National Renewable Energy Laboratory
Innovation for Our Energy Future

Wind Electric Generating Equipment R&D

Asian Pacific Partnership – Wind Electric Generation Event

Brian Smith

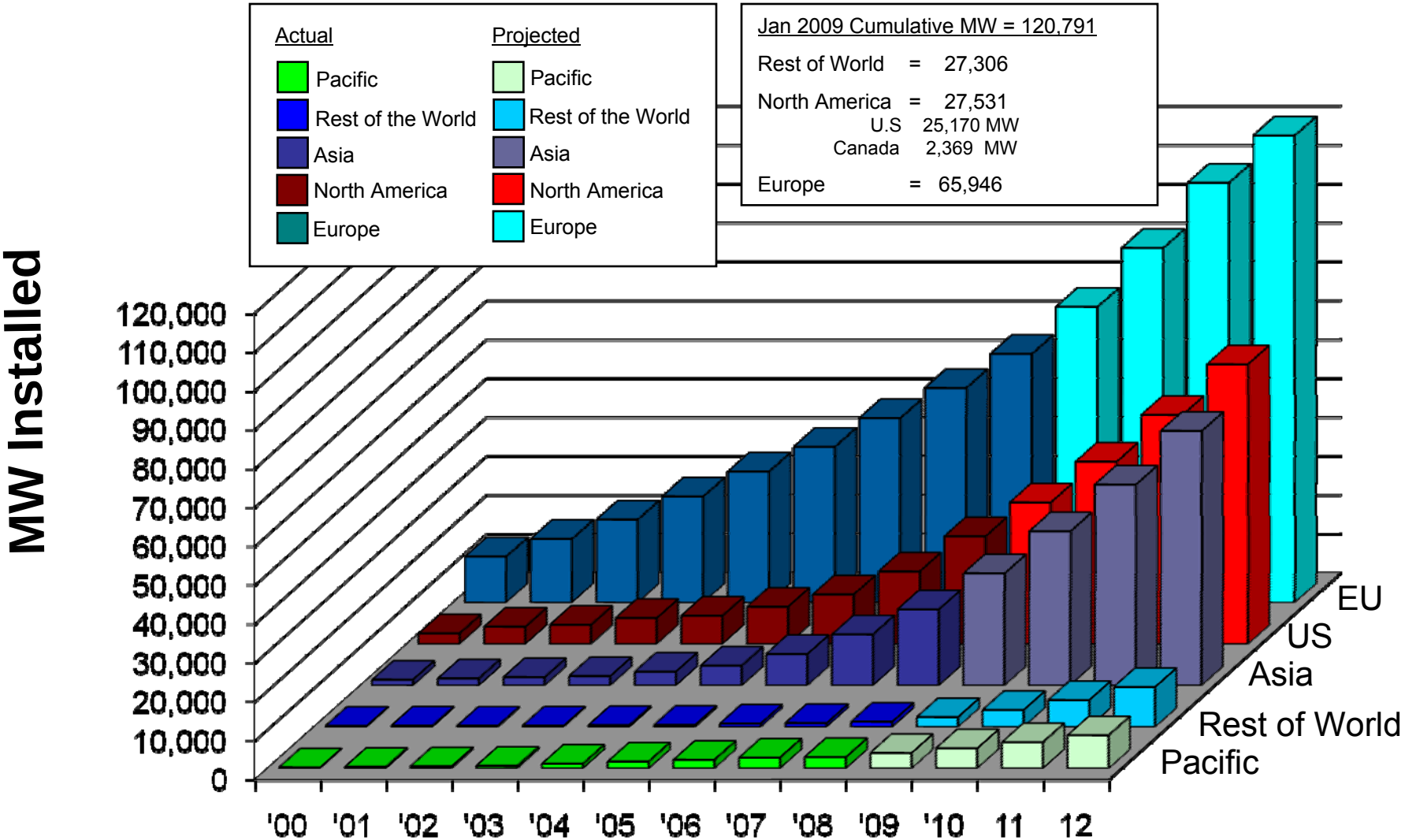
March 3, 2009

San Francisco, CA USA

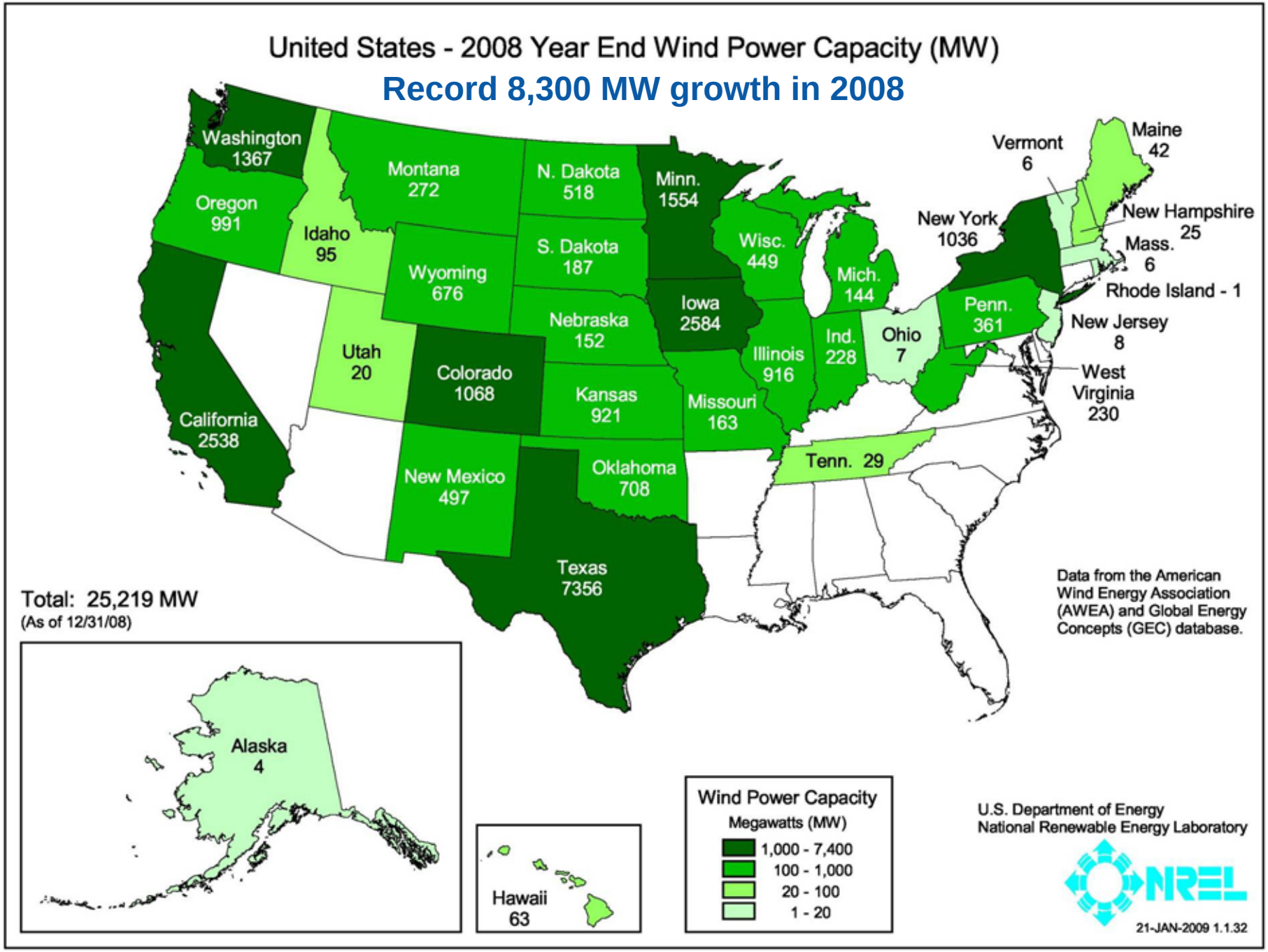
Outline

- Industry Status
- The 20% Challenge
- Technology Improvements Options
- Addressing Technical & Financial Risks
- Offshore Technology
- Summary of Technology Development Opportunities

Growth of Wind Energy Capacity Worldwide



Sources: BTM World Market Update 2007
AWEA/EWEA/GWEC, January 2009
Windpower Monthly, January 2009


United States - 2008 Year End Wind Power Capacity (MW)
Record 8,300 MW growth in 2008
Washington 1367
Oregon 991
California 2538
Idaho 95
Montana 272
Wyoming 676
Utah 20
Colorado 1068
New Mexico 497
N. Dakota 518
S. Dakota 187
Nebraska 152
Kansas 921
Oklahoma 708
Texas 7356
Minn. 1554
Iowa 2584
Missouri 163
Wisc. 449
Illinois 916
Mich. 144
Ind. 228
Ohio 7
Penn. 361
New York 1036
Vermont 6
Maine 42
New Hampshire 25
Mass. 6
Rhode Island - 1
New Jersey 8
West Virginia 230
Tenn. 29
Total: 25,219 MW
(As of 12/31/08)
Data from the American Wind Energy Association (AWEA) and Global Energy Concepts (GEC) database.
Alaska 4
Hawaii 63
Wind Power Capacity
Megawatts (MW)
1,000 - 7,400
100 - 1,000
20 - 100
1 - 20
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
21-JAN-2009 1.1.32

The “20% Wind Report” Informs our RD&D

How it began:

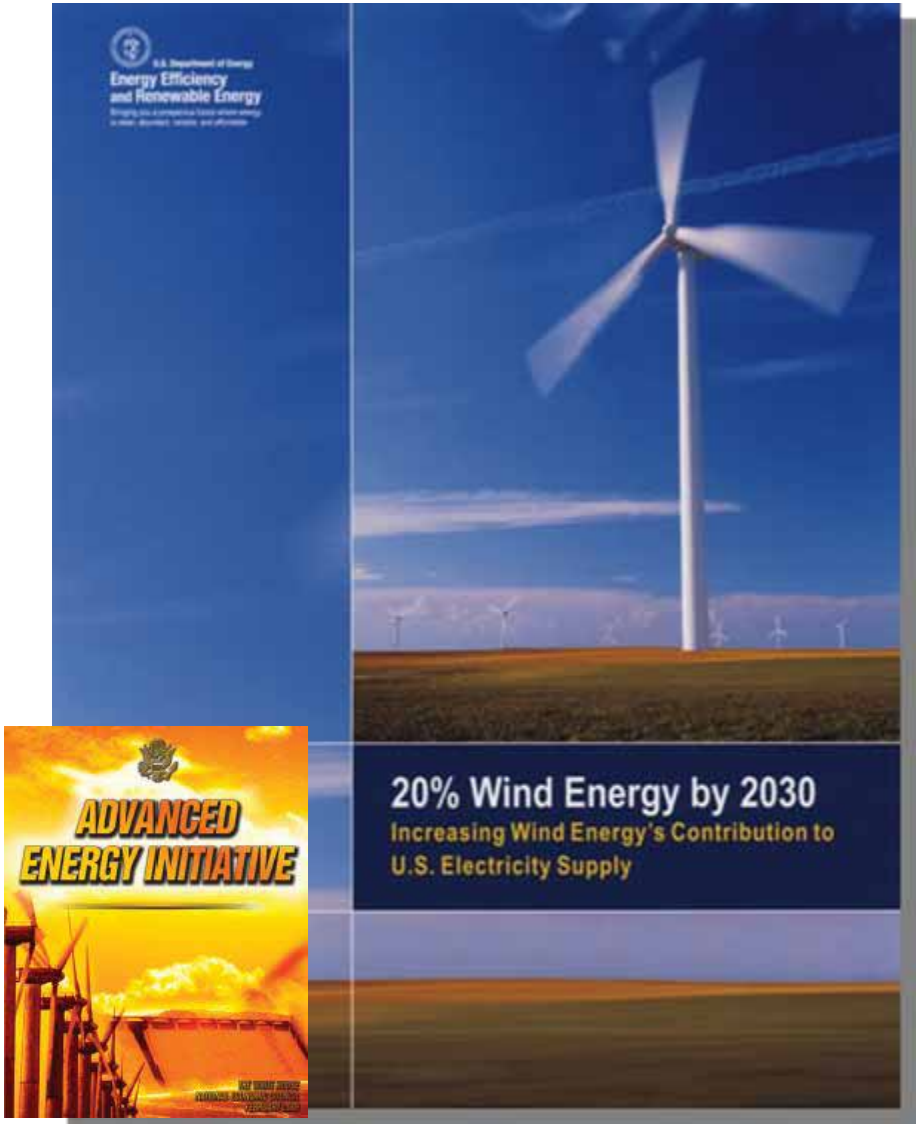
- 2006 State of the Union and Advanced Energy Initiative
- Collaborative effort of more than 100 individuals from government and industry (DOE, NREL, and AWEA) to explore a modeled energy scenario in which wind provides 20% of U.S. electricity by 2030

Primary Assumptions:

- U.S. electricity consumption grows 39% from 2005 to 2030 -- to 5.8 billion MWh (Source: EIA)
- Wind turbine energy production (capacity factor) increases about 15% by 2030
- Wind turbine costs decrease about 10% by 2030
- No major breakthroughs in wind technology

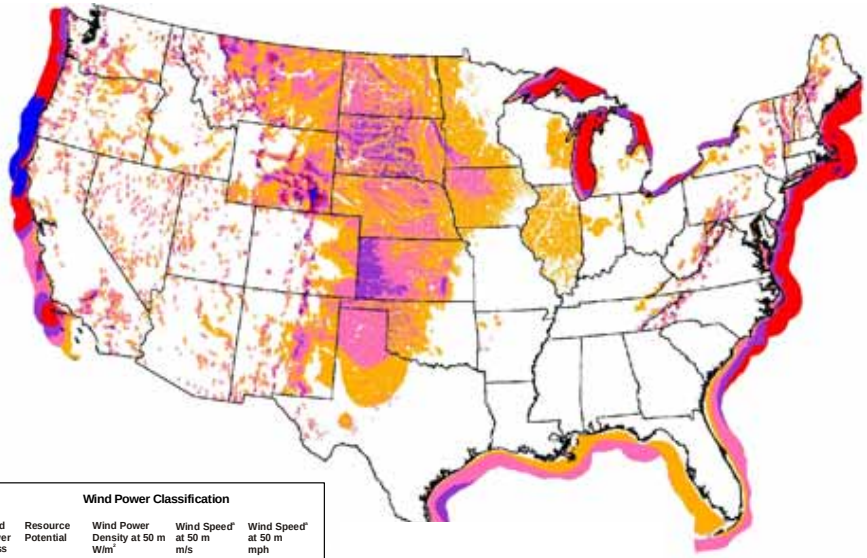
Primary Findings:

- 20% wind electricity would require about 300 GW (300,000 MW) of wind generation
- Affordable, accessible wind resources available across the nation
- Cost to integrate wind modest
- Raw materials are available
- Emissions reductions and water savings
- Transmission a challenge



www.eere.energy.gov/windandhydro

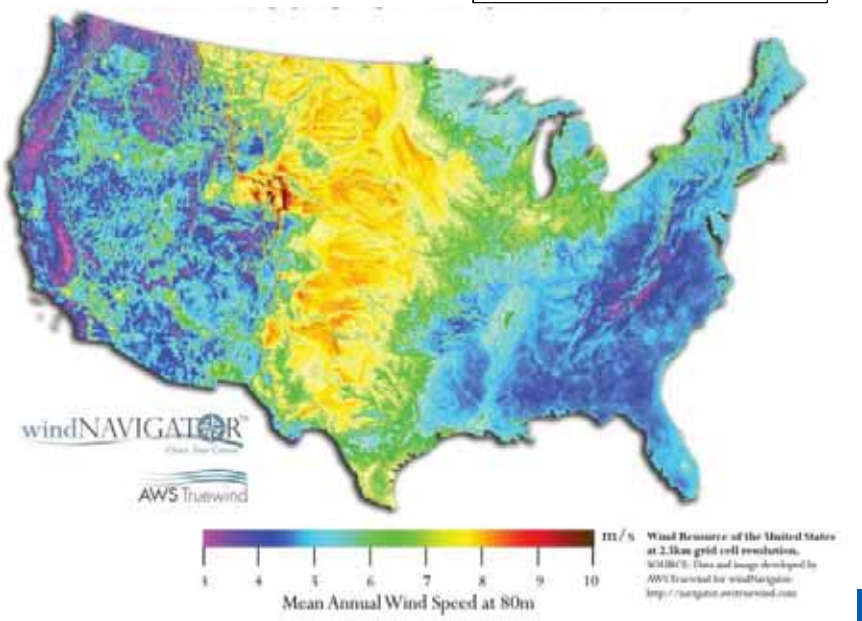
U.S. Wind Resource Maps

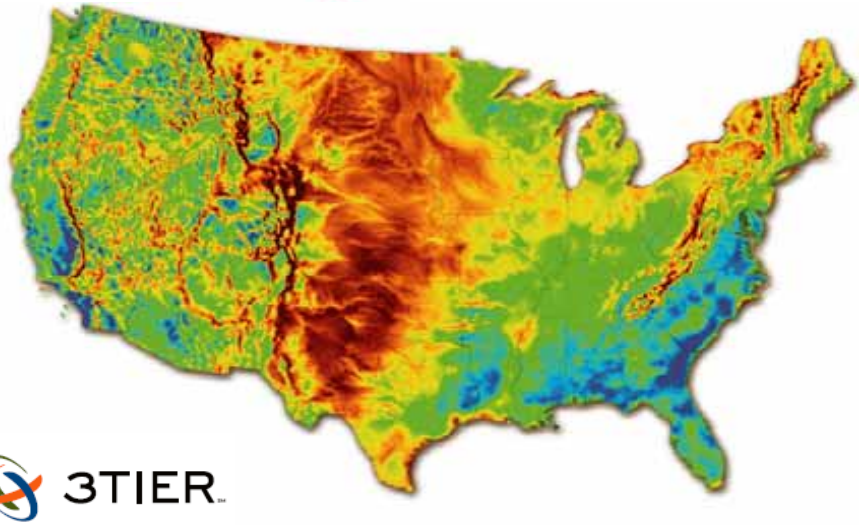


Wind Power Classification

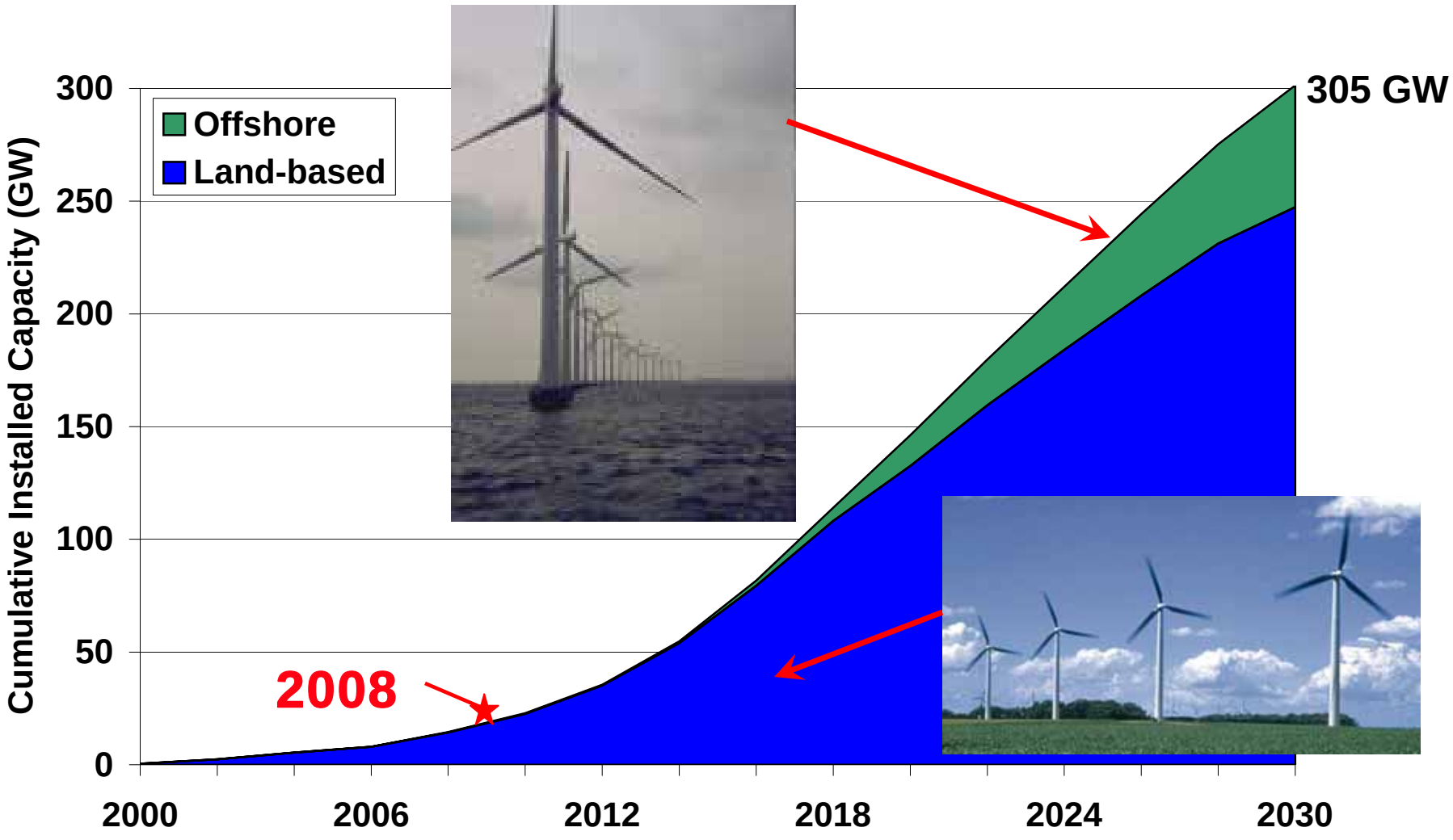
Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

* Wind speeds are based on a Weibull k value of 2.0





Vision: 20% Wind by 2030



46 States Would have Substantial Wind Development by 2030

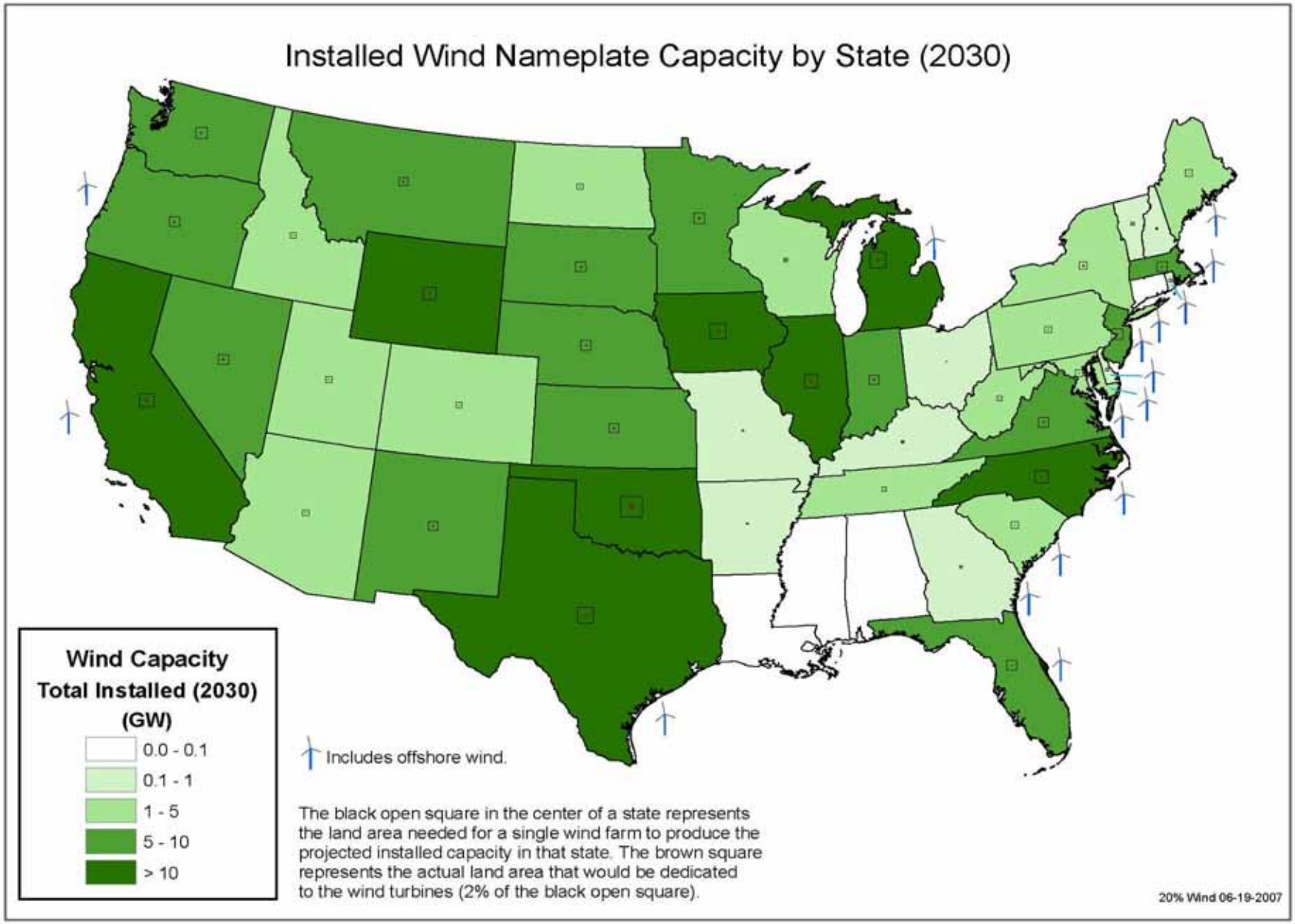
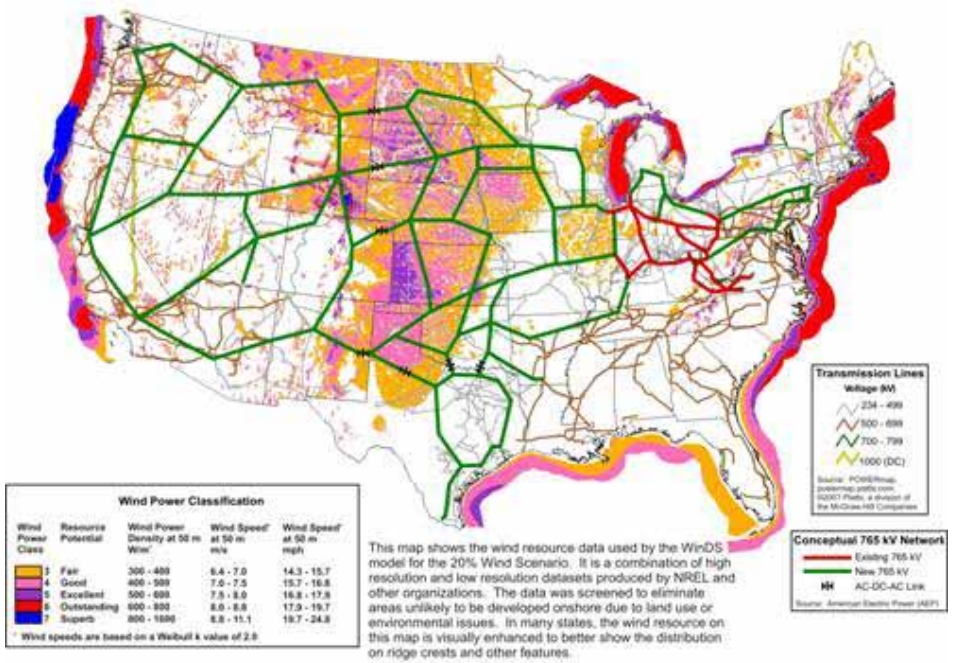


Fig 1-6

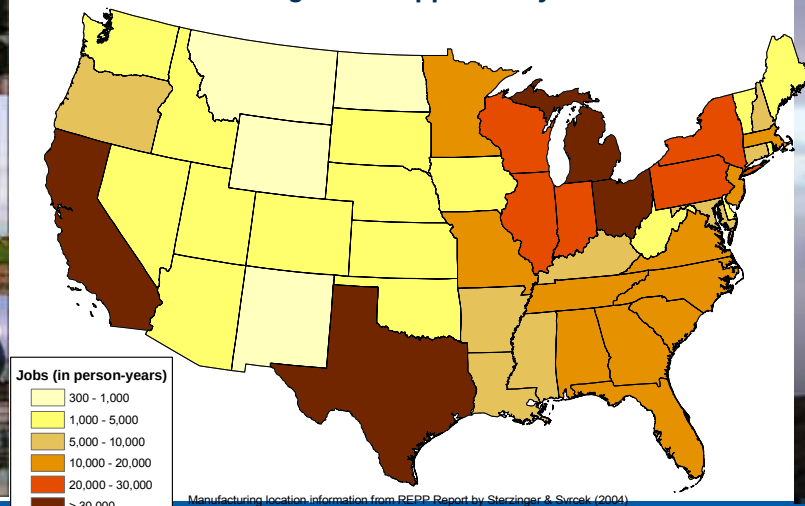
Critical Elements for 20% Scenario

- **Improved Performance**
  - 10% reduction in capital cost
  - 15% increase in capacity factor
  - Improve Wind Farm performance
- **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 miles of line
  - Supports 200-400 GW addition
- **Policy, Communication & Outreach**

Infrastructure Development



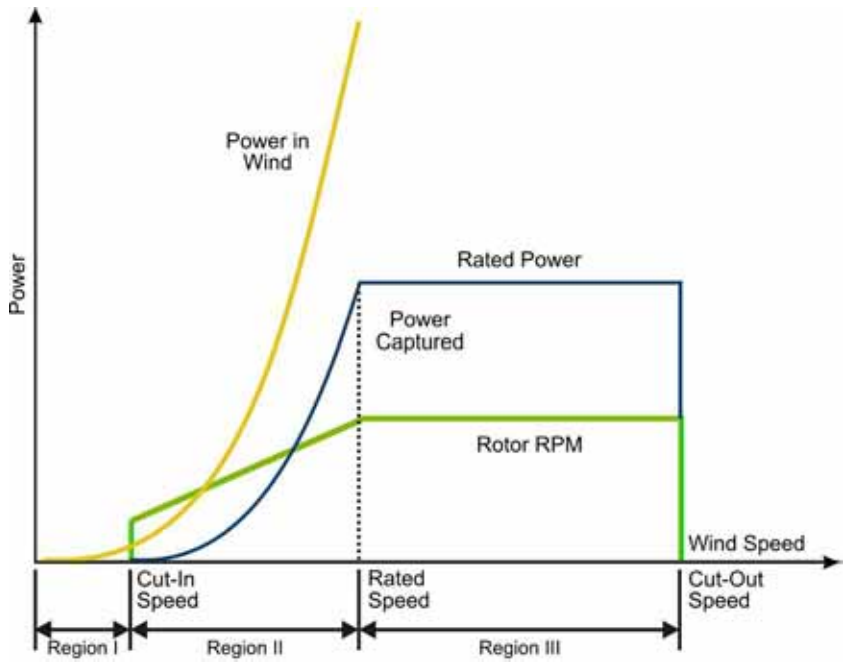
Manufacturing Jobs Supported by States

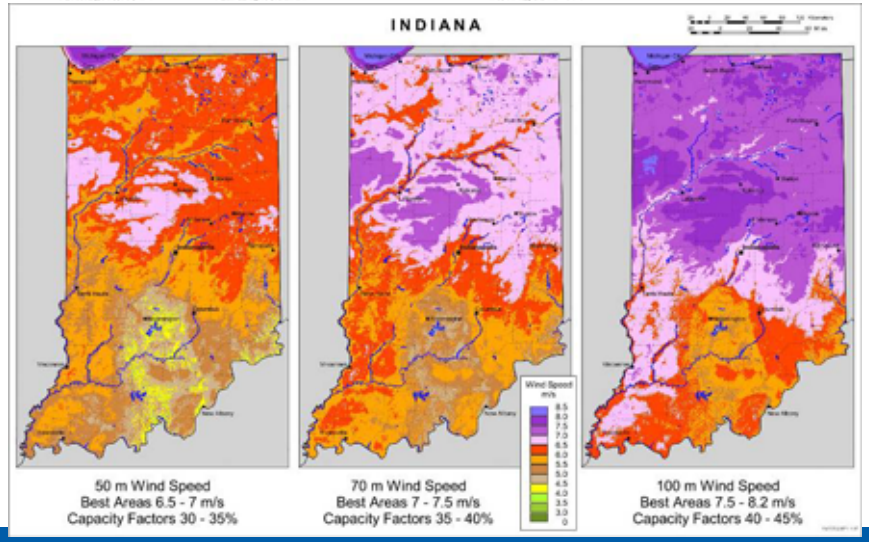


Manufacturing location information from REPP Report by Sterzinger & Svrcek (2004)

Major component assumptions: 50% of blades are manufactured in U.S. in 2007 increasing to 80% by 2030, 26% of towers are from the U.S. in 2007 increasing to 50% by 2030 and 20% of turbines are made in the U.S.

The Physics of the Power Curve Drives Technology Development

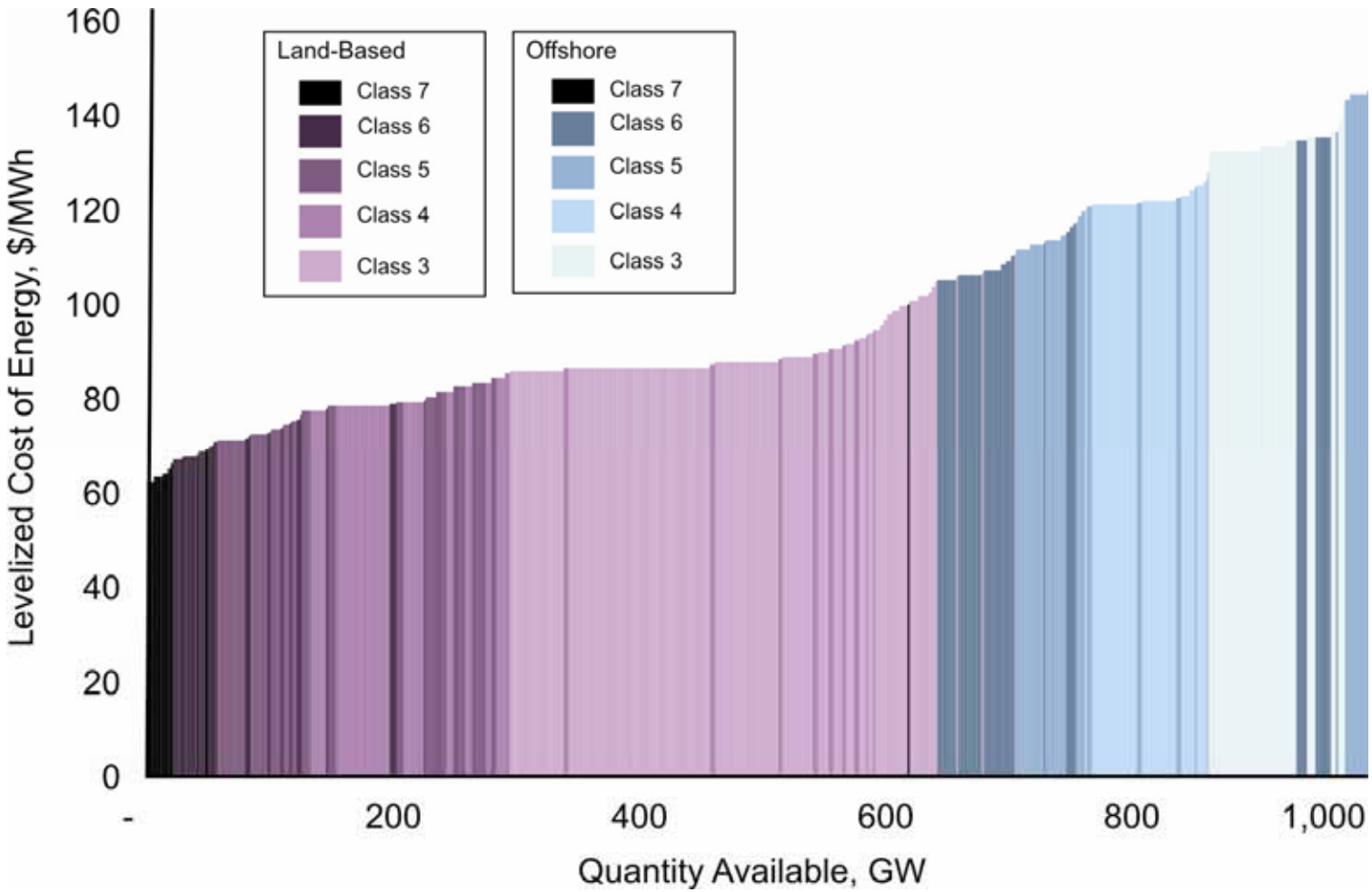




Motherhood and Apple-Pie Truths about Wind Technology

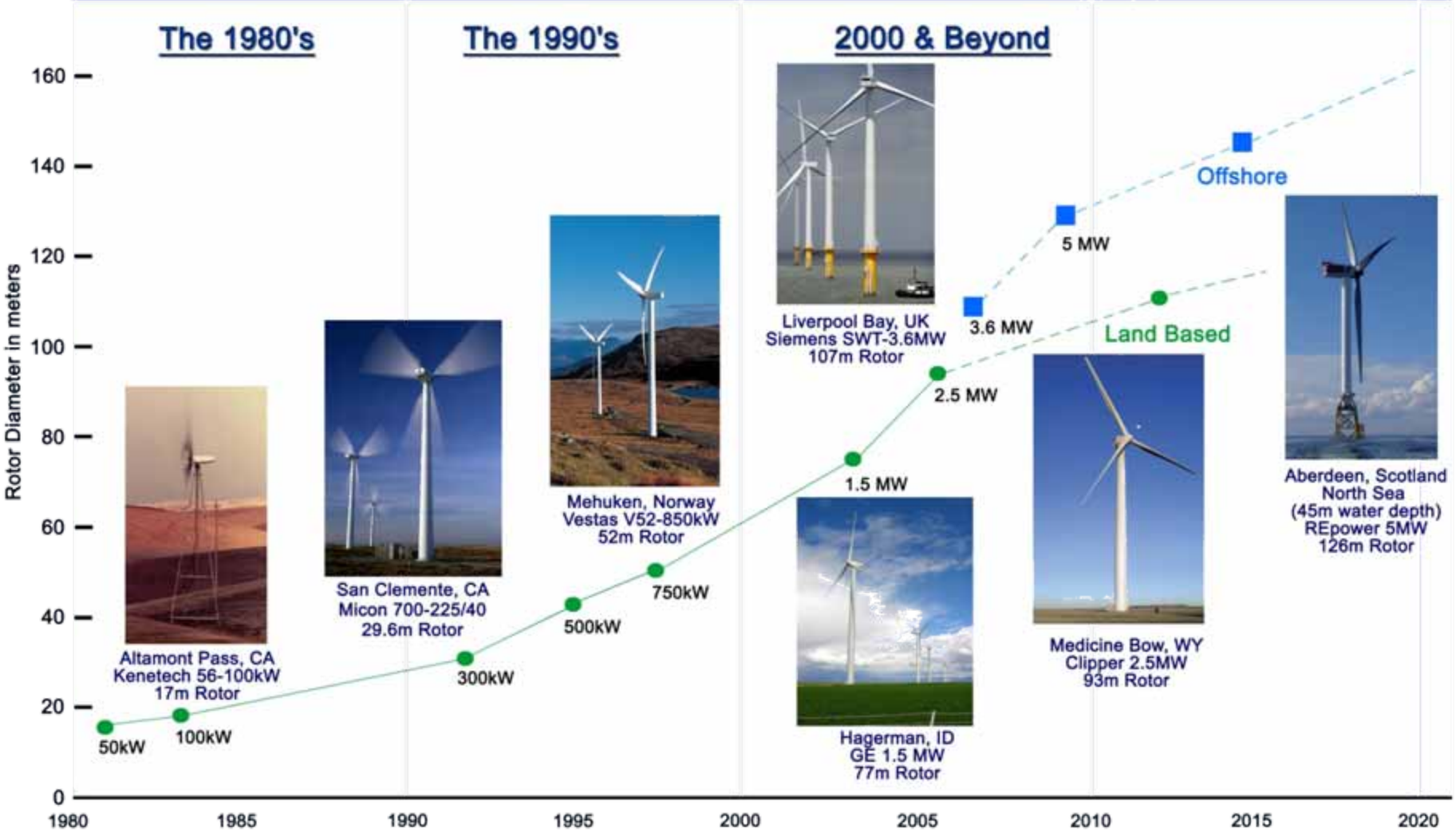
- Power in the wind is proportional to wind speed cubed
- At best, we can capture 59% (the Betz limit)
- "Rated Power" governs the size and cost of the entire turbine infrastructure
- Energy is power multiplied by the amount of time spent at that power level
- Capacity Factor is the ratio of total output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

More than 600 GW available between 6 and 10 cents per KWh (Supply Curve)



…including cost of connecting to 10% of the existing transmission system within 500 miles of wind resource

Evolution of Commercial Wind Technology



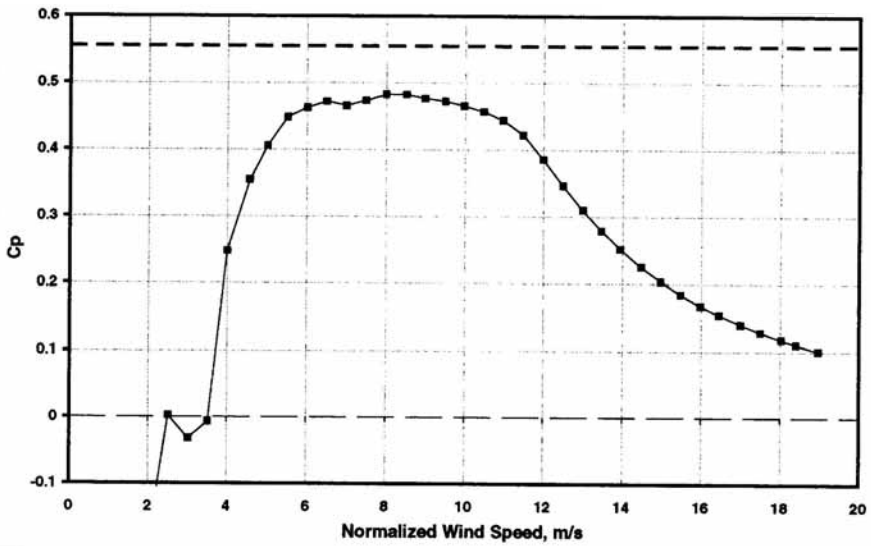
Technology Development Status

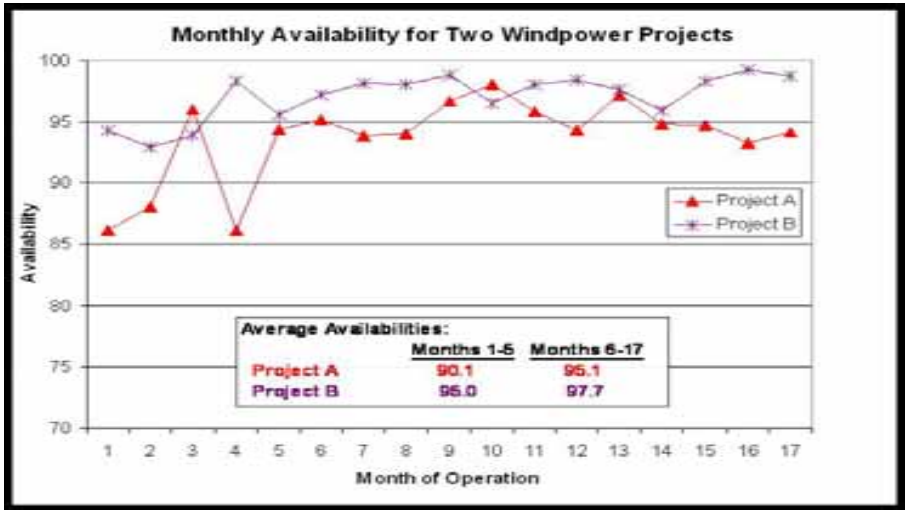
What's Working:

- 98% reported availability
- Capital costs drastically reduced
- Blade development & performance
- Product evolution strategy
- Power quality control
- System Integration

Why:

- Design process, design tools
- Test & validation
- Standards for design, test, certification
- Advanced manufacturing and quality control practices
- Stretch rotor, control loads
- Power electronics

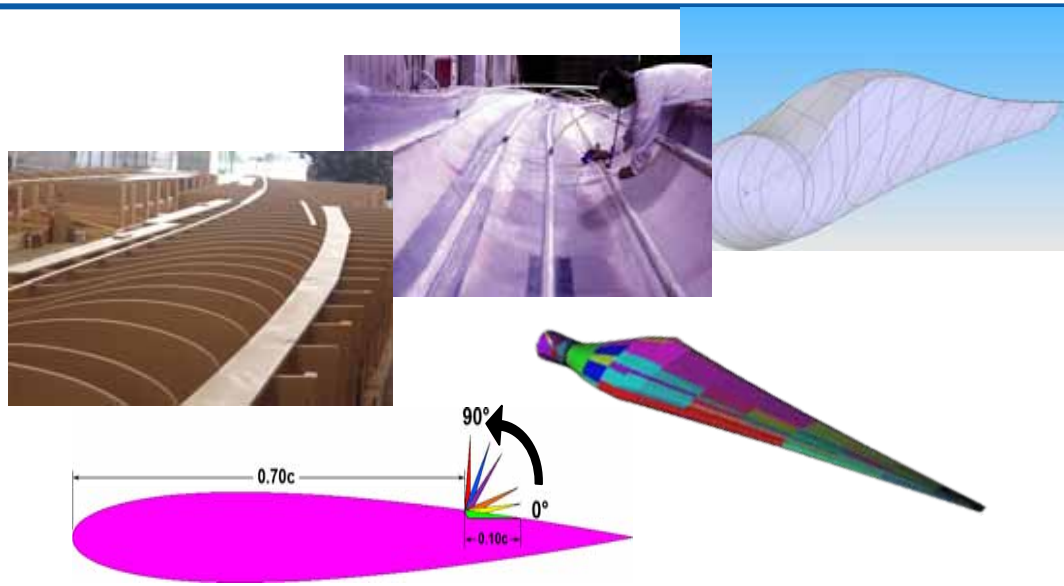




Land Based Technology Improvement Options

Advanced Rotor Technology

- ❑ Extended rotor architectures through **load control**
- ❑ Incorporate advanced materials for hybrid blades
- ❑ Cyclic & independent blade pitch control for load mitigation
- ❑ Sweep and flap twist coupled architectures
- ❑ Light weight, high TSR with attenuated aeroacoustics



Power Train Enhancements

- ❑ Permanent Magnet DD Architectures
- ❑ Split load path multi-stage generation topologies
- ❑ Reduced stage (1-2) integrated gearbox designs
- ❑ Convoloid gearing for load distribution

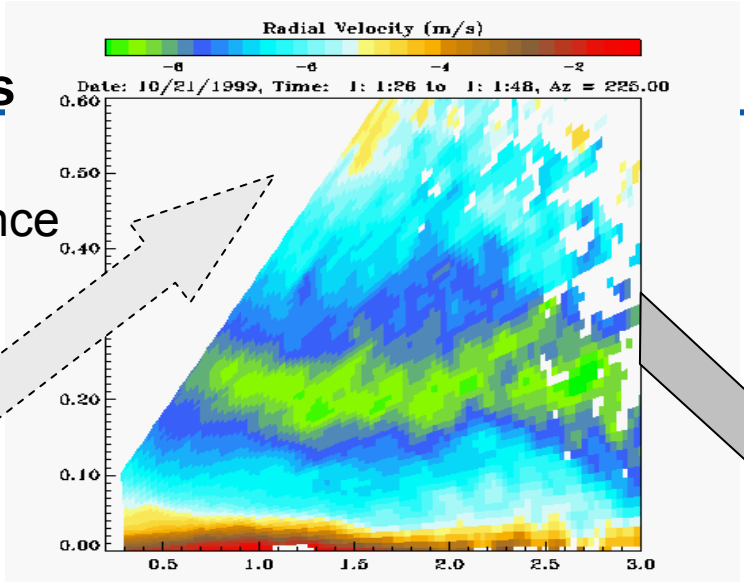
DOE/Industry Partnerships for Innovative Blades Designs

Knight & Carver developed a sweep twist adaptive rotor (STAR) blade for gust load reduction and the prototype blade is being tested at NWTC.

Knight & Carver STAR blade is being field-tested on a 750 kW wind turbine in Tehachapi, CA in collaboration with DOE/Sandia National Lab.

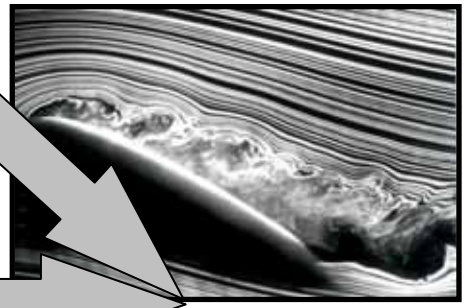
Powerful winds

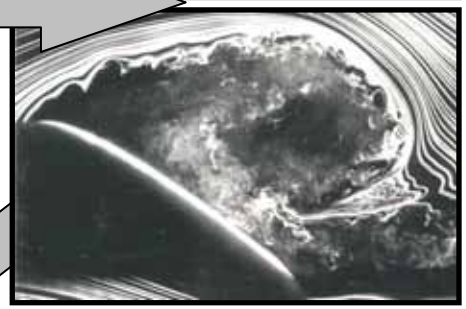
U_∞, direction vary
Coherent turbulence
Turbine wakes



Energetic flowfield

Globally separated
Steep gradients
Dynamically active



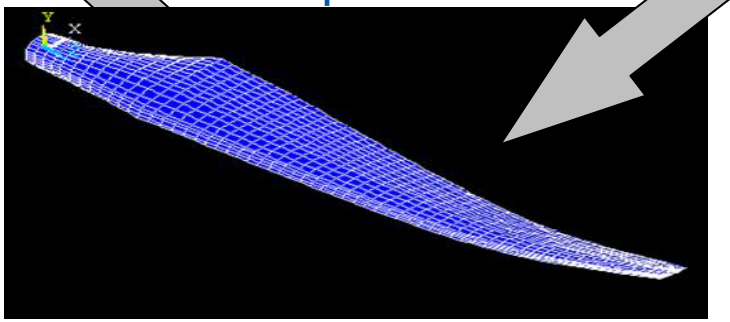


Basic R&D Needs: Aeroelasticity

Nonlinear & coupled
Multiple physics
Multiple Scales

Complex wake

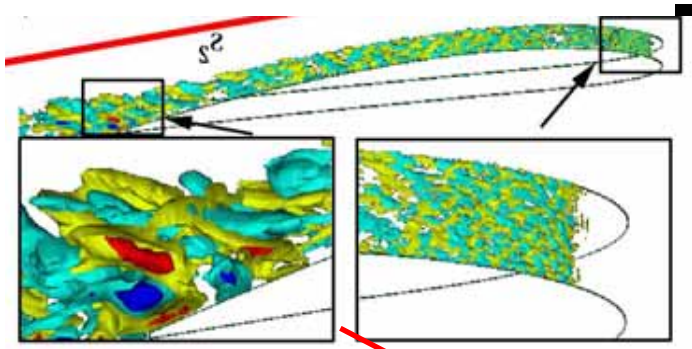
Trailed vortices
Shed vortices
Persistent

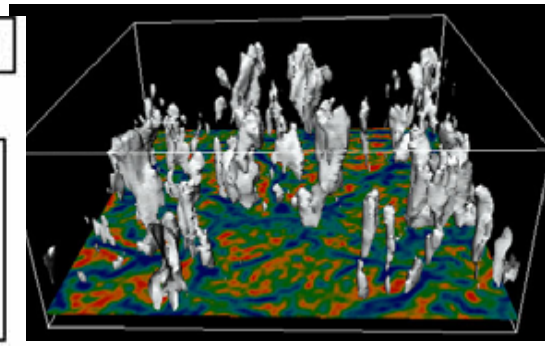


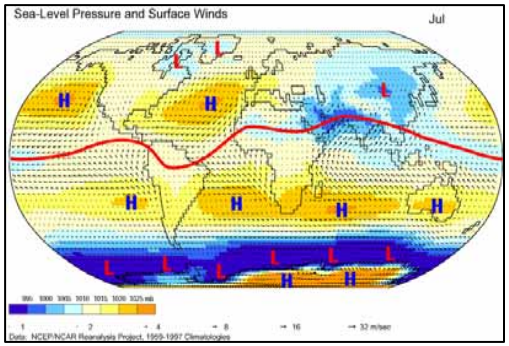
Responsive structure

Light and flexible
Advanced materials
Aeroelastic load control

Wind Energy Computational Research Challenges (Scales Range Over 10 Orders of Magnitude)







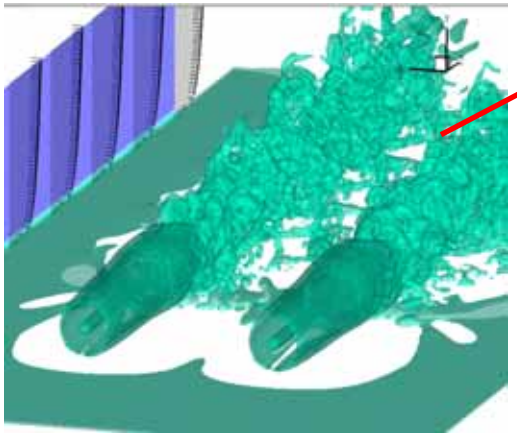
Airfoil Turbulence

Terrain Flows

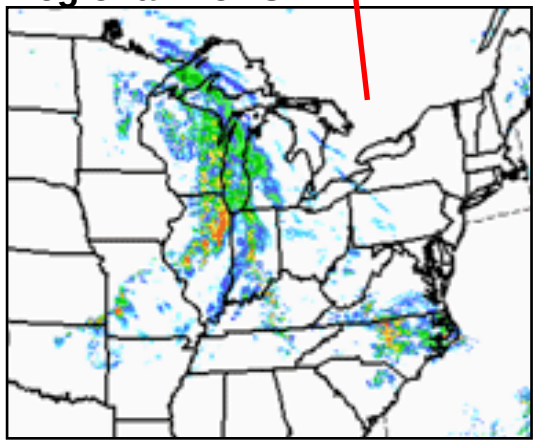
Global Flows

Δx(m) 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Turbine Wake Turbulence



Regional Flows



Impacts of Multi-Array & Complex Terrain Environments

- Multi-array environments are unique.
- Microclimatology impacts becoming a greater concern
- Power performance and reliability influenced by several factors.
- Understanding inflow / array interaction is key.
- Computational models, control paradigms and hardware development will be required.
- Requires a detailed understanding of:
  - Rotor Wake Interactions
  - PBL Characteristics
  - Inflow / Wind farm Interaction
  - Complex Terrain Effects

Improved Performance Capacity Factor (+15%)

<u>Larger Rotors</u>: to sweep greater area

- Longer and lighter blades (new materials and designs)
- Load-mitigating control (passive and active)

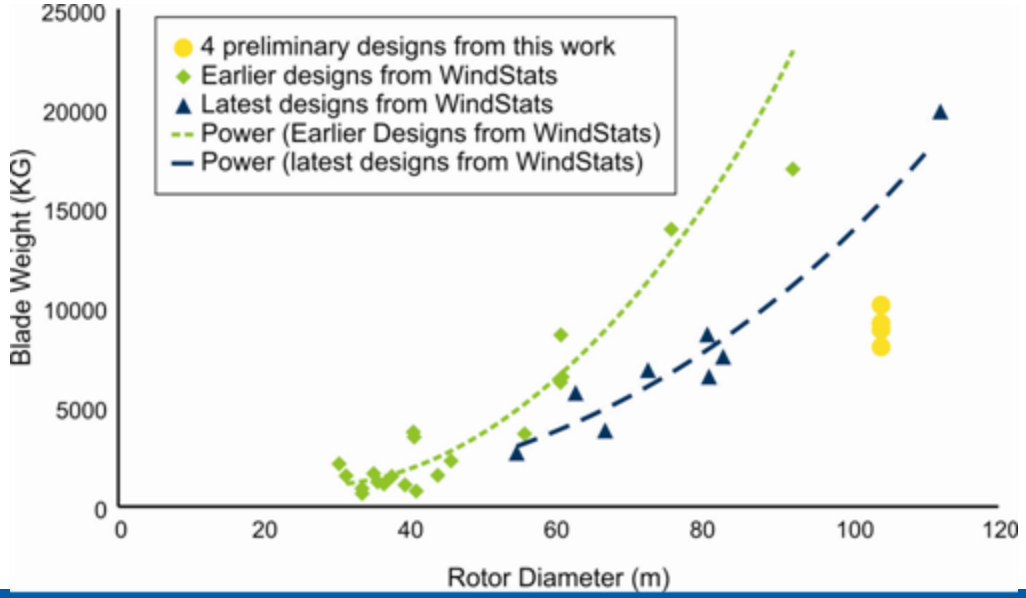
<u>Taller Towers</u>: to access greater resource

- Lower tower-head mass (lighter components)
- Innovations in towers, foundations, erection and maintenance access

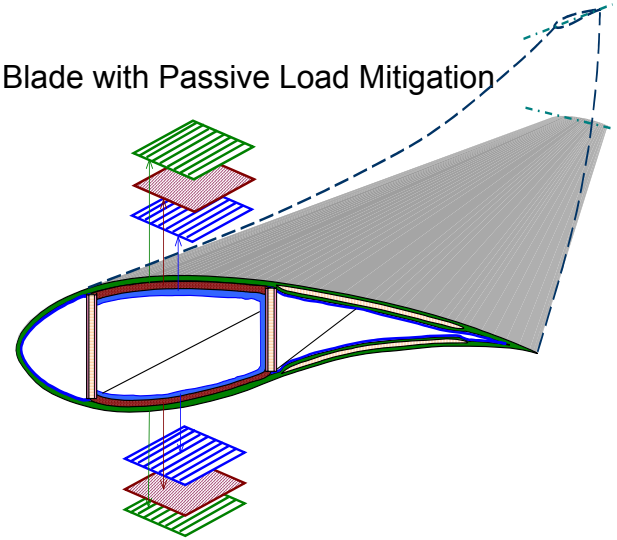
<u>Reduced Losses</u>: to deliver what is generated

- Power electronics, gearboxes, generators, medium-voltage, etc.
- Arrays, wakes, and siting issues

Clipper's innovative drive train



Blade with Passive Load Mitigation



DOE/Industry Partnerships to Advance Technology

Southwest Windpower 1.8-kW Skystream wind turbine with a 3.7-m rotor diameter developed in collaborative R&D with DOE/NREL

Clipper Windpower produced a prototype of its 2.5-MW wind turbine, 93-m rotor diameter in 2005 after only three years of cooperative R&D with DOE/NREL

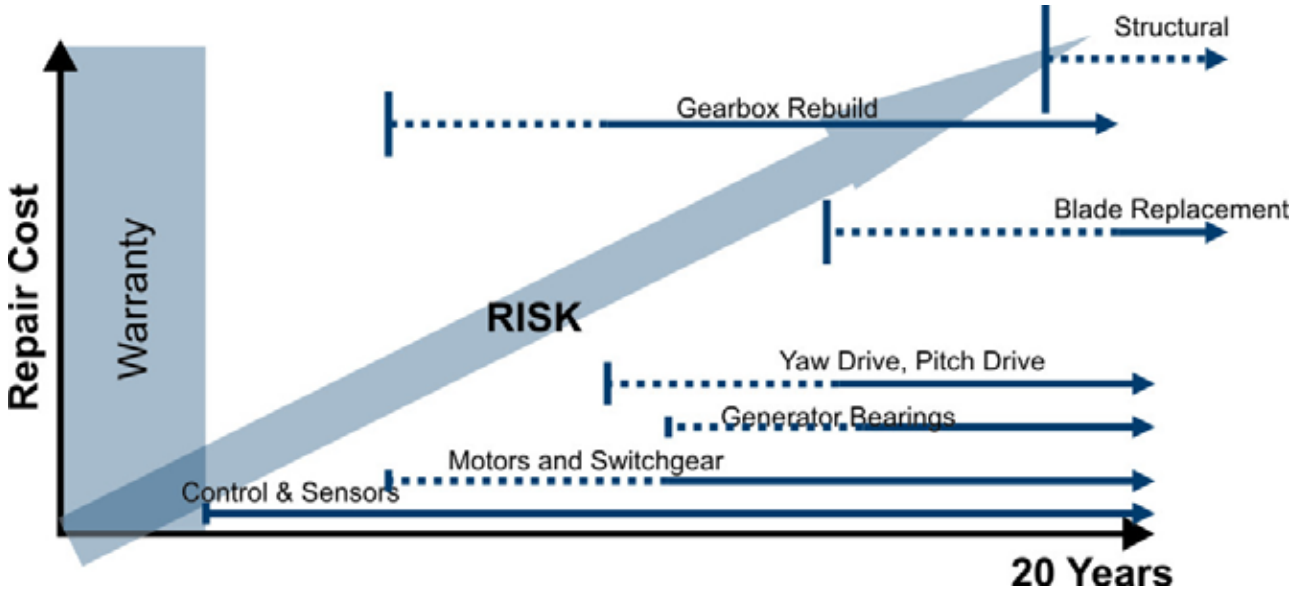
Risks to Continued Large-Scale Deployment

<u>Direct impacts</u> – Poor performance

- Energy payments – lost revenue
- O&M costs – above expectations
- Component failure – early replacement

<u>Indirect impacts</u> – Loss of confidence

- Cost of financing and insurance
- Slowing development
- Loss of public support (drives policies)



Initiatives to Mitigate Risk

Avoid Problems Before Installation

- Full Scale Testing
- Appropriate design criteria (specifications and standards)
- Validated design evaluation tools

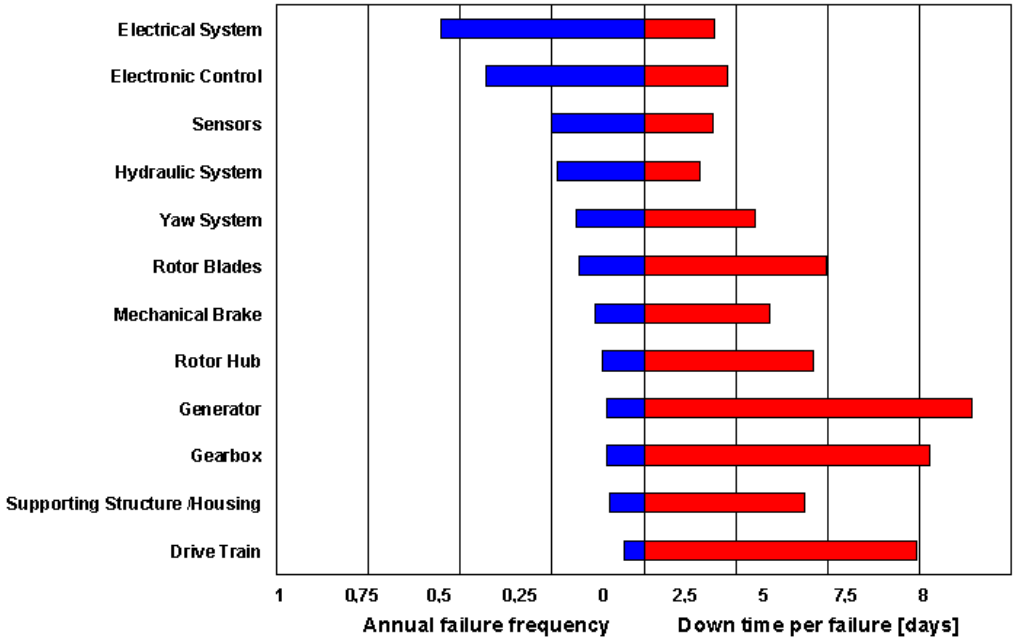
Monitor Performance

- "Tracking, tracking, tracking"
- Maintain reliability tracking database
- Define the problems before they get out of hand

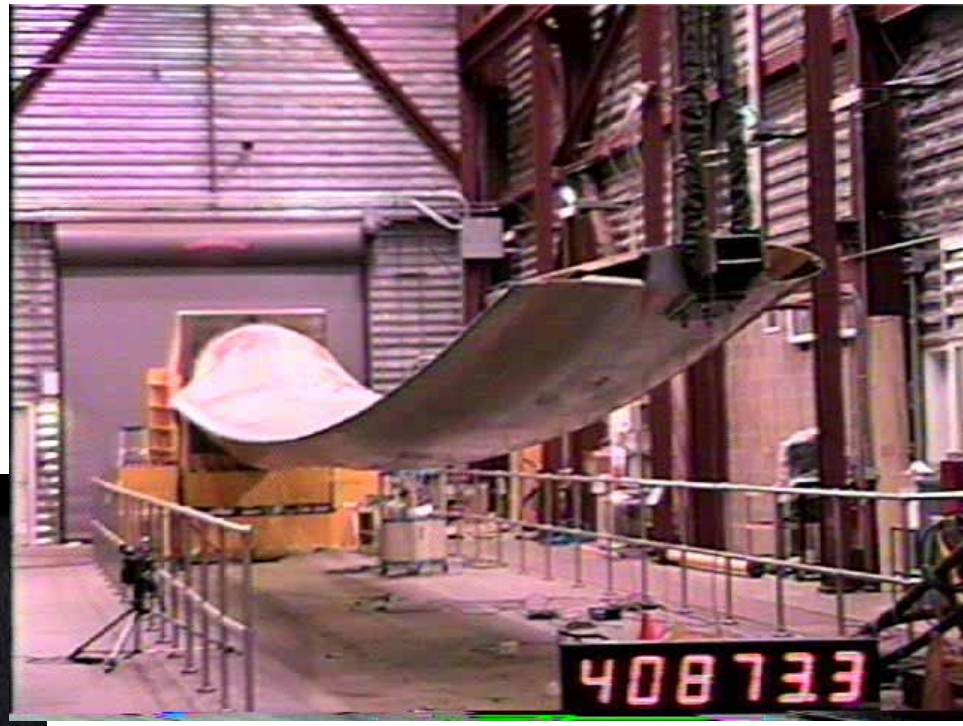
Problem Resolution Initiatives

- Targeted activities in to address critical issues
- Example: Gearbox Collaborative

Photo by Lee Jay Fingersh



DOE/Industry Partnerships to Structurally Test Large (up to 50 meters) Wind Turbine Blades



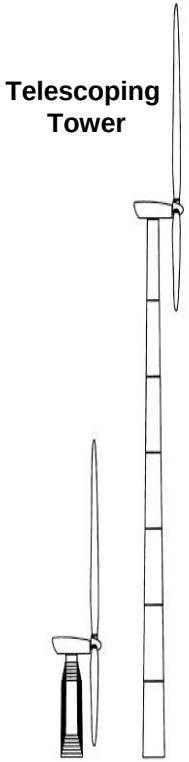
Ultimate strength testing of a new blade design at the NWTC

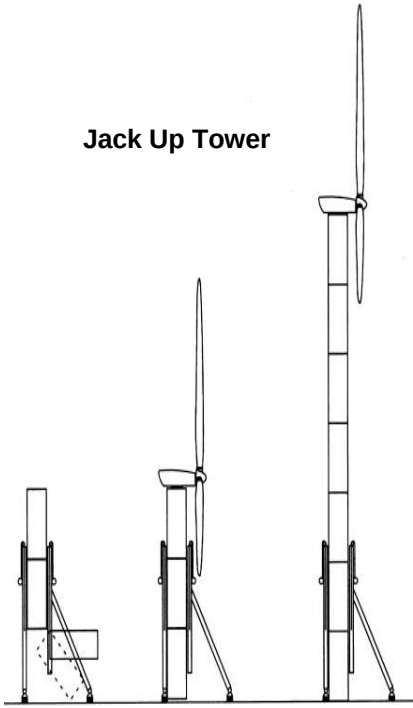
Fatigue strength testing of a new blade design at the NWTC

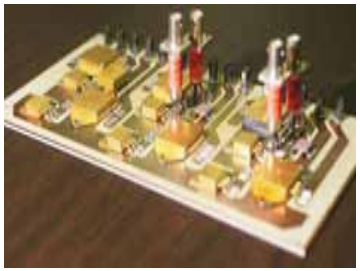
Land Based Technology Improvement Options

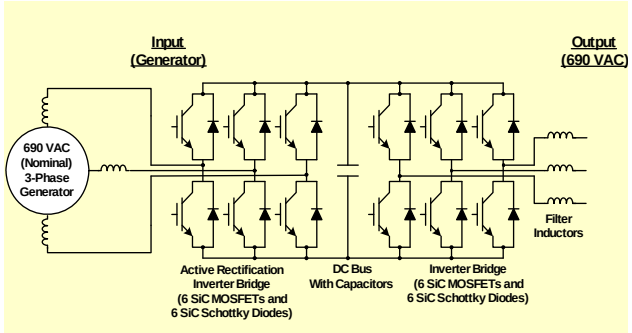
Power Conversion

- ❑ High temperature silicon carbide device; improved reliability & reduce hardware volume
- ❑ Novel circuit topologies for high voltage & power quality improvement
- ❑ Medium voltage designs for multi-megawatt architectures







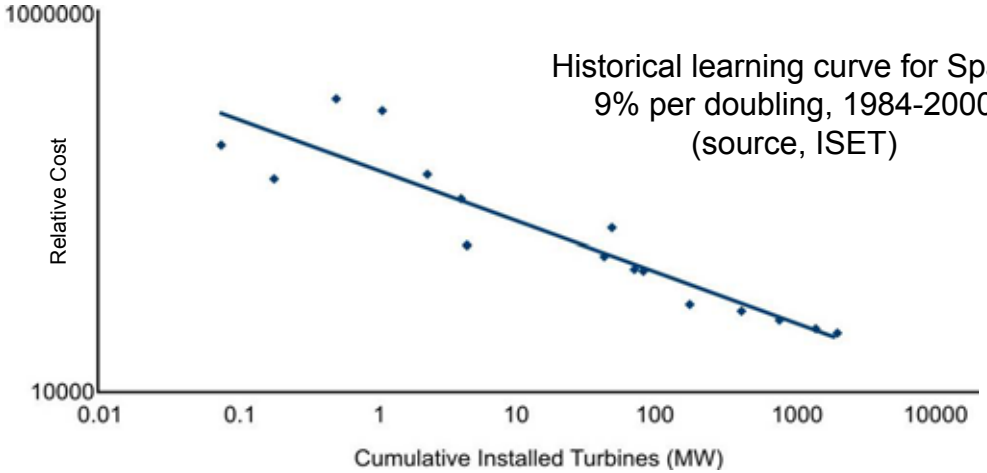


Tower Support Structures

- ❑ Tall tower & complex terrain deployment
- ❑ Advanced structures & foundations
- ❑ New materials and processes
- ❑ Self erecting designs

Reduced Capital Cost (-10%)


Courtesy TPI Composites



Historical learning curve for Spain, 9% per doubling, 1984-2000 (source, ISET)

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 – both Design and Manufacturing

- Lighter – less material, advanced materials
- More automation
- Design for manufacturability

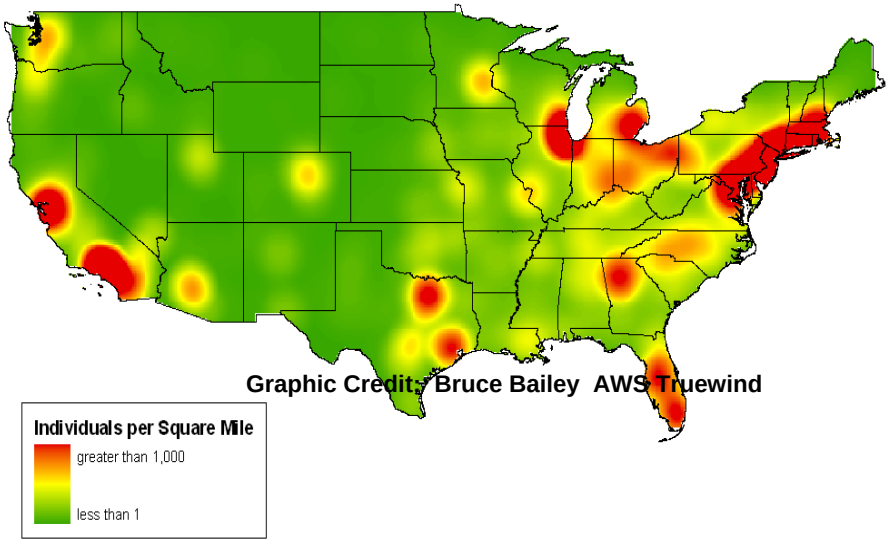
Why Offshore Wind?

28 coastal states use 78% of the electricity in U.S.

Many Coastal Load Centers Cannot Be Served by Land-based Renewable Resources

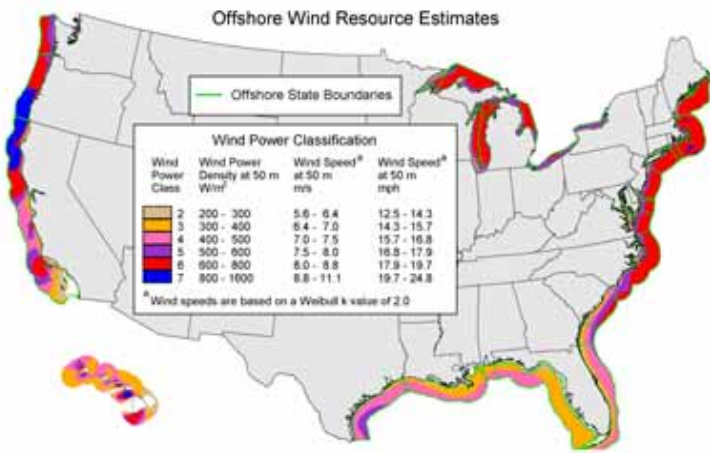
Renewable Energy Goals Cannot be Achieved Without Offshore Contributions

US Population Concentration



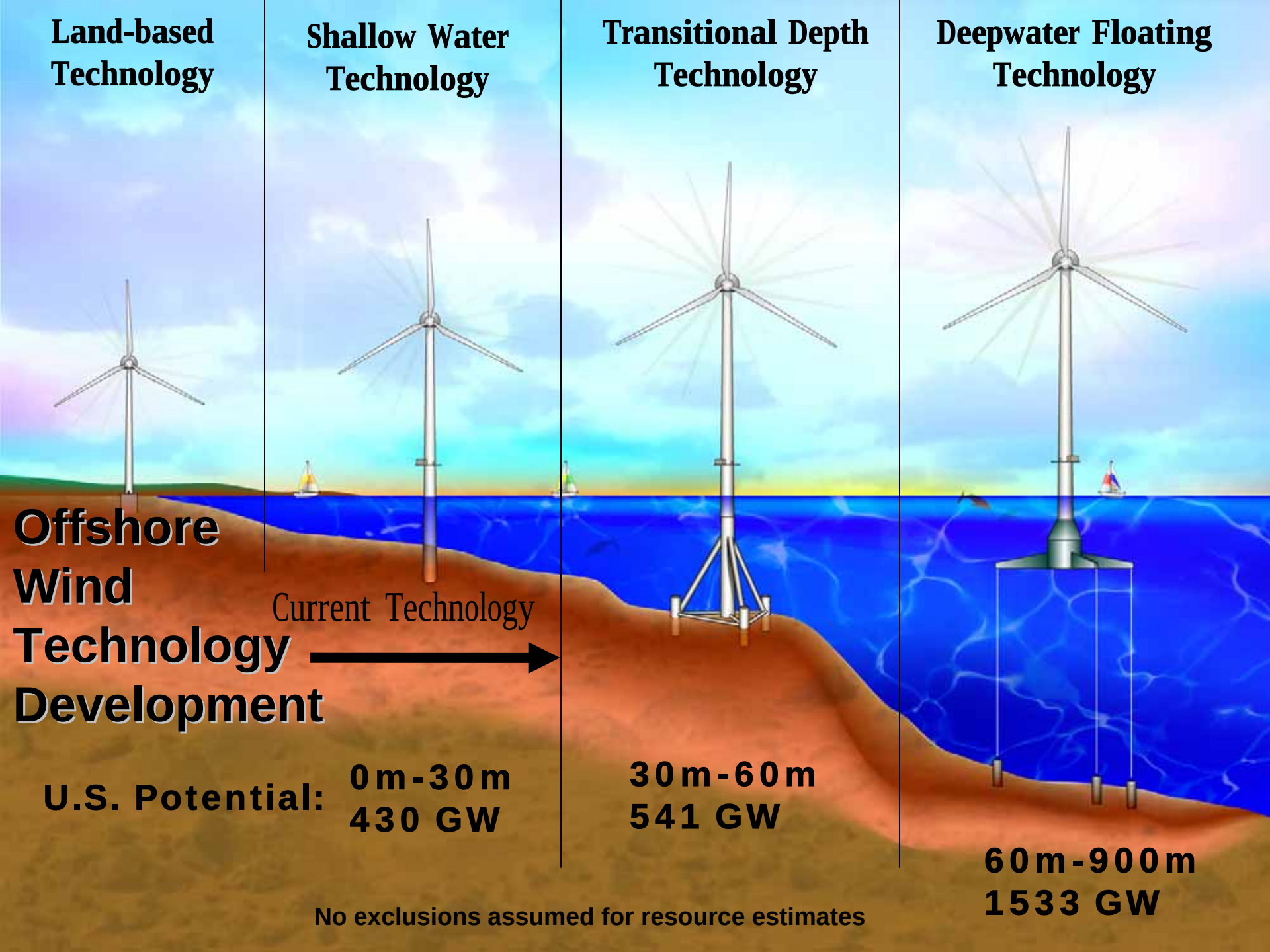
Graphic Credit: Bruce Bailey AWS Truewind

U.S. Wind Resource



Rationale for Offshore Wind

- Constrained land use
- Better wind resources
  - Reduced turbulence – steadier wind
  - Higher wind = better energy production
  - Higher capacity factors – load matching
- Minimize visual impacts with greater distances.
- Proximity to load centers
  - Lower transmission constraints
  - Serve high cost regions
  - Exploits indigenous energy
- Avoids size limits
  - **Shipping** – Land-based roadway limits
  - **Erection** – crane limits
  - Larger machines are more economical.


Land-based Technology
Shallow Water Technology
Transitional Depth Technology
Deepwater Floating Technology
Offshore Wind Technology Development
Current Technology
U.S. Potential:
0m-30m
430 GW
30m-60m
541 GW
60m-900m
1533 GW
No exclusions assumed for resource estimates

Offshore Technology Challenges

Short-Term R&D Needs

- Define Exclusion Zones
- Certification and Standards
- Design Codes, Tools, Methods
- Siting and Array Configurations
- Hybrid Wind-Wave Databases

Long-Term R&D Needs

- Minimization of Work at Sea
- Enhanced Manufacturing and Deployment
- Service and Accessibility
- Foundations, Anchors, and Moorings
- Resource Modeling and Remote Sensing
- Offshore Turbine Reliability
- Ultra-large Turbines

Wind Technology Improvement Summary

Subsystem	Description of Potential Advances	Performance and Cost Increments (Best/Expected/Least Percentages)	
		Annual Energy Production	Turbine Capital Cost
Towers	Taller with new materials/self erecting	+11/+11/+11	+8/+12/+20
Rotors	Lighter & larger with smart structures	+35/+25/+10	-6/-3/+3
Site Energy	Improved reliability – less losses	+7/+5/0	0/0/0
Drive Train	Innovative designs – high reliability	+8/+4/0	-11/-6/+1
Manufacturing	Process evolution and automation	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

Ref: 20% Wind by 2030 Report, Table 2-1, page 41 (working from 2002 baseline)

A Future Vision for Wind Energy Markets

Tomorrow

Today
2008
Bulk Power Generator
5-9¢ at 13mph*
With No PTC

- Land Based
- Bulk Electricity
- Wind Farms

Less than 2% of Electricity Market

Land Based Electricity Path

Land-Based Turbines
2–5 MW & Distributed
1 kW – 1 MW

Transmission Barriers

Land-based Turbines:
- **Cost Reduction**
- **Increased Energy & Reliability**
- **20% of Electricity Market**

Offshore Electricity Path

Offshore Turbines
5 MW and Larger

Cost & Regulatory Barriers

Offshore Turbine:
- Higher Wind Sites
- Shallow/***Deep*** *water*
- Coastal Cities
- 35% Cost Reduction needed

New Applications Path

- **Hydrogen**
- **Clean Water**
- **Storage: PHEV-CAES**

Cost & Infrastructure Barriers

Custom Turbines for Multi-markets:
- Electricity
- H2 production
- Desalinate water

2020 and Beyond

* Note: The site wind speed is measured at 10m and assumes a 1/7 power law wind shear giving a hub height wind speed of 18mph, while the siting, land and related project costs are assumed to be average for the US.

National Renewable Energy Laboratory
Innovation for Our Energy Future

Questions?

Brian Smith

Lab Program Manager

Wind & Hydropower Technologies

National Renewable Energy Laboratory

Chair, IEA Wind Implementing Agreement

303-384-6911

brian.smith@nrel.gov