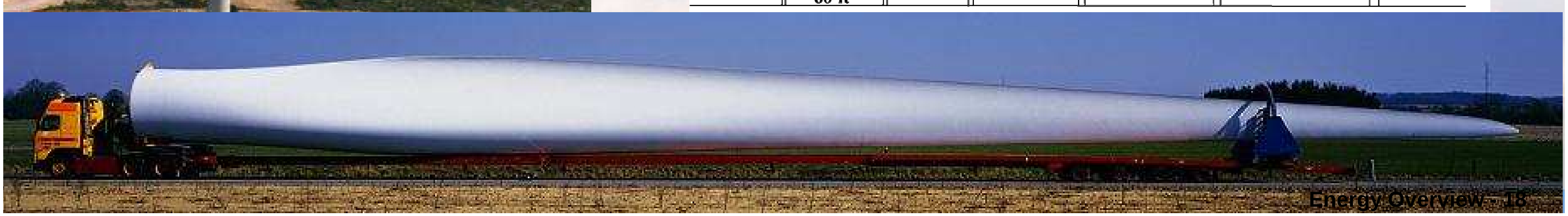
•High-end Military ~ $1000/lb
•Aerospace Industry ~ $100/lb

2008: ~$1.6 – $2.0/Watt

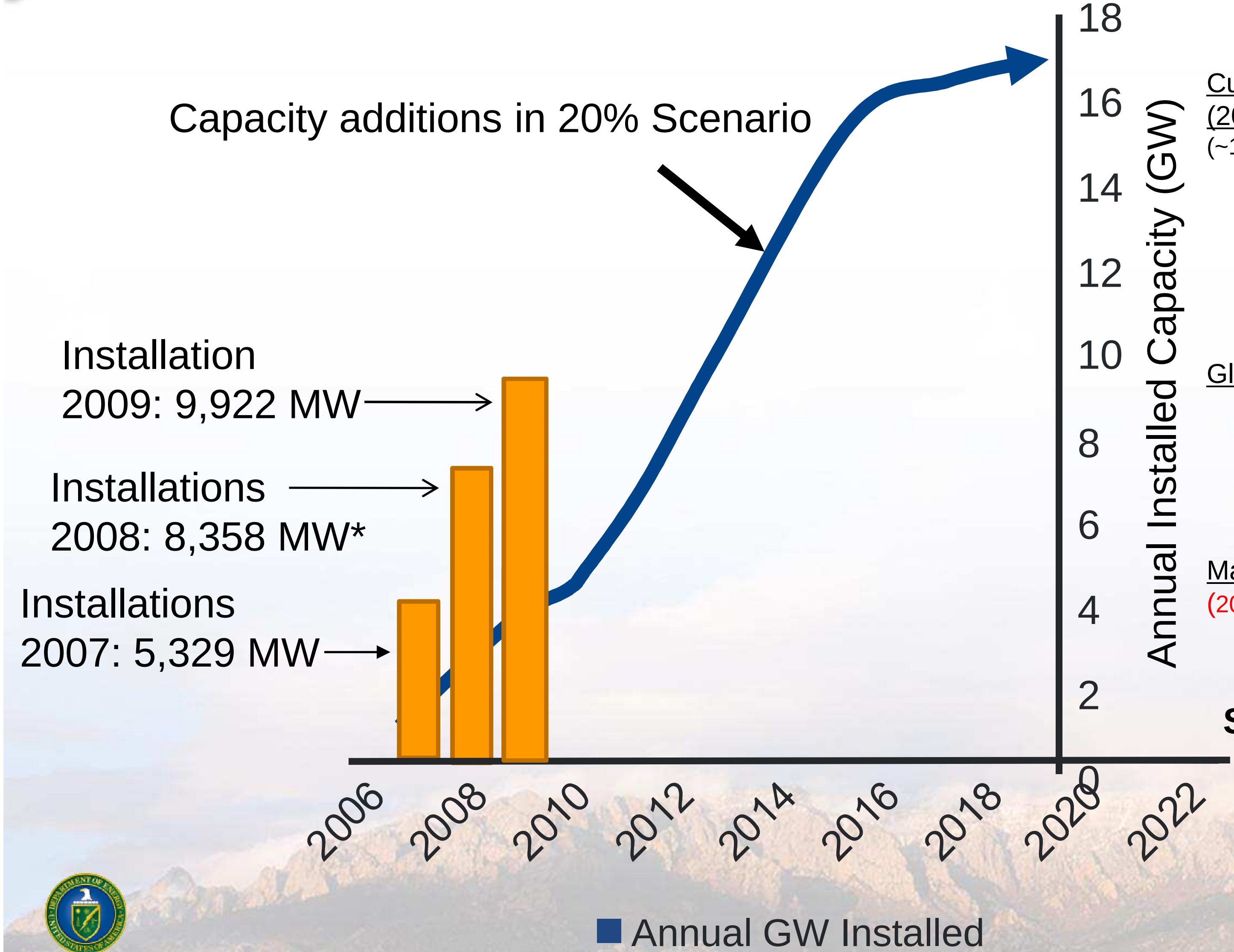
- Size
  - 1.5-5.0 MW
  - Towers: 65-100 meters
  - Blades: 34-50 meters
  - Weight: 150-500 tons







Scenario Installed Capacity vs. Current Installed Capacity



Current Blade Manufacturing (2009*):

(~1.5MW Baseline – U.S. Market)

- ~19,850 New Blades
  - ~ 9,000lb of fiber glass
  - ~600lb of core mat.
  - ~3,500lb of resin
- ~178M lb of Fiber Glass

Global Market (2008):

- ~27 GW of New Wind
  - ~54,000 new blades
  - ~ 486M lb of fiber glass
- ~121 GW Total Capacity

Market Potential:

(20% Scenario – U.S. Market, 2016)

- ~33,000 New Blades
- ~300M lb of Fiber Glass

Source*: AWEA, 2009

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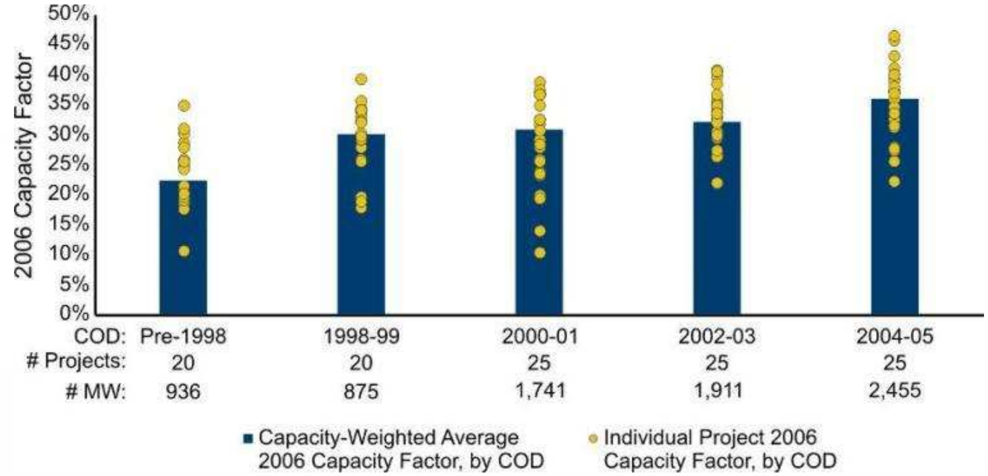
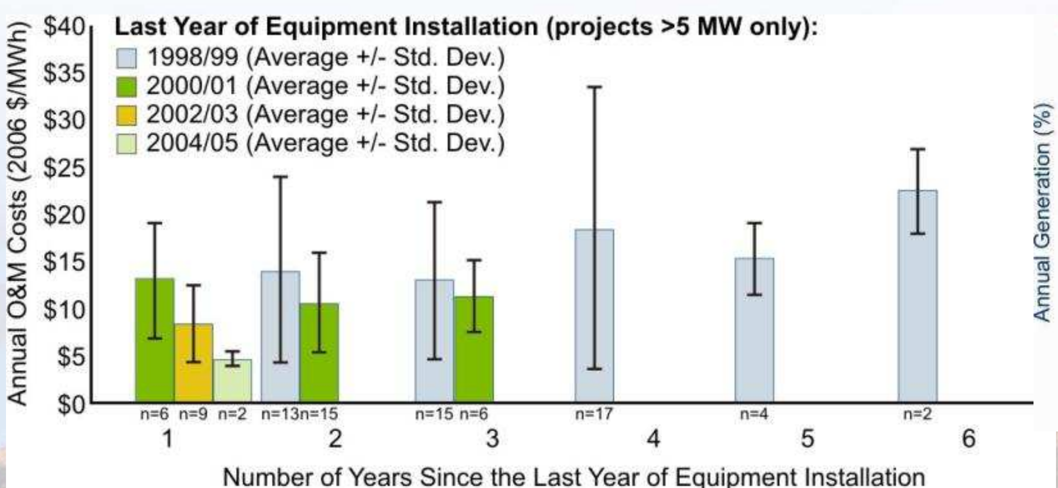
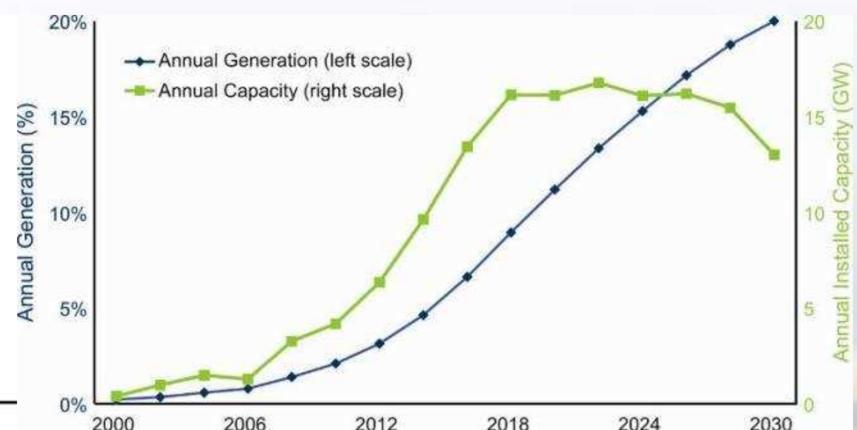
Critical Elements for 20% Scenario Planning



- **Improved Performance**
  - 10% reduction in capital cost
  - 15% increase in capacity factor
  - Net result: 1.3-2.2 cents/KWh
- **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





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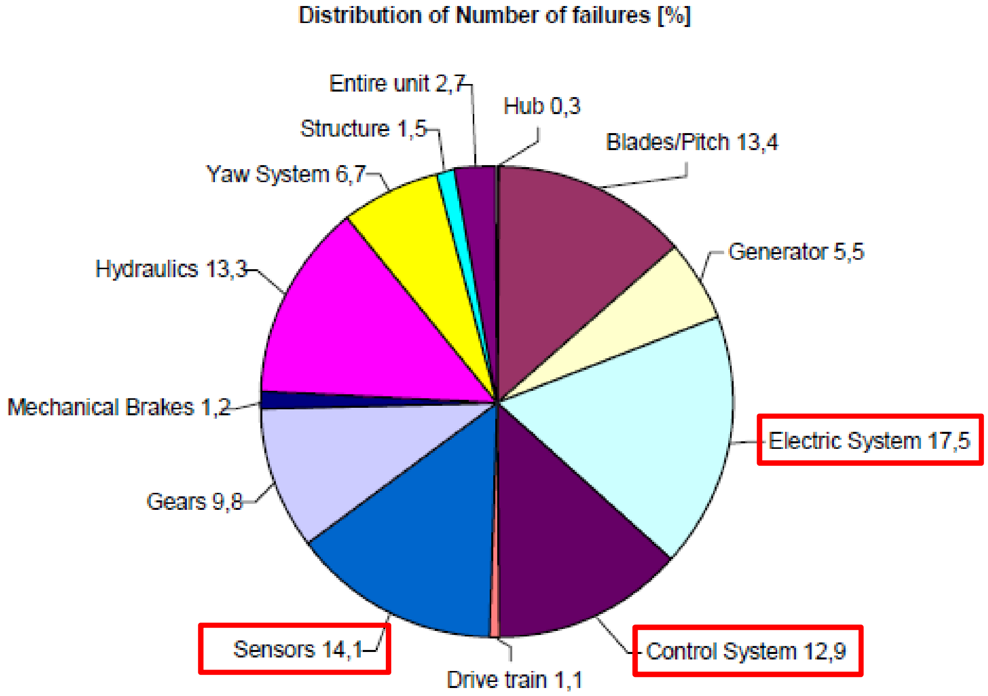
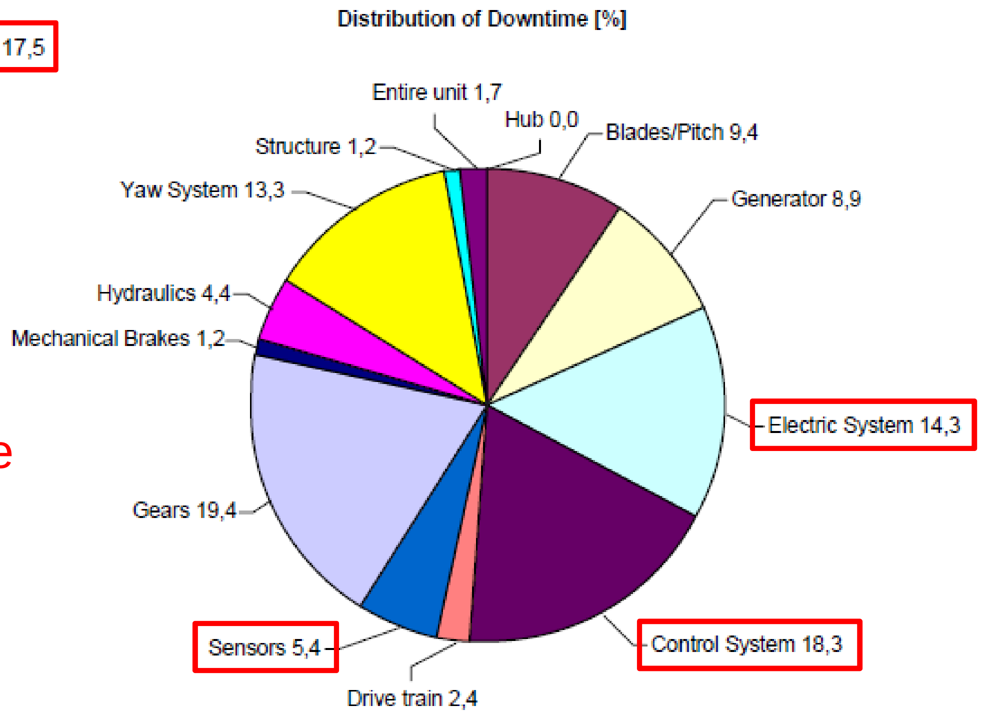
Ribrant, J. "Reliability performance and maintenance – A Survey of failures in wind power systems." 2006.

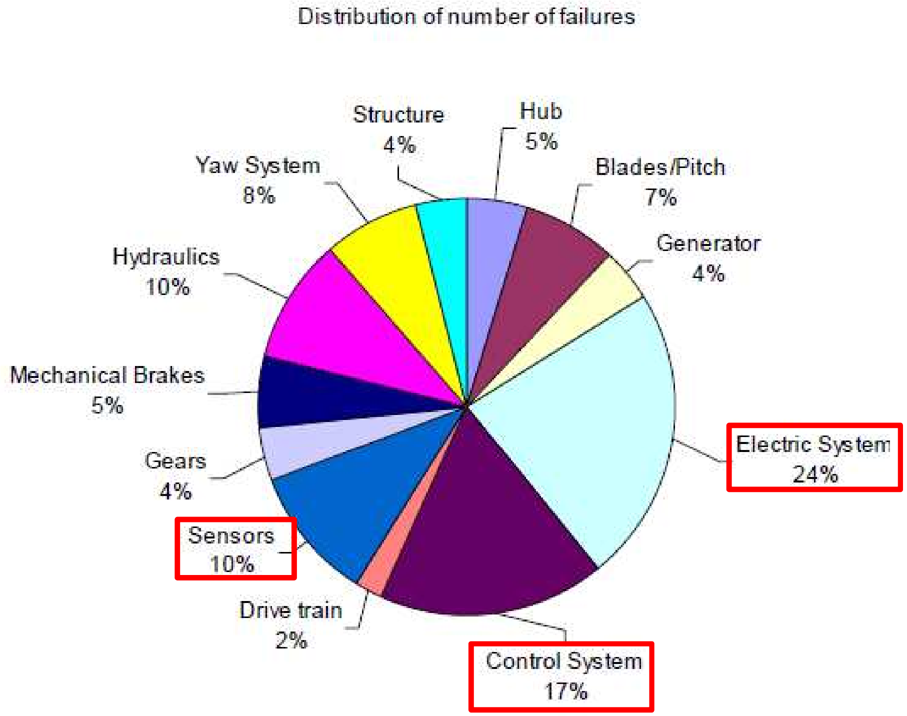


~625 Turbines in Sweden (2000-2004)

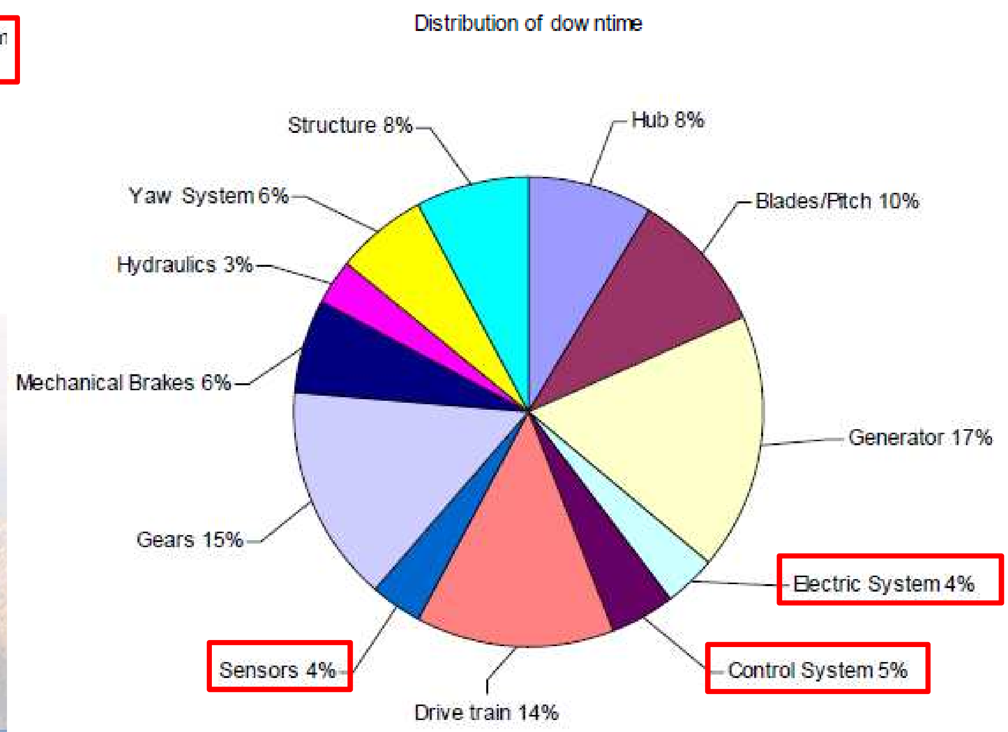


Sensors: 14.1% Failures / 5.4% Downtime
Elec Sys: 17.5% Failures / 14.3% Downtime
Ctrl sys: 12.9% Failures / 18.3% Downtime
Total: 44.5% Failures / 38% Downtime

Ribrant, J. "Reliability performance and maintenance – A Survey of failures in wind power systems." 2006.

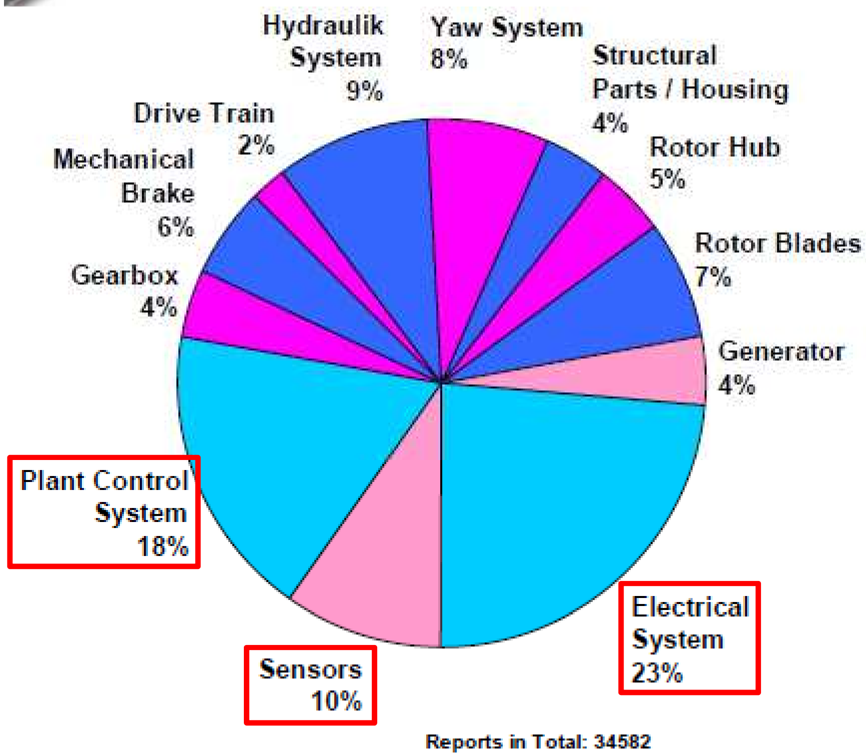


~865 Turbines in Germany (2004-2005)

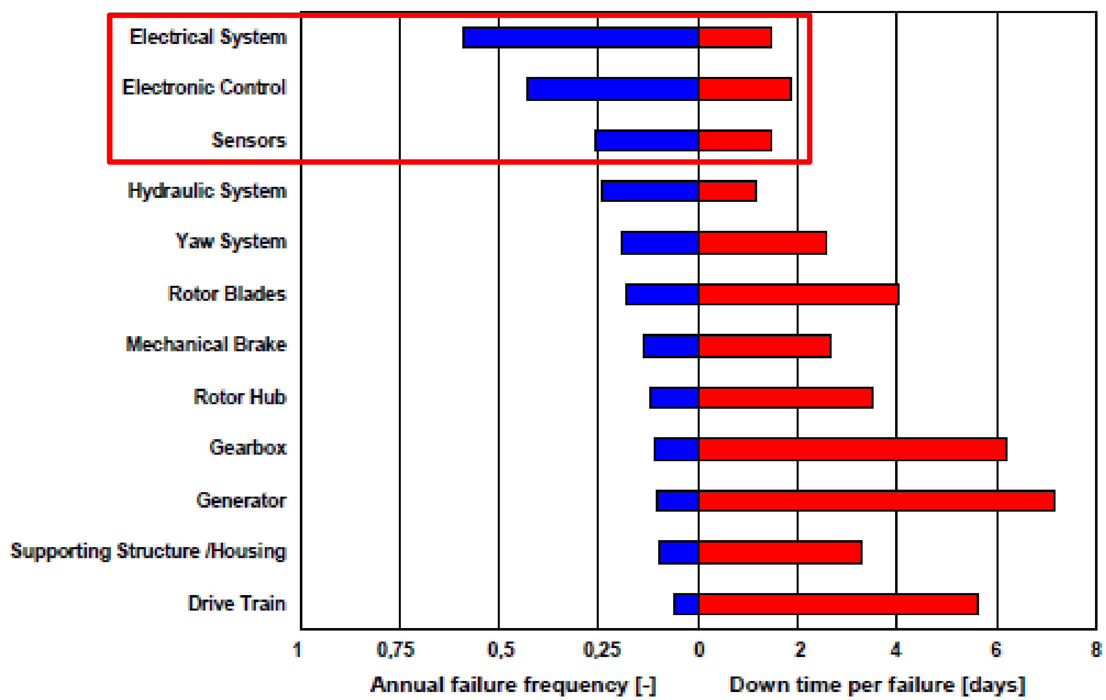


Sensors: 10% Failures / 4% Downtime
Elec Sys: 24% Failures / 4% Downtime
Ctrl sys: 17% Failures / 5% Downtime
Total: 51% Failures / 13% Downtime

ISET 250 MW Wind Programme



Hahn, B. et al.
"Reliability of Wind Turbines." 2006.



Sensors: 10% Failures
Elec Sys: 23% Failures
Ctrl sys: 18% Failures
Total: 51% Failures

Sandia Research Efforts

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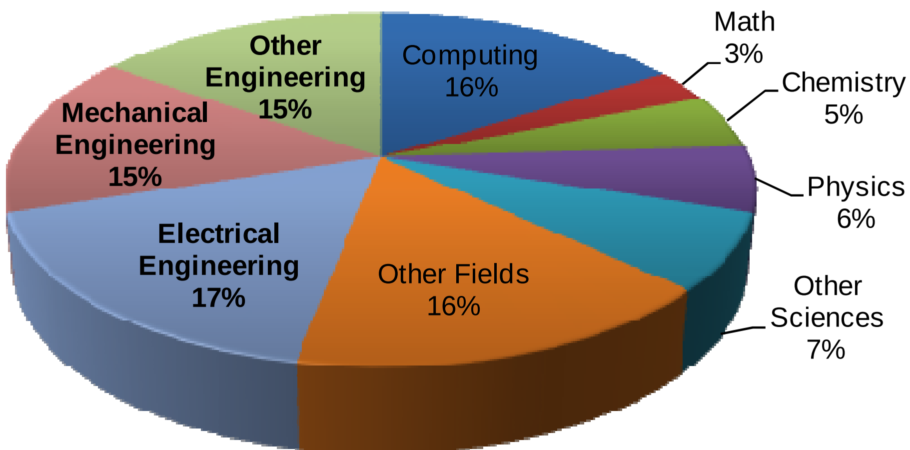
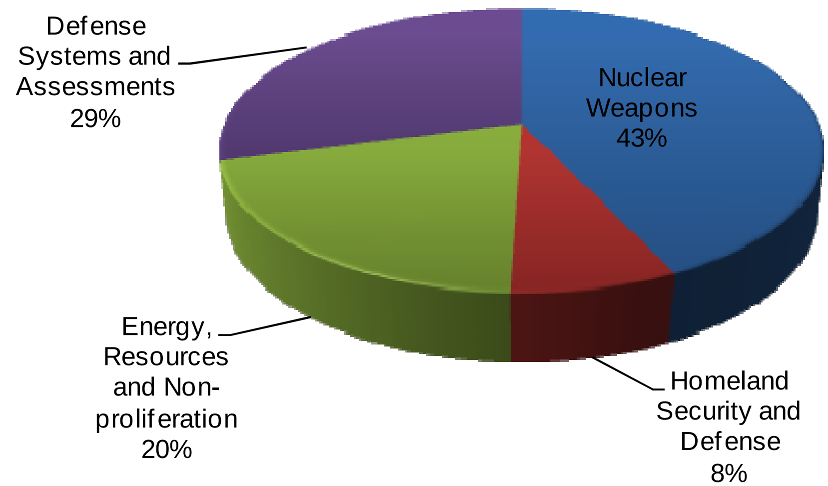
- **FY09 permanent workforce: 8,478**
- **FY09 budget: $2.4B**

Technical Staff (3,921) by Degree

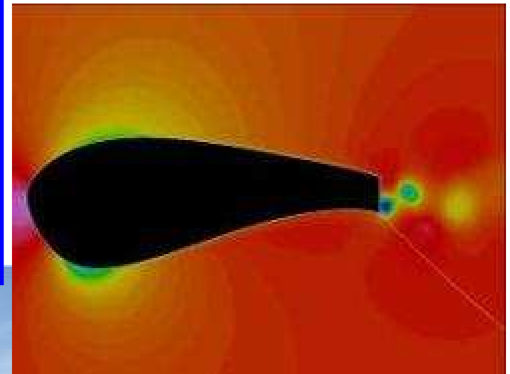


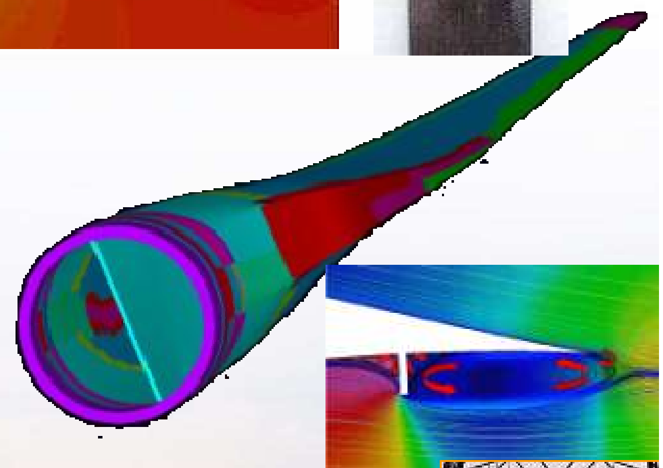
Operating Budget



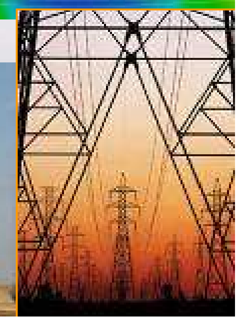
SNL's Wind & Water Power Program

- **Wind Technology**
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
  - Lab - Field Testing and Data Acquisition
- **System Reliability**
  - Industry Data Collection
  - Improve reliability of the existing technology and future designs
  - Blade Reliability Collaborative
- **System Integration & Outreach**
  - Wind/RADAR Interaction
  - Integration Assessment
  - SNL Wind Farm Feasibility
- **Advanced Water Power**
  - Lead Lab for MHK Technology and Environmental Analysis
  - Supporting R&D on Conv. Hydro

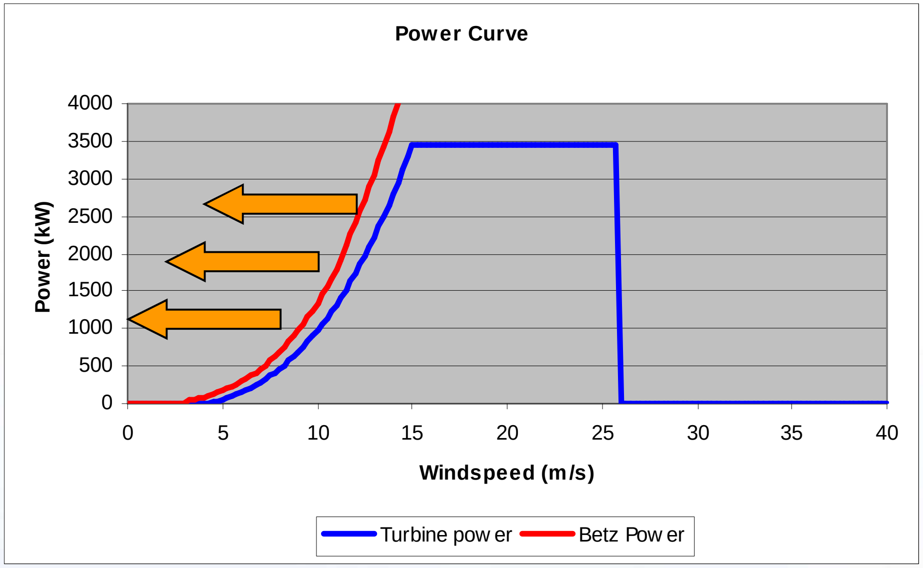





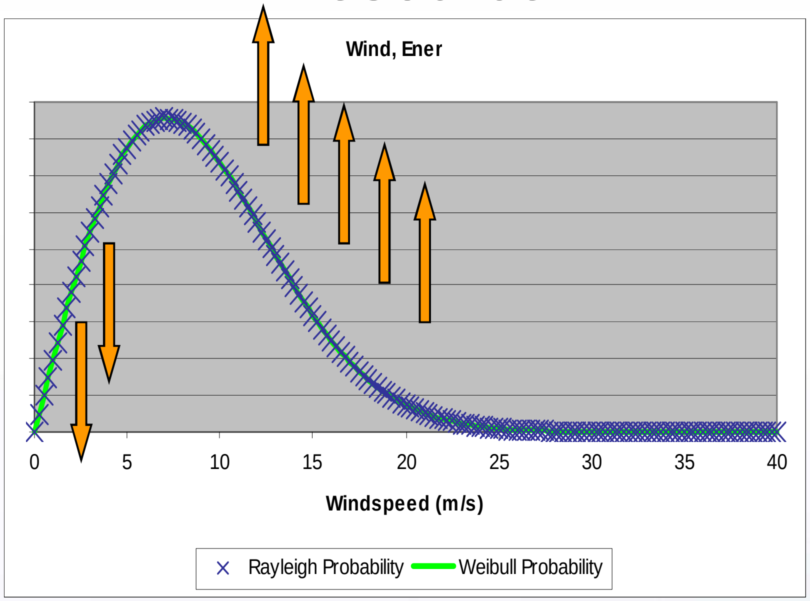


Performance Enhancement Options

Power



Resource



Larger Rotor

Rotor *costs* increase with diameter *cubed,* Rotor *power* grows with the diameter *squared*

Taller Tower

Tower costs increase with height to the *fourth* power

We can only win this battle if we build rotors that are smarter and components that are lighter to beat the squared-cubed law.

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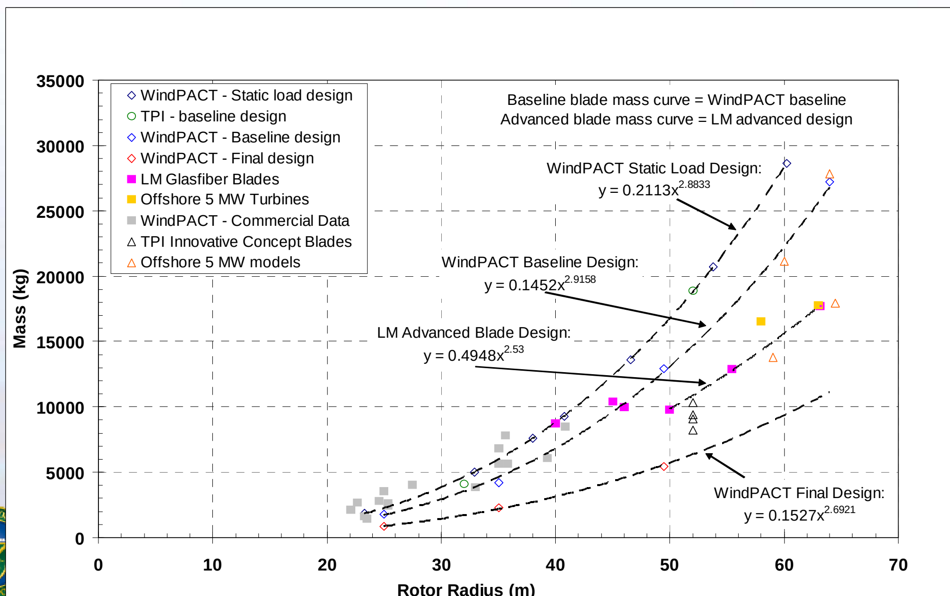
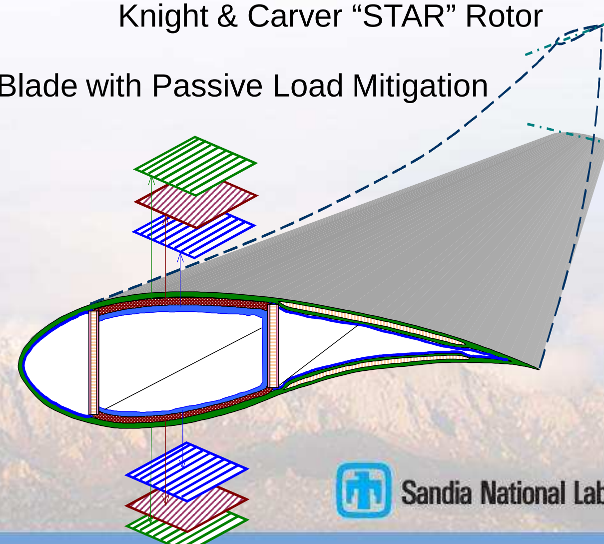
Improved Performance Achieved through Increased Capacity Factor

- **<u>Larger Rotors</u>: to sweep greater area**
  - Longer and lighter blades (new materials and designs)
  - Load-mitigating control (passive and active)
- **<u>Taller Towers</u>: to access greater resource**
  - Lower tower-head mass (lighter components)
  - Innovations in towers, foundations, erection and maintenance access
- **<u>Reduced Losses</u>: to deliver more of what is generated**
  - Power electronics, gearboxes, generators, medium-voltage, etc.
  - Arrays, wakes, and siting issues





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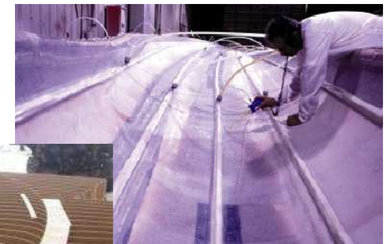
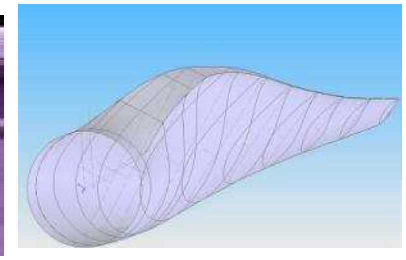
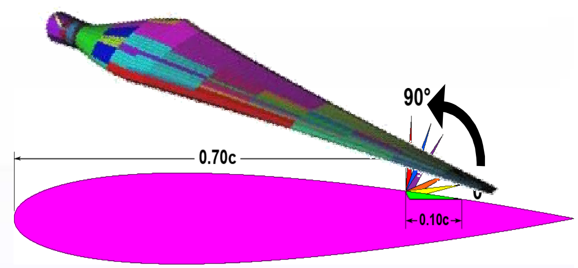
Paths to Improved Capacity Factor

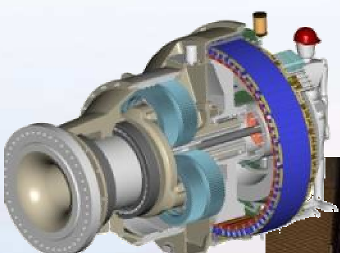
- Advanced Rotor Technology
  - Extended rotor architectures through <u>load control</u>
    - Cyclic & independent blade pitch control for load mitigation
    - Sweep and flap twist coupled architectures
    - Active Aerodynamics
  - Incorporate advanced materials for hybrid blades
  - Light weight, high TSR with attenuated aeroacoustics







- Power Train Enhancements
  - Permanent Magnet Direct Drive Architectures
  - Split load path multi-stage generation topologies
  - Reduced stage (1-2) integrated gearbox designs
  - Convoloid gearing for load distribution

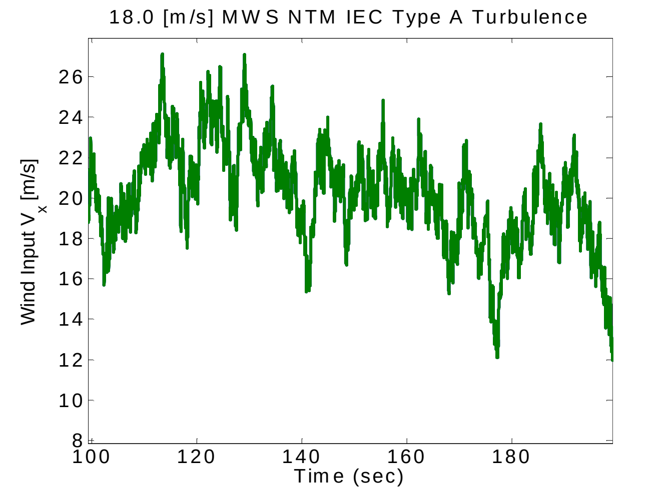



NPS 1.5MW Direct Drive Generator

Reductions in Capital Cost

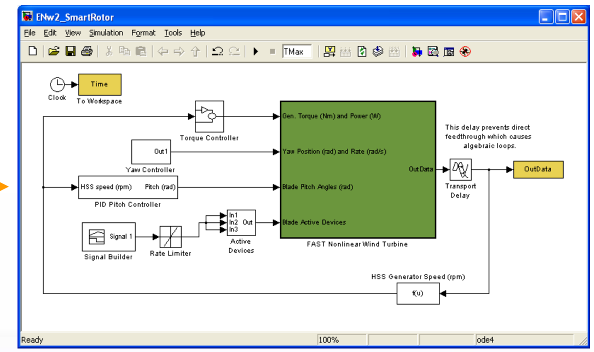
- **Learning Curve Effects**
  - Measures cost reduction in each doubling of capacity
    - Greater Efficiency & New Technology
  - Historical rates were about 9% per doubling
  - 4.6 doublings from 2006 to 2030.
  - A 10% reduction – 2.2% per doubling
- **Opportunities – Design, Manufacturing, & Transportation**
  - Lighter – less material, advanced materials
  - More automation
  - Design for manufacturability
  - Segmented Blades - ??

Innovation Evaluation Methodology

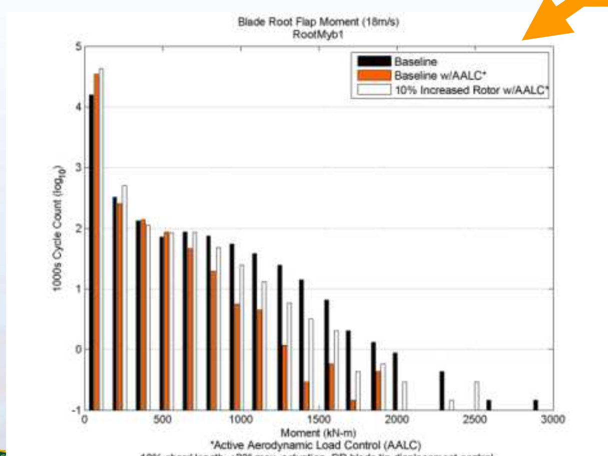


Turbulent Wind Input

Turbine



FAST/Aerodyn/Simulink Simulation



Rain Flow Counting

	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	-1.7	-4.9	-33.5	-3.1	-7.3
Blade Root Edge Moment	1.7	1.9	-2.5	0.8	0.8
Blade Root Flap Moment	-31.2	-27.1	-30.4	-23.1	-26.3
Blade Root Pitch Moment	-11.4	-4.5	-14.1	-7.1	-7
Tower Base Side-Side Moment	-0.1	-8	-7.2	-0.9	-2.9
Tower Base Fore-Aft Moment	-18.6	-16.5	-13.8	-5	-8
Tower Top Yaw Moment	-53.2	-42.9	-43.4	-25.1	-32.2

Fatigue Damage Summary

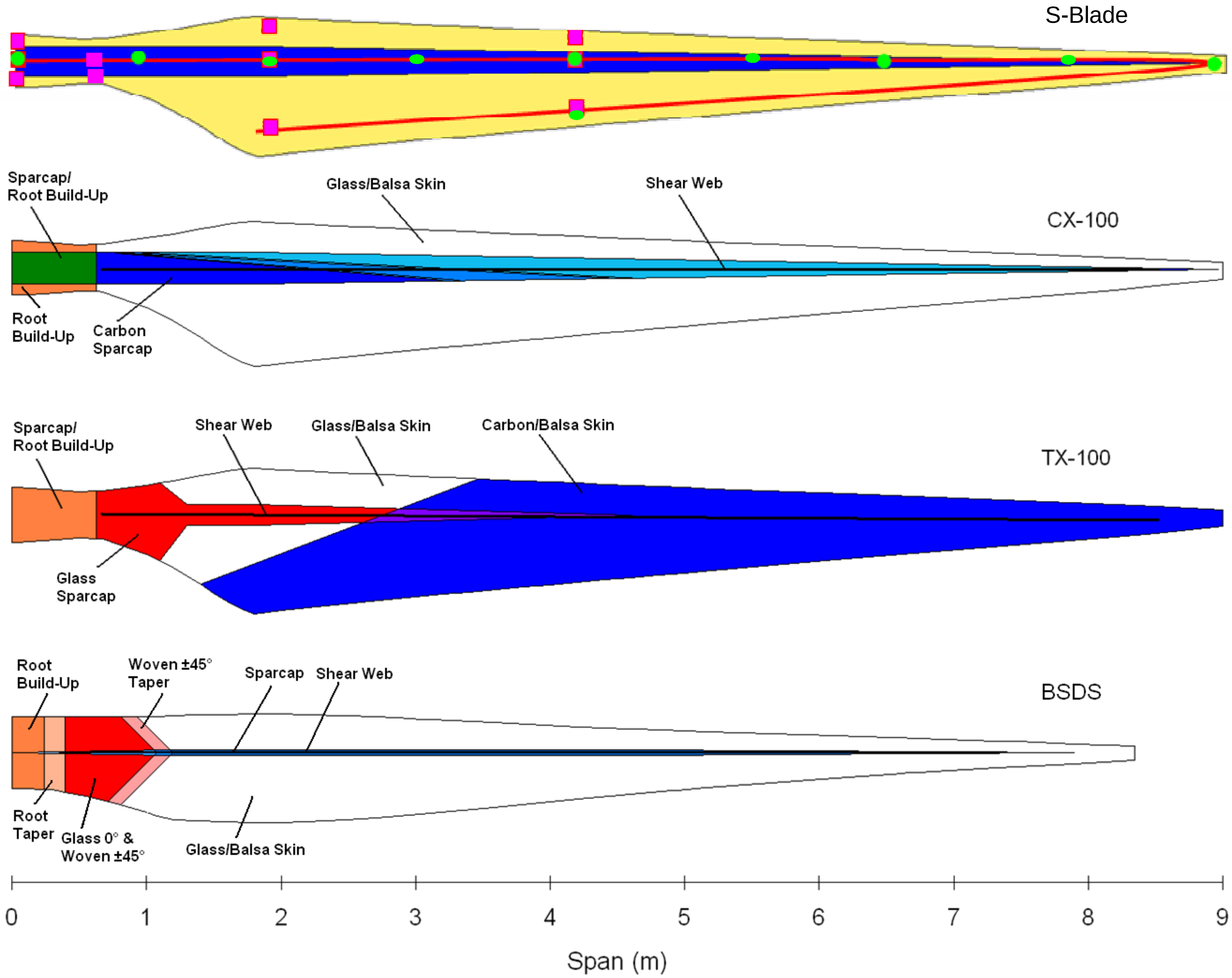
9m Research Blades

Advanced Blade Sensing

Strategic use of carbon for weight reduction

Passive aero-structural load mitigation

Structural efficiency improvement



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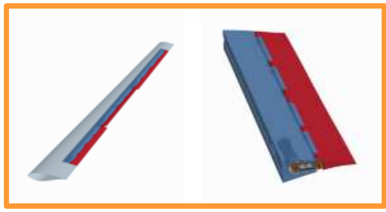
Sensored and SMART Rotor Technology

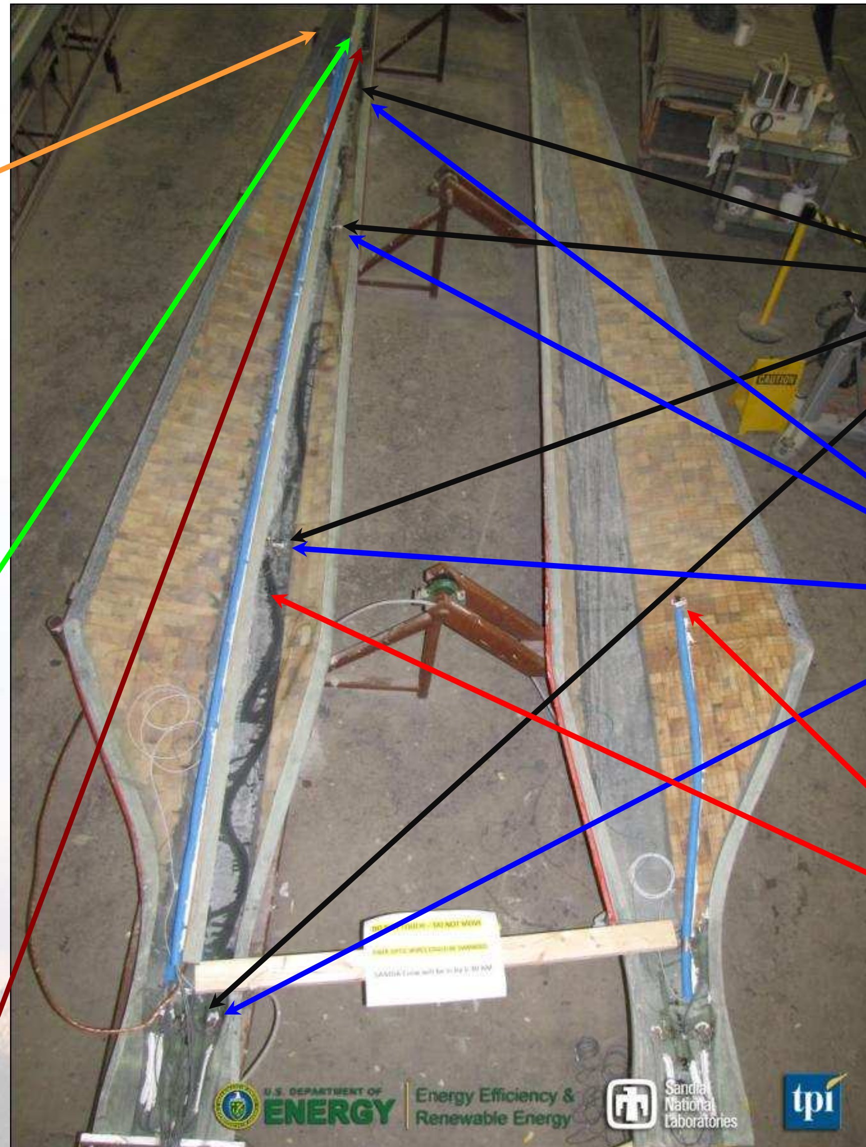
Aero Actuator



Aero Sensors

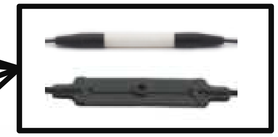
Pressure Taps
(surface pressure)

5-Hole Pitot Tube
(AOA and Velocity)

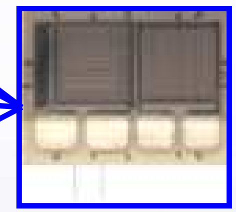


Structural Sensors

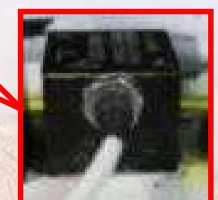
Fiber Optic
(strain and temperature)



Strain Gage
(strain)



Accelerometer
(acceleration)



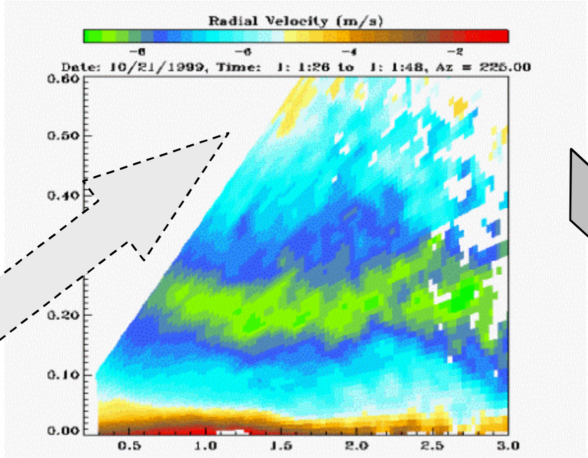
Enhanced Modeling Required

Powerful winds

U_{∞}, direction vary

Coherent turbulence

Turbine wakes

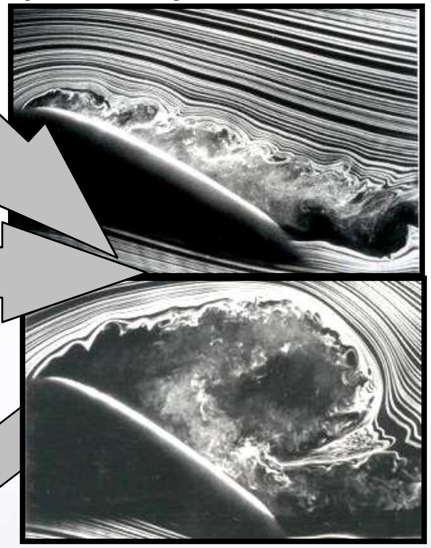


Energetic flow-field

Globally separated

Steep gradients

Dynamically active



Basic R&D Needs:

Aeroelasticity

Nonlinear & coupled

Multiple physics

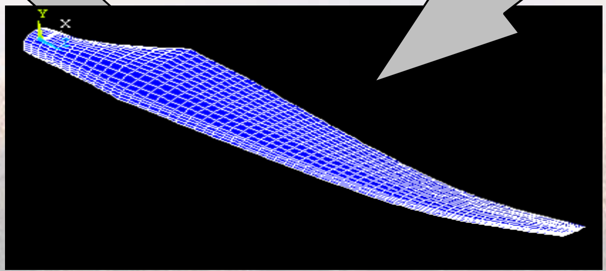
Multiple scales

Complex wake

Trailed vortices

Shed vortices

Persistent



Responsive structure

Light and flexible

Advanced materials

Aeroelastic load control

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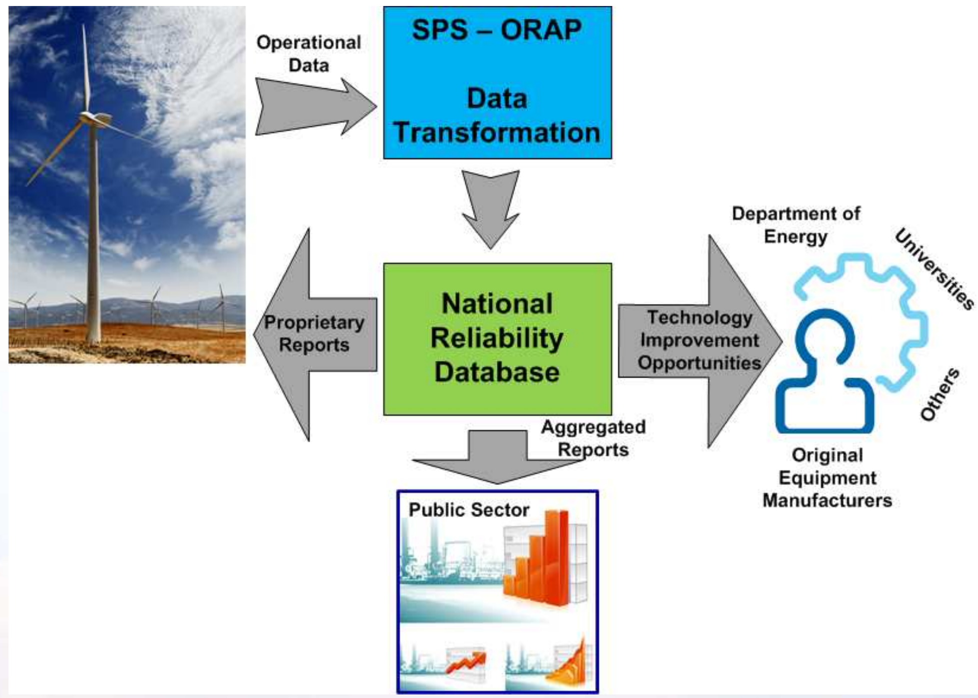
Initiatives to Mitigate Risk

- **Avoid Problems before they get Installed**
  - Full Scale Testing
  - Appropriate design criteria (specifications and standards)
  - Validated design evaluation tools
- **Monitor Performance**
  - "Tracking, tracking, tracking"
  - Maintain reliability tracking database
  - Define the problems before they get out of hand
- **Problem Resolution Initiatives**
  - Targeted activities in to address critical issues
  - Example: Gearbox & Blade Collaborative

Photo by Lee Jay Fingersh

Reliability Database and Analysis

- **<u>Goal</u>: Create an industry-wide capability that can *track* operating experience, *benchmark* reliability performance, *characterize* issues, and *identify* opportunities for improving reliability of the national wind energy investment.**



- **<u>Program Focus</u>:**
  - Manage and Analyze the National Reliability Database
    - Insightful analysis and benchmarking
    - Feedback at system, component, and part levels
      - Current (maintenance inputs)
      - Future (design opportunities)
    - Multi-level, secure, searchable data
  - Strategic Partnerships
    - Continuous access to operating data
  - Direct industry support and partnerships

- **<u>Industry Impact & Opportunities</u>:**
  - Increased availability, productivity, and reliability
  - Continued confidence: financial sector and policy makers

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Summary

- **Utility Turbine Size has Evolved to 1.5+MW Range (65m + Rotor)**
- **20% Wind Energy by 2030 Scenario Provides New DOE Wind Program Focus**
  - Increase installed wind from 35,000MW to 305,000 MW
    - 50,000MW Offshore
- **Technology Opportunities and Needs Exist:**
  - Increase Capacity Factor
    - Reduce Blade Weight Growth for Larger Blades
      - **Material research, enhance modeling, improve structural efficiency**
    - Implement Active Aero Load Control Technology
      - **Integrate sensors & devices, reduce loads & fatigue**
    - Enhance Power Train
    - Enhance Power Conversion
    - Improve Tower Structure
  - Reduce Capital Cost
    - Improve Design for Manufacturing
    - Enhance Manufacturing
  - Improve O & M
    - Enhance Design and Testing
    - Monitor Performance
    - Resolve Problems Promptly