Overview: Wind Energy Technology Fundamentals , the 20% Scenario, and Innovation Opportunities

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"Exceptional Service in the National Interest"

- **National Security Laboratory**
- **Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges**
- **Safety, security and reliability of our nation's nuclear weapons stockpile**

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Sandia Sites

8500 Employees
>7000 in New Mexico

Albuquerque, New Mexico

Livermore, California

Yucca Mountain, Nevada

WIPP, New Mexico

Kauai, Hawaii

Pantex, Texas

Tonopah, Nevada

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Outline

- Wind Turbine design evolution
- Typical modern turbine
- How it works:
  - ✓ Limitations
  - ✓ Opportunities
- 20% wind scenario
- Efforts to enhance the technology

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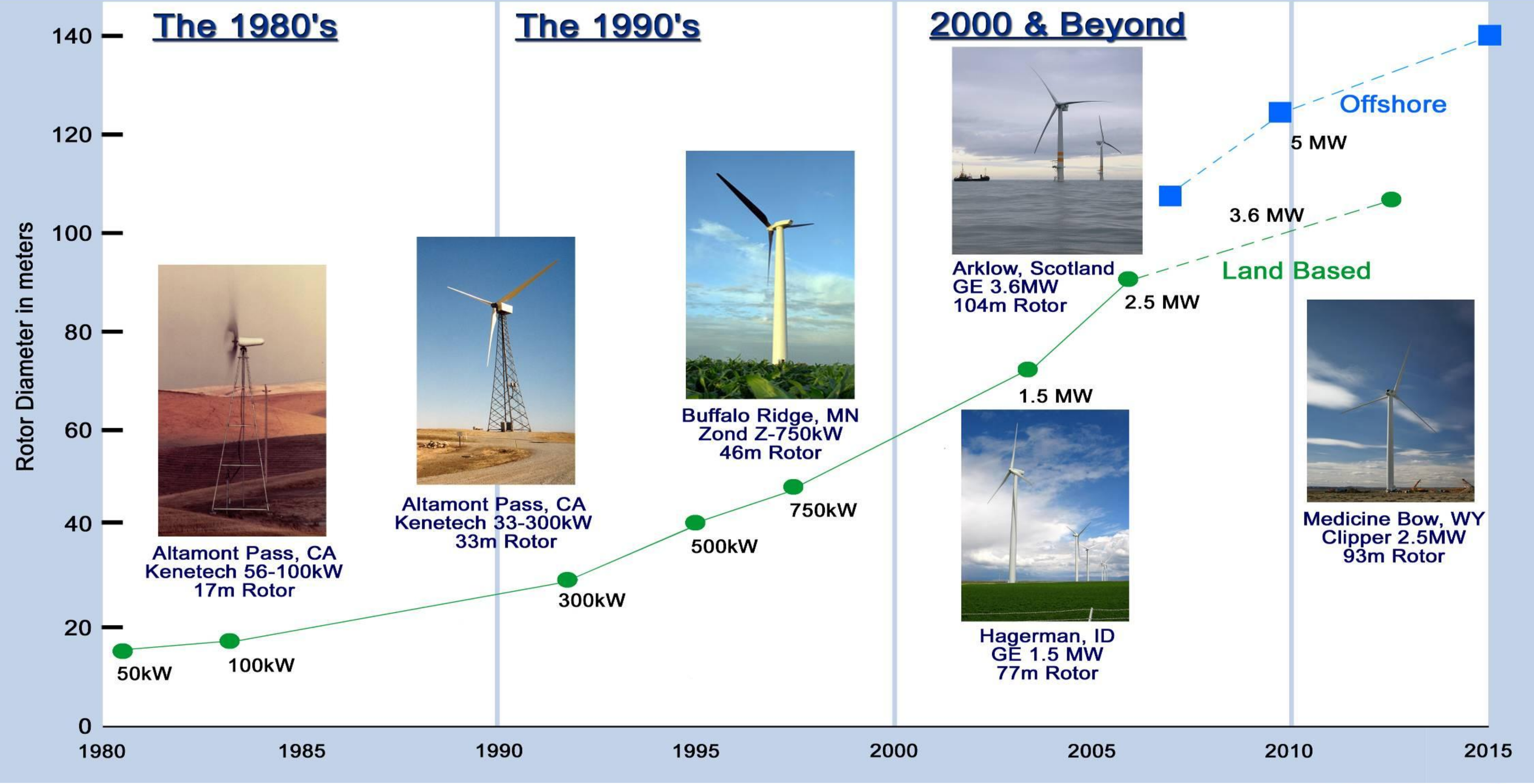
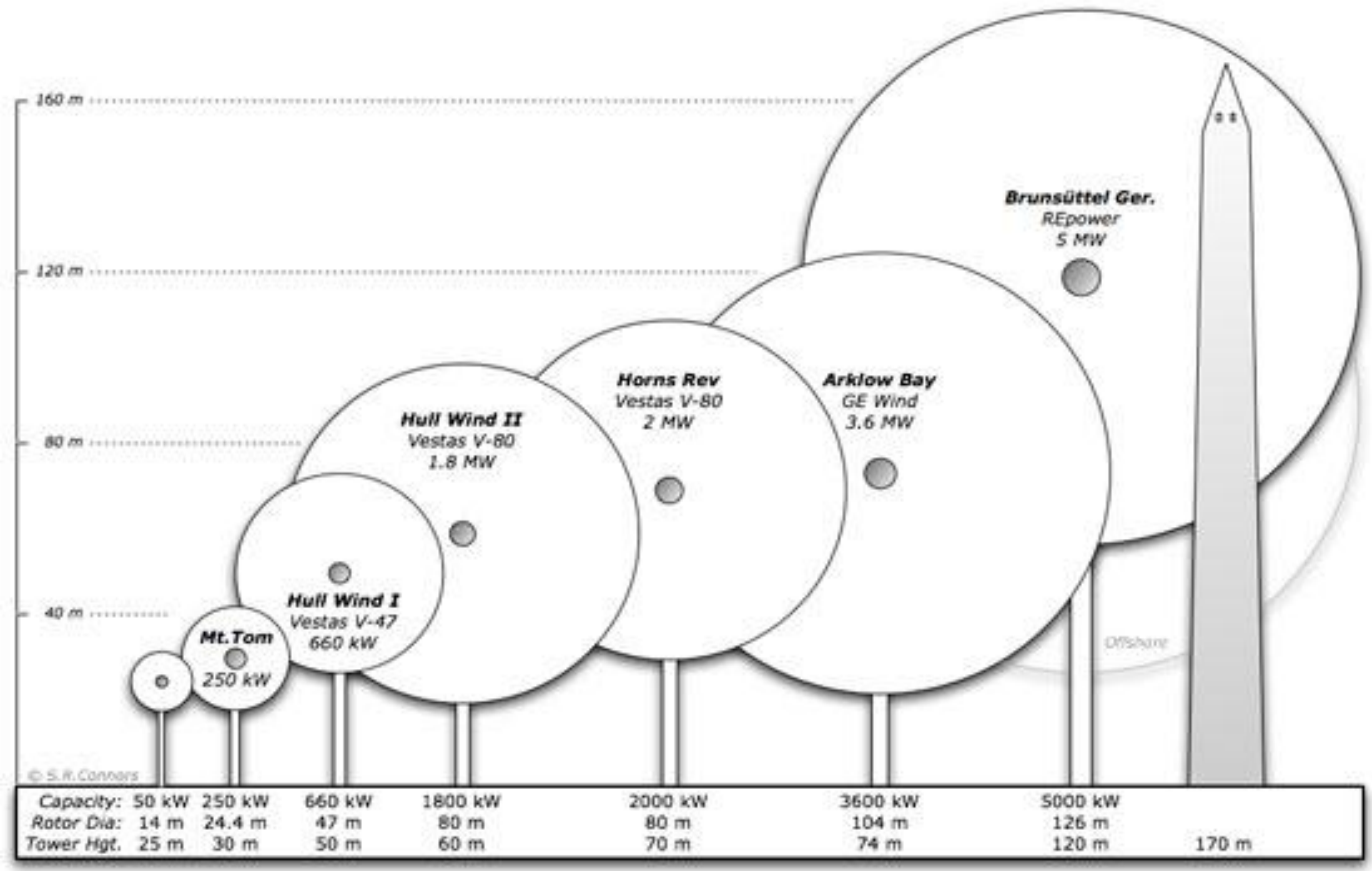
Evolution of U.S. Commercial Wind Technology



Wind Turbine Size



Wind Power – large and small

Small Wind

(1-100 kW)

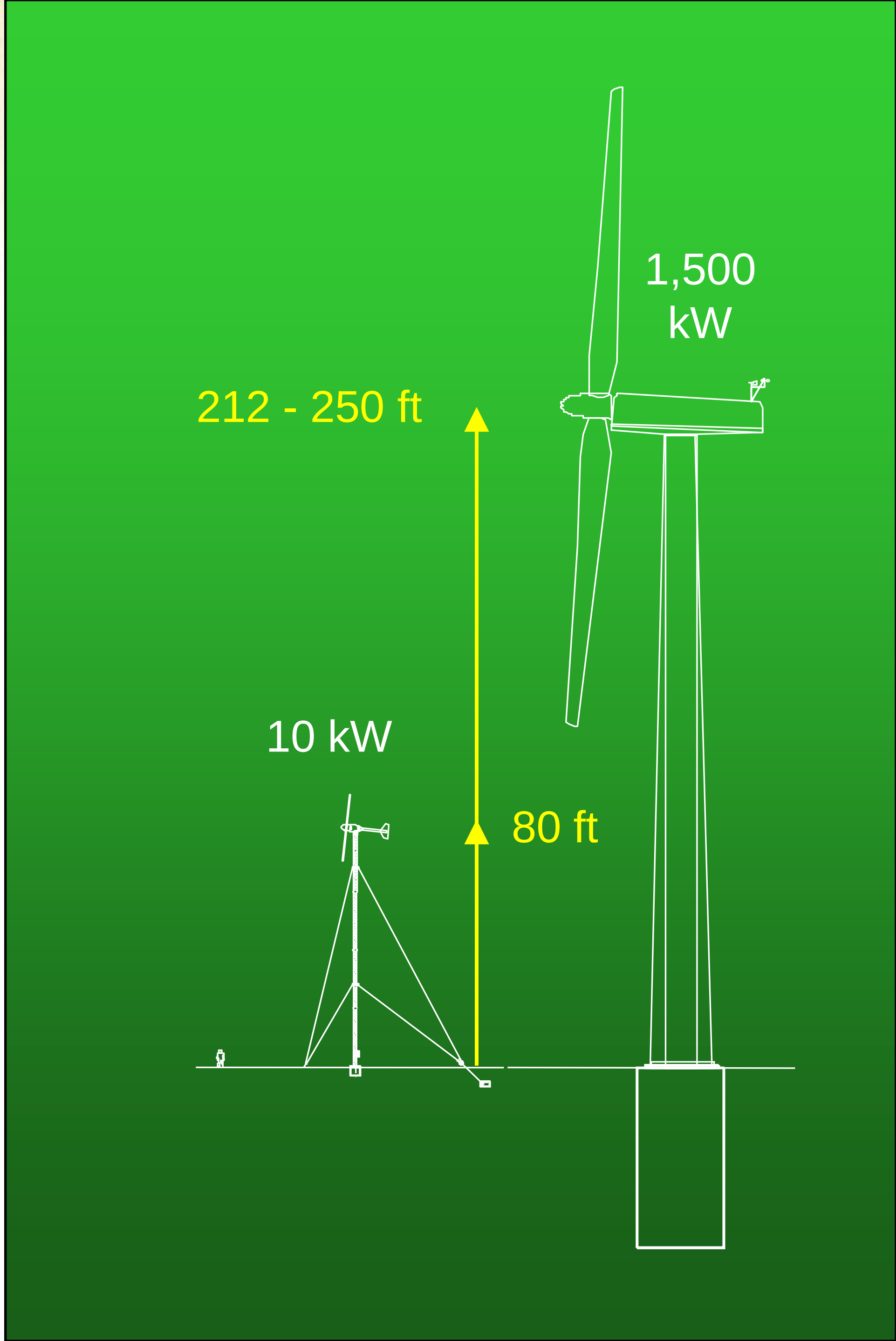
Utility-Scale Wind

(1-5 MW)

American Wind Energy Association
www.awea.org

Small Wind Turbines Are Different

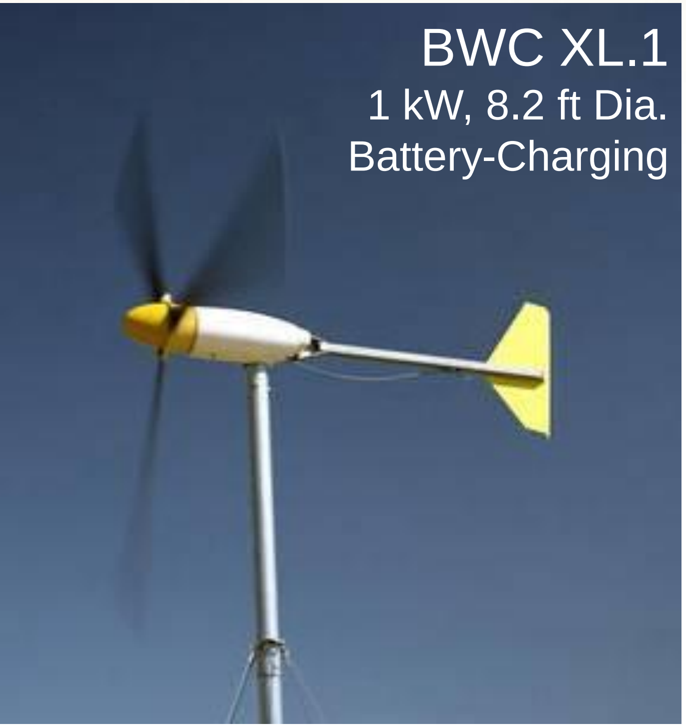
- **Utility-Scale Wind Power 1,000-3,000 kW wind turbines**
  - Installed on wind farms, 10–700 MW
  - Interconnected to transmission
  - Professional maintenance crews
  - Class 4-6 (quality) wind resource
- **Small Wind Power up to 100 kW wind turbines**
  - Installed at individual homes, farms, businesses,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



Courtesy Jim Green, NREL

Example Small Wind Systems

Bergey Windpower



Southwest Windpower

Northern Power Systems

Endurance Wind Power Inc.

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

Courtesy Jim Green, NREL

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The Change 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 lager machines in foreground (~750kW)

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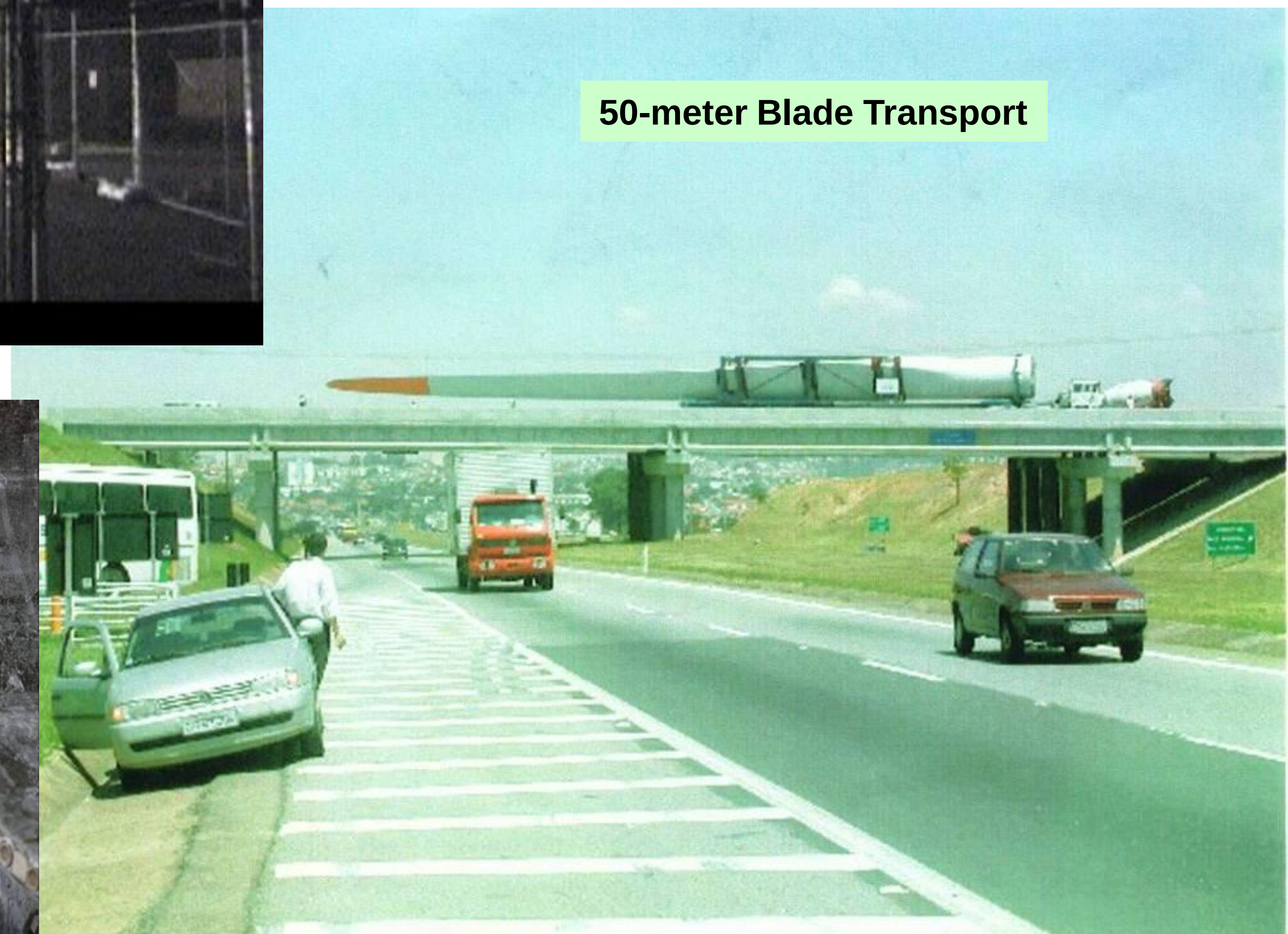
GE 1.5 MW machines in Fort Sumner, NM and Bonus (Siemens) 2.0 MW machines in Copenhagen Harbor

Logistics become difficult as size increases

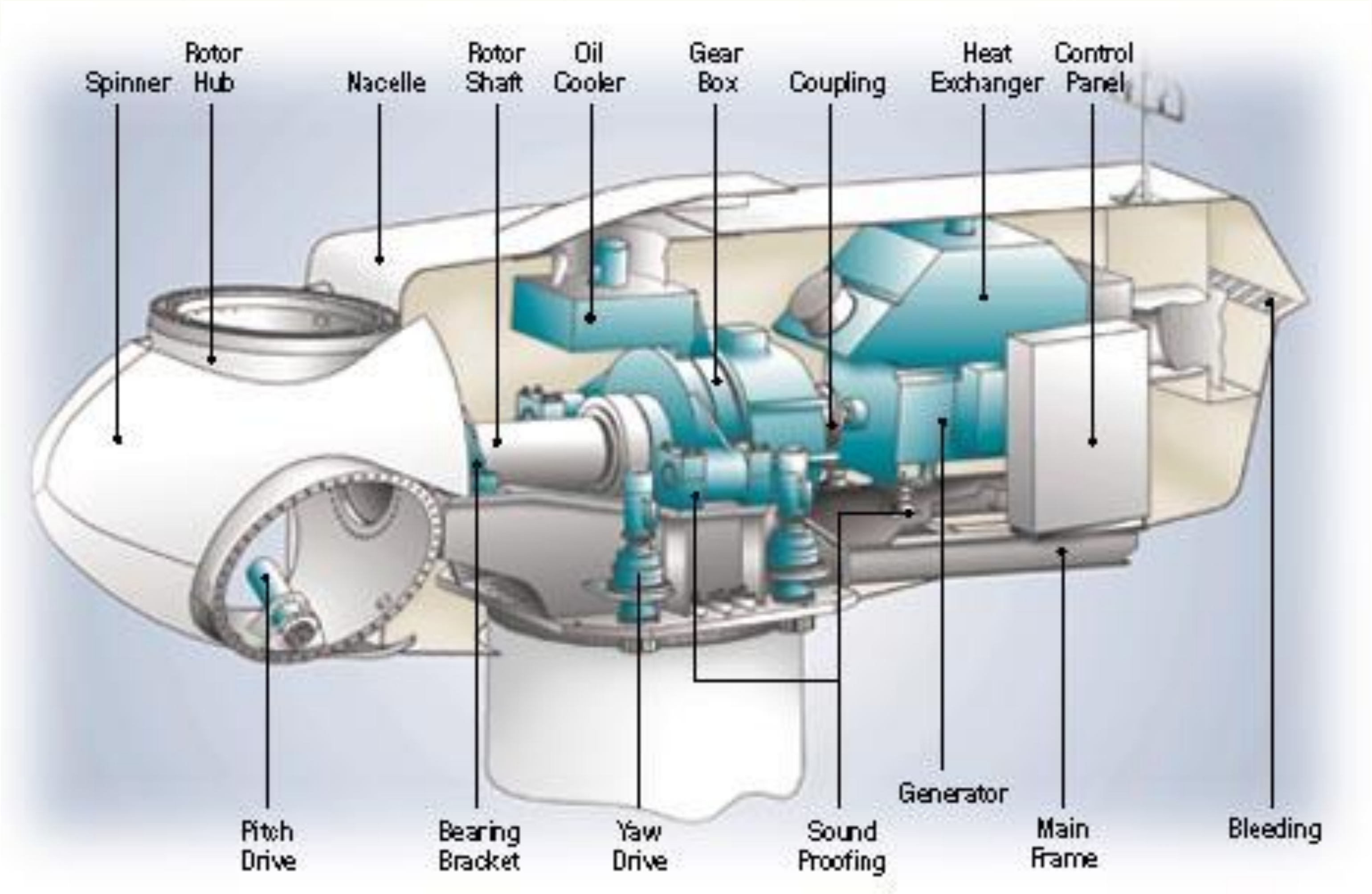
45-meter Blade Fatigue Test at NREL/NWTC



50-meter Blade Transport

Courtesy of LM Glassfiber

Typical Modern Turbine



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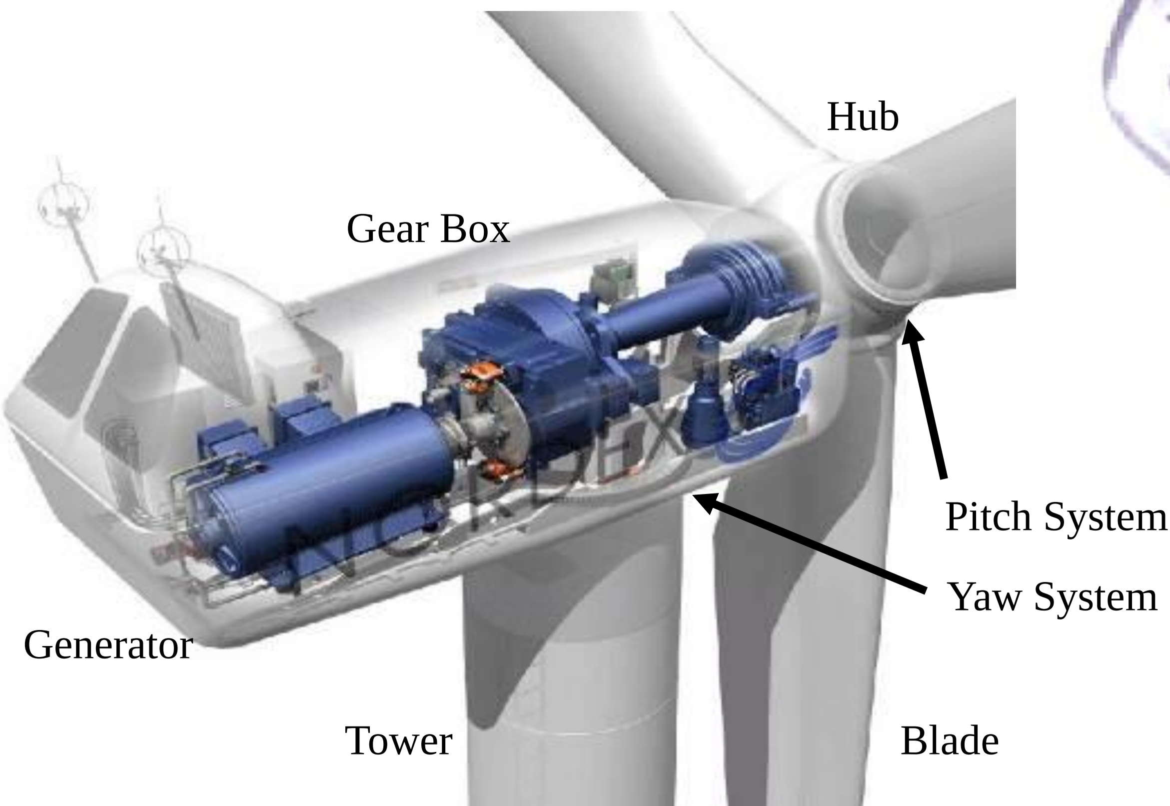
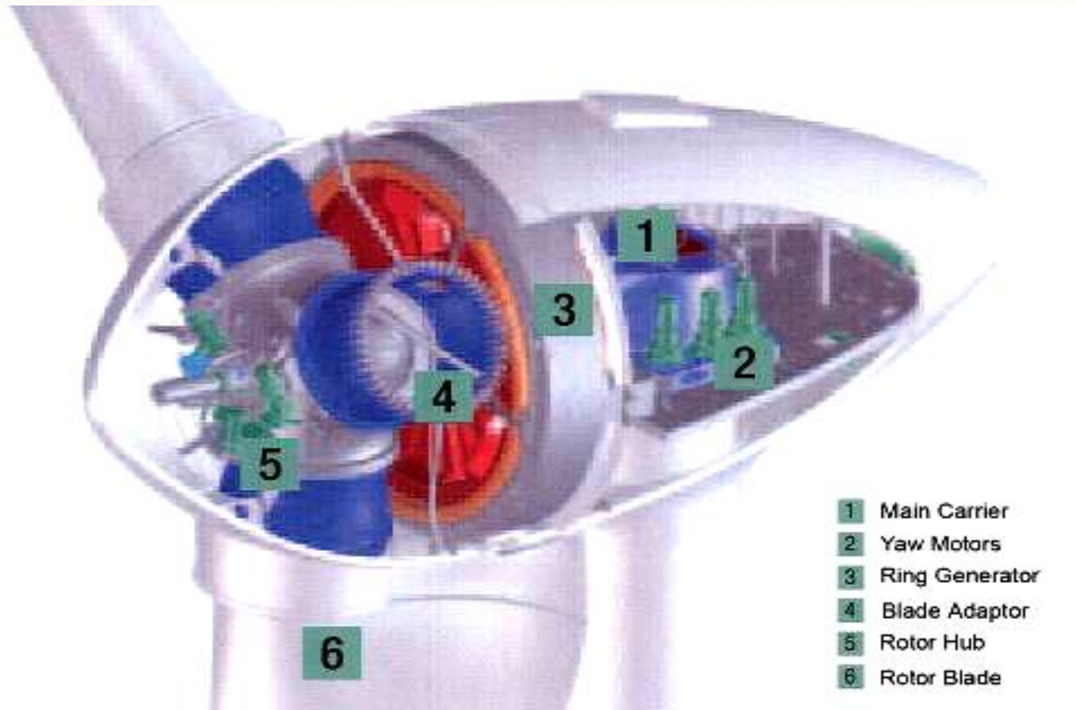
Current Wind Turbine Systems

Conventional Drive Train





Direct Drive System

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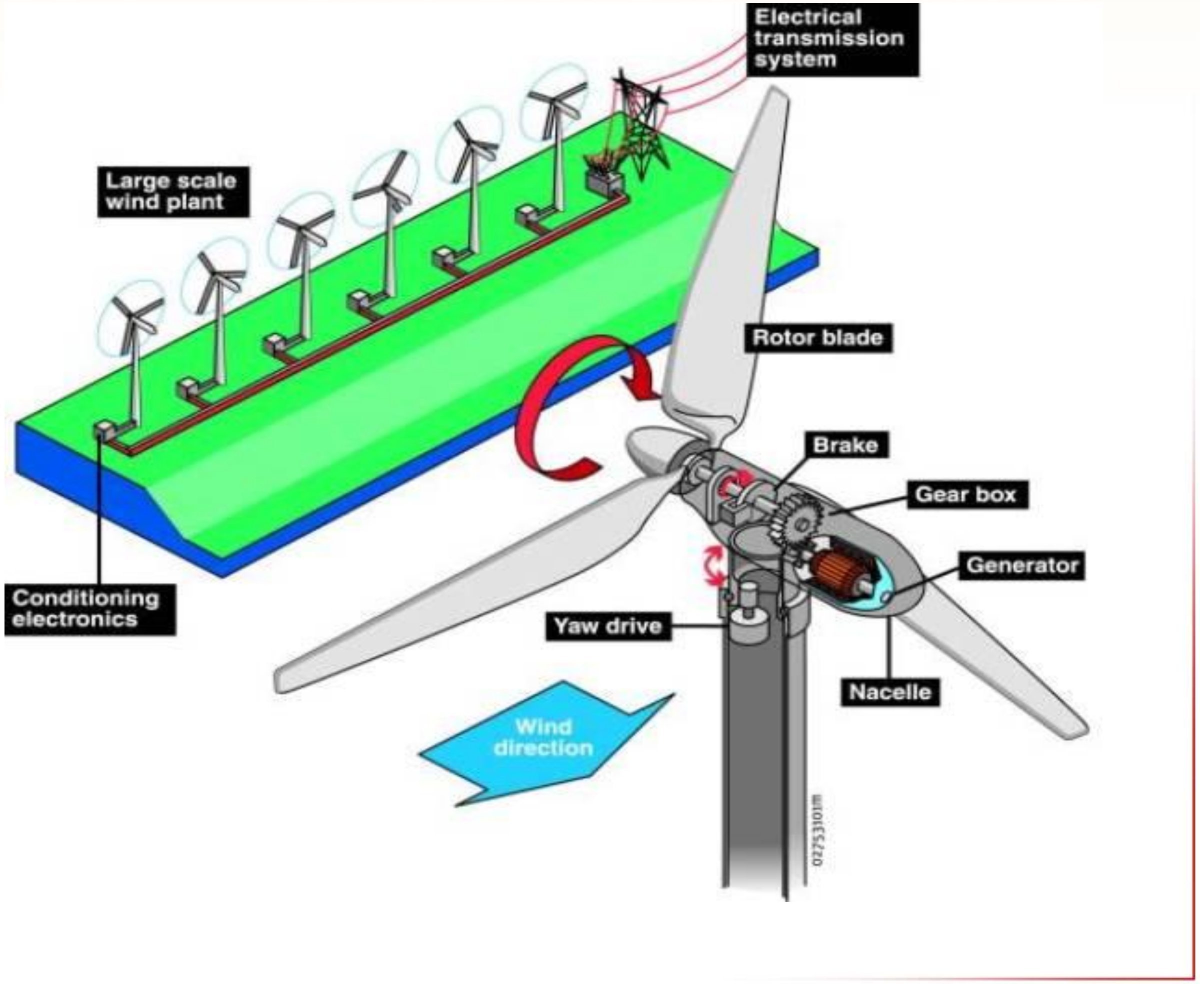
Typical Wind Farm Components

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



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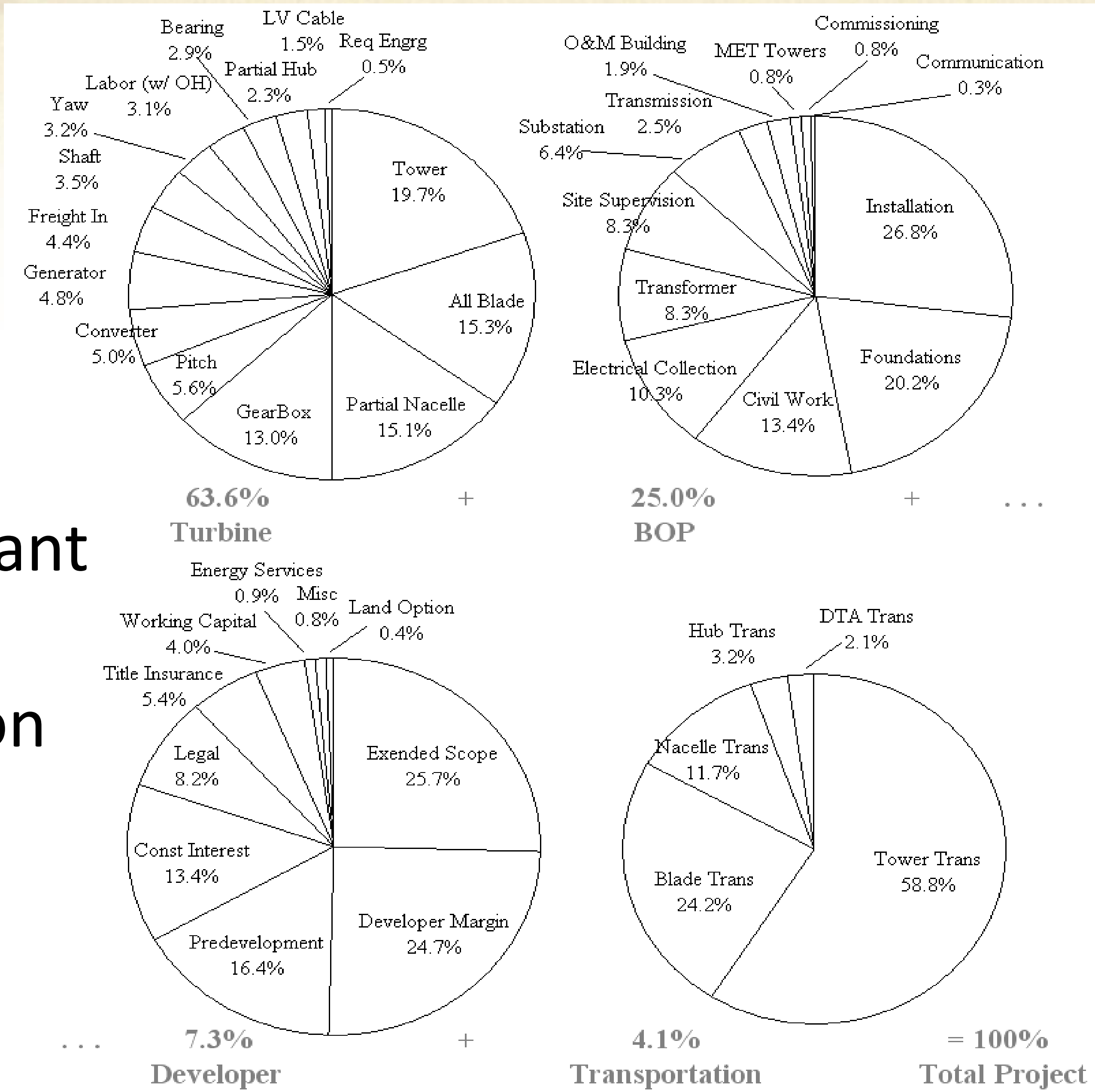
Bottom Up Wind Capital Costs (current on-shore)

64% Turbine

25% Balance of Plant

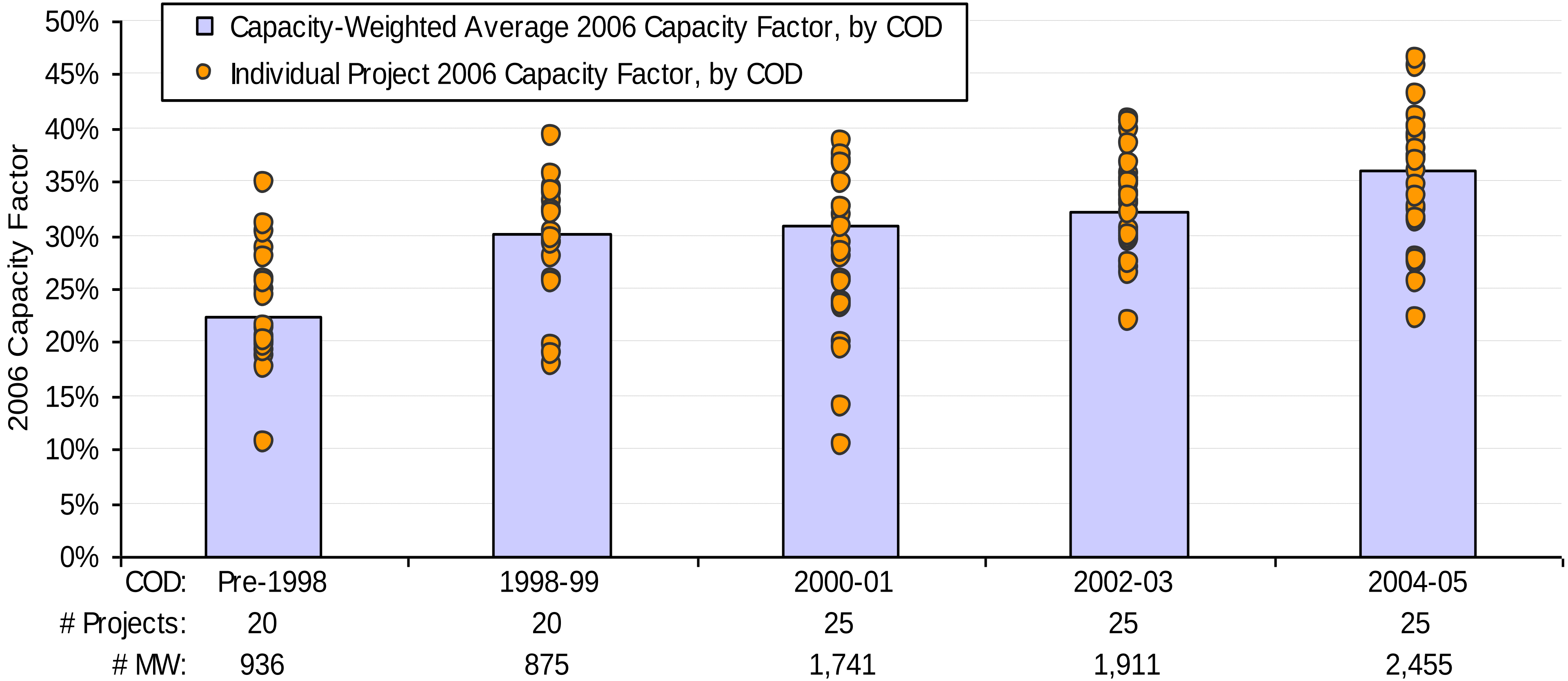
7% Developer

4% Transportation



Notes: 100MW Wind Power Plant; Flat terrain w/ easy access and good geotechnical conditions; Nominal technology MMW Wind Turbine price; 10% BOP contingency inclusive

Reported Capacity Factors - Trends



CF = Average Output/ Rated Power

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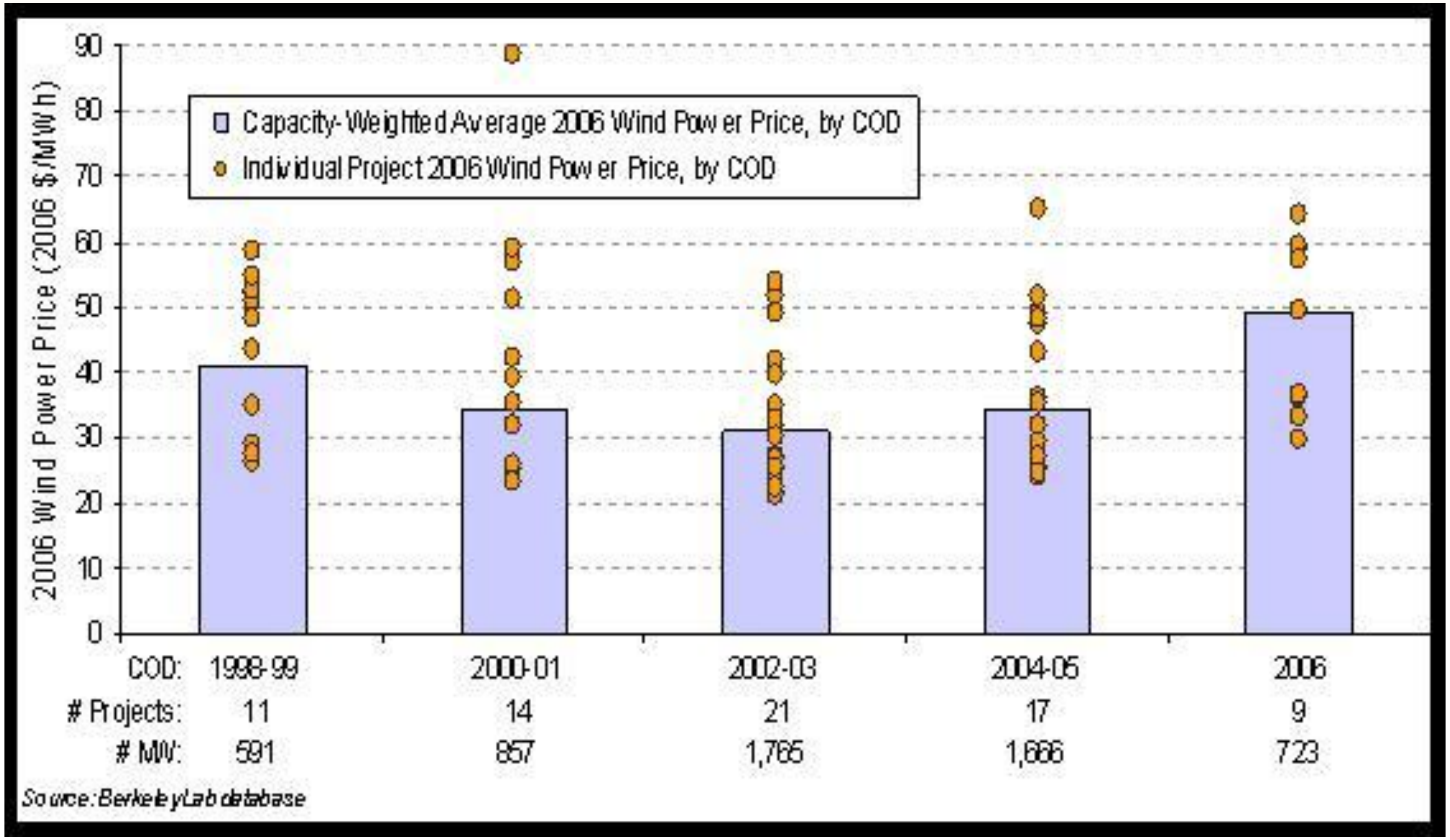
Cost of Energy: Sales Prices - Trends

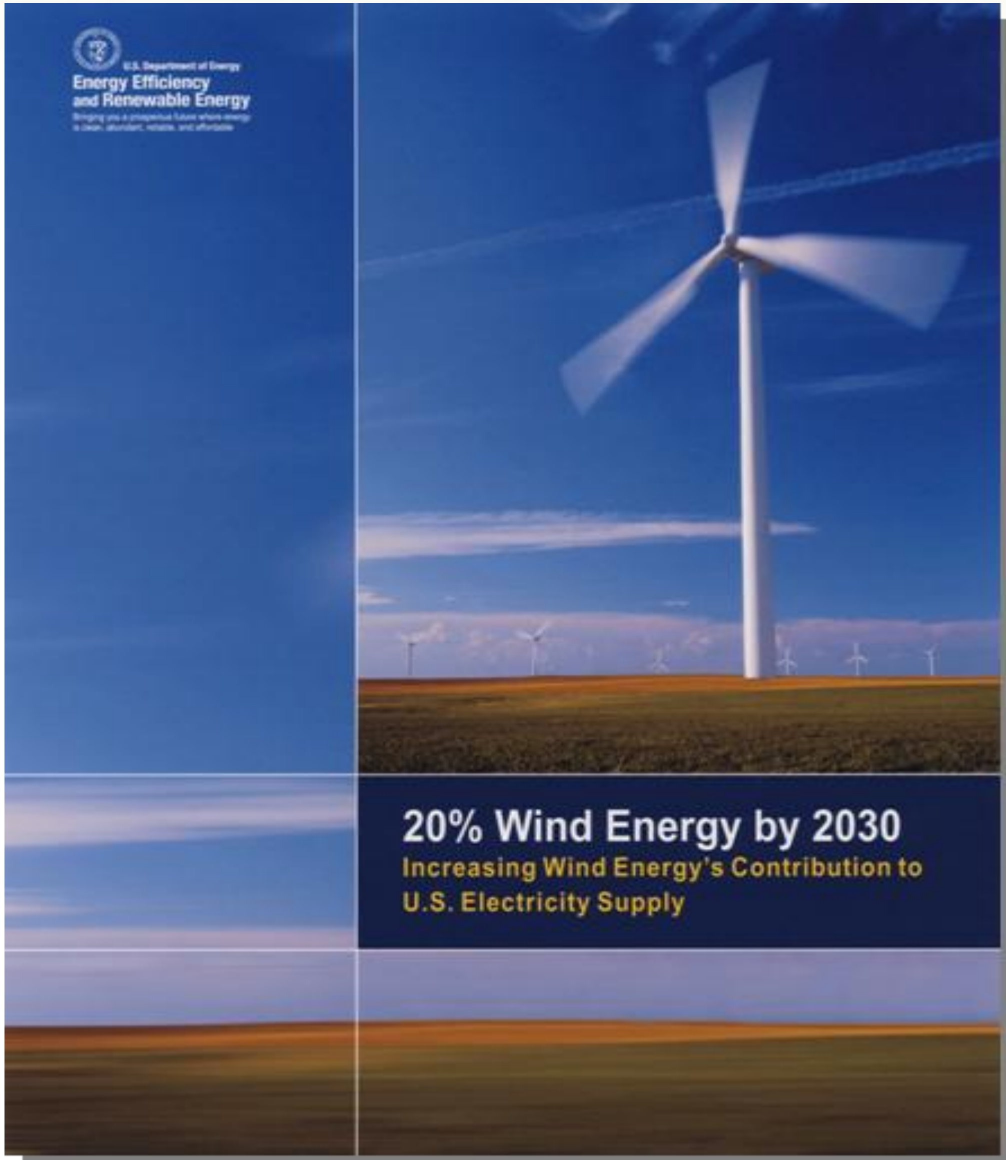


Rising prices are caused by:

- Weak Dollar
- Growing commodity prices
  - steel
  - copper
  - concrete
- Limited availability of machines (seller's market)

20% Wind Energy by 2030

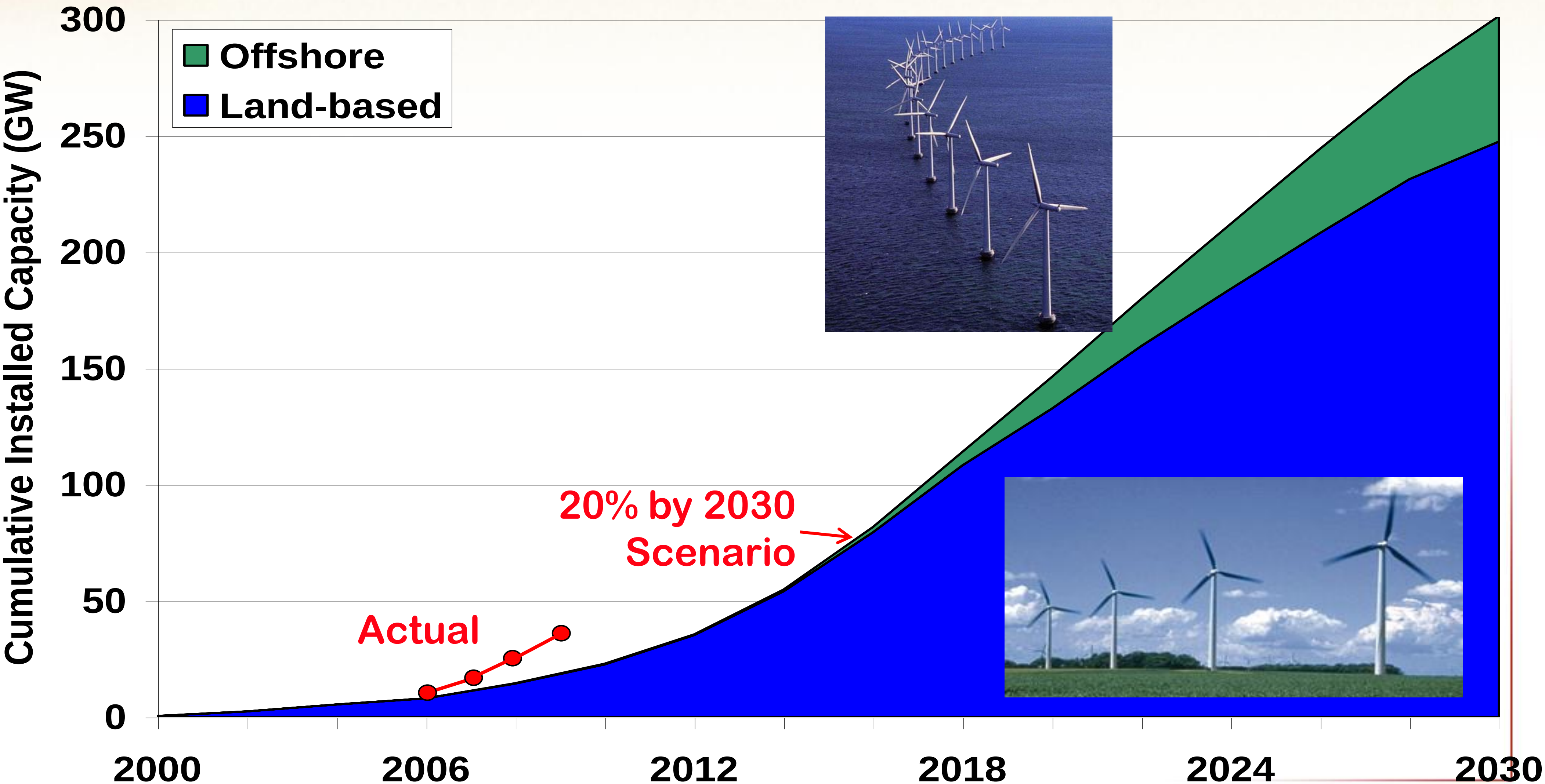
- **The Scenario**
- **Costs**
- **Benefits**
- **Summary**



The 20% Technical Report

- Explores one scenario for reaching 20% wind energy by 2030 and contrasts it to a scenario in which no new U.S. wind power capacity is installed
- Is not a prediction, but an analysis based on one scenario
- Does not assume specific policy support for wind
- Is the work of more than 100 individuals involved from 2006 - 2008 (government, industry, utilities, NGOs)
- Analyzes wind's potential contributions to energy security, economic prosperity and environmental sustainability

20% Wind by 2030 Scenario Requires 300 GW



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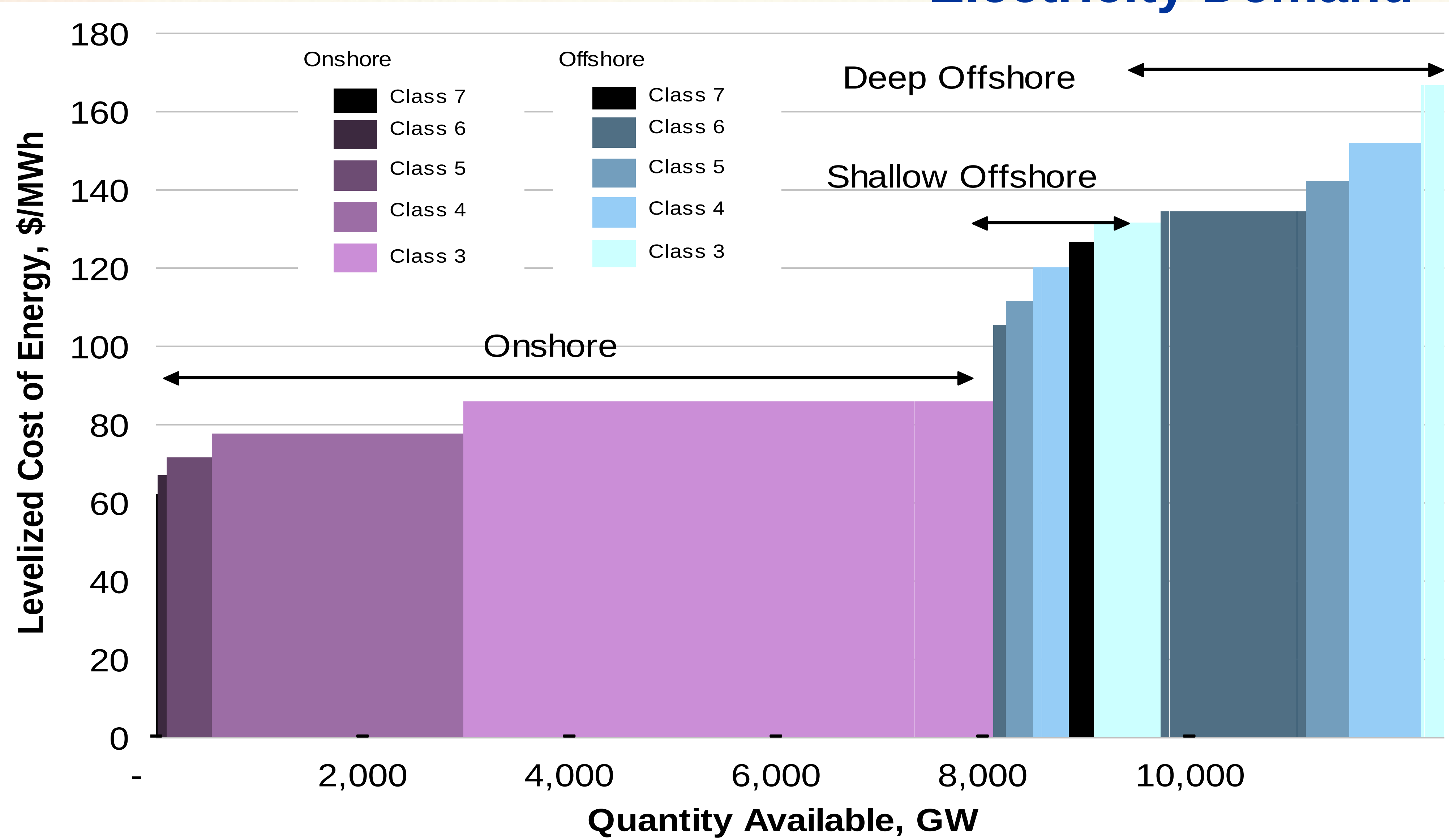
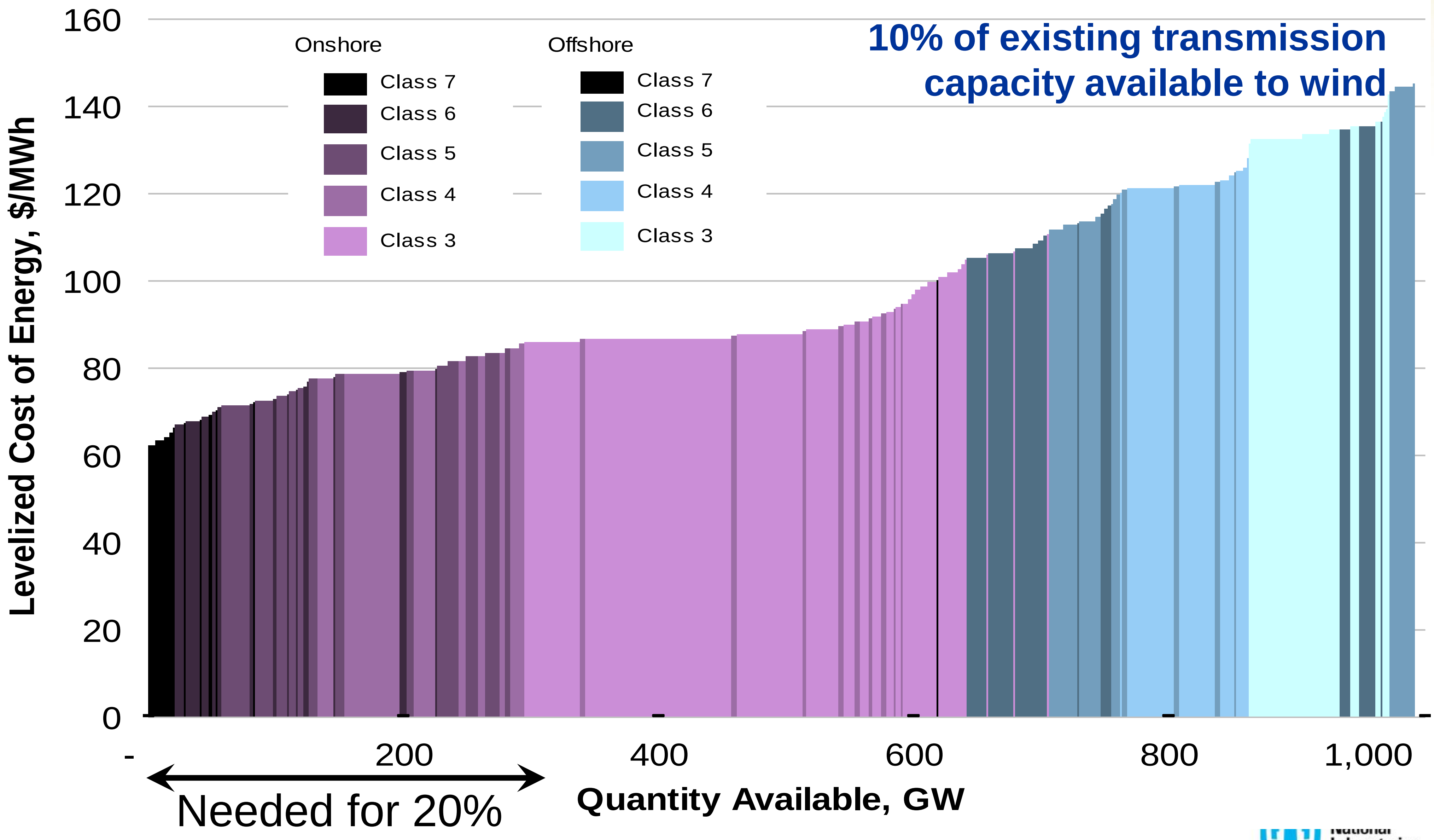
Resource Potential Exceeds Total Electricity Demand

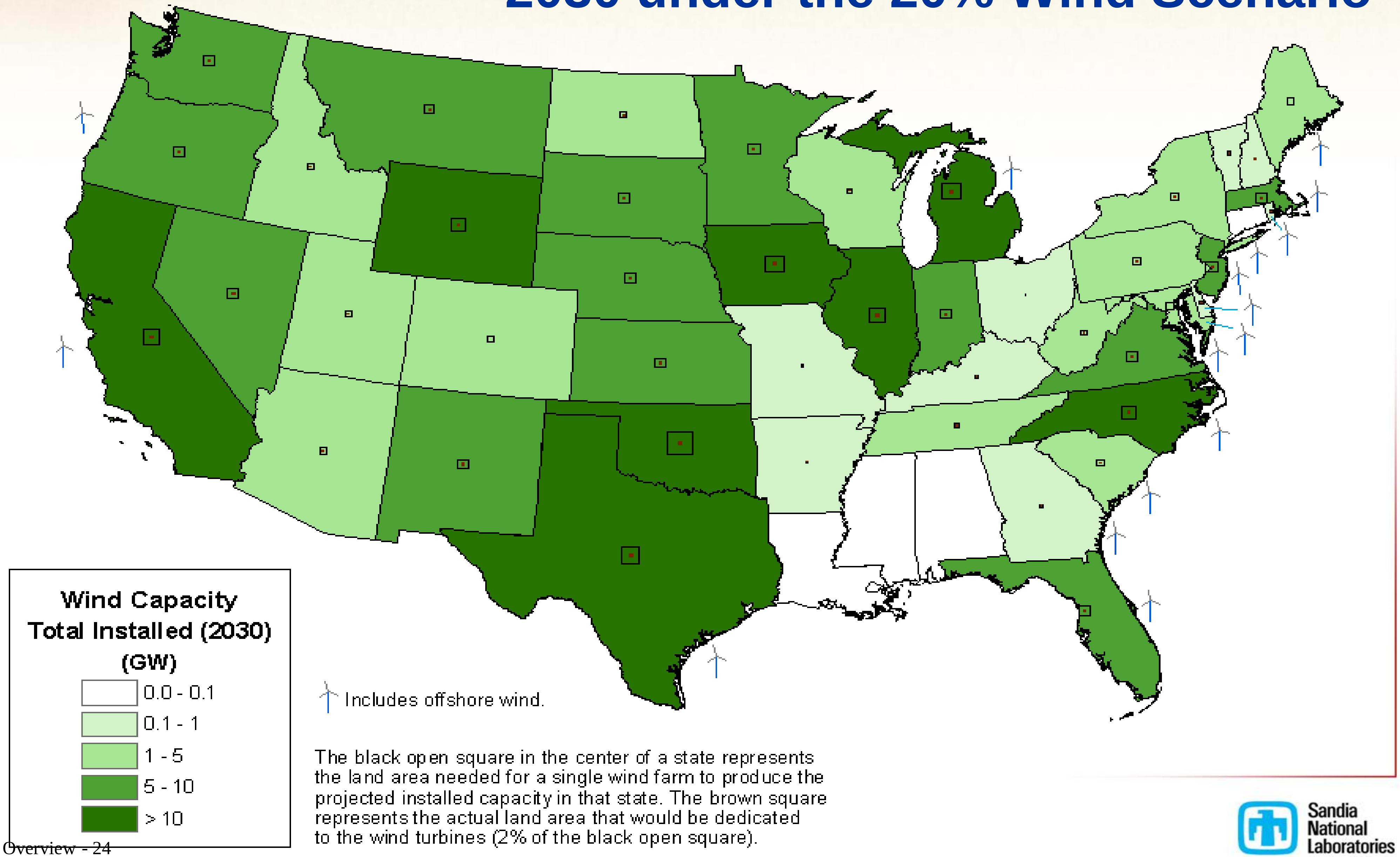


2010 Costs w/o PTC, w/o Transmission or Integration costs

Cost of Wind and Transmission: Economically Available



46 States Will Have Wind Development by 2030 under the 20% Wind Scenario



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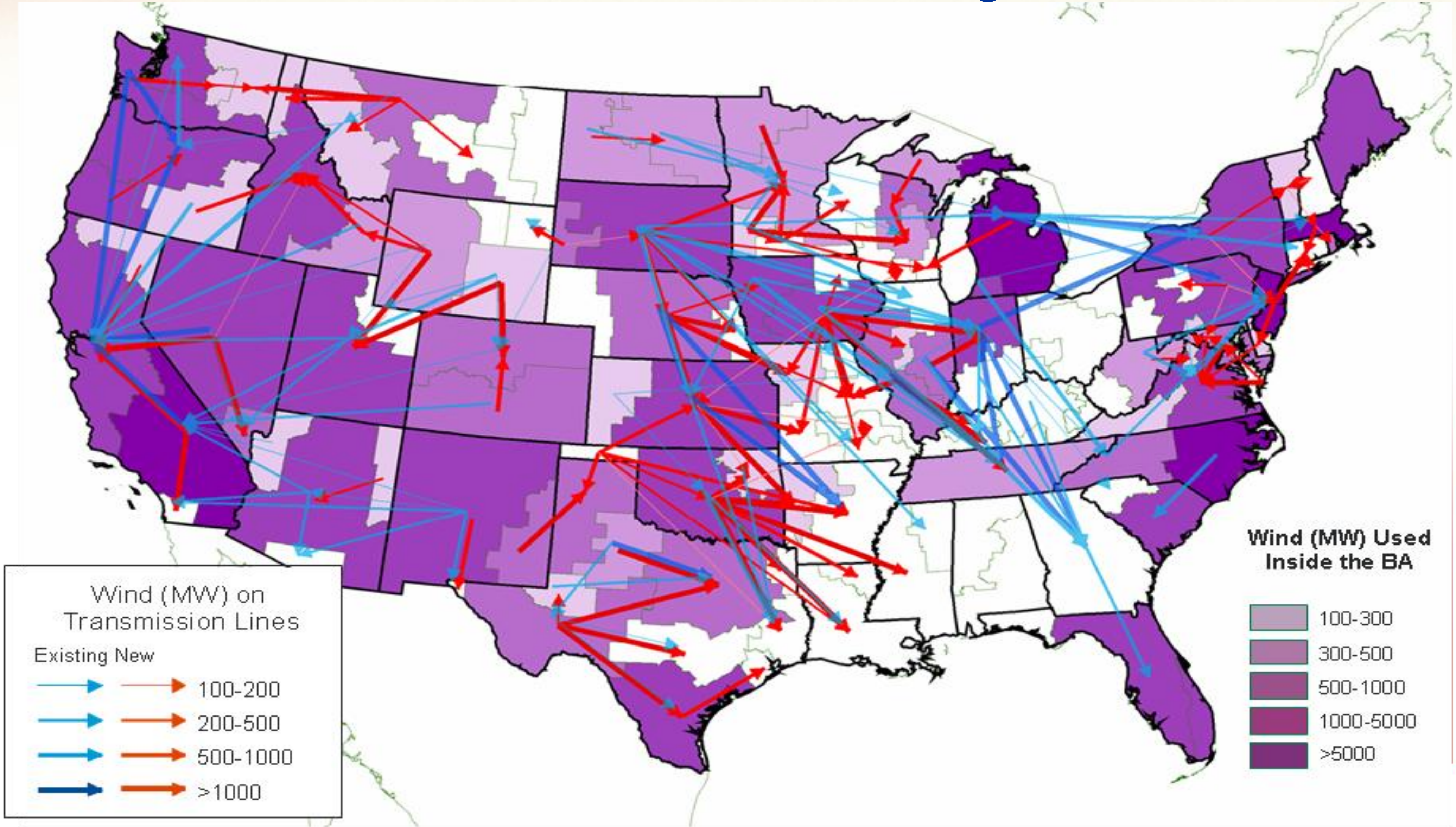
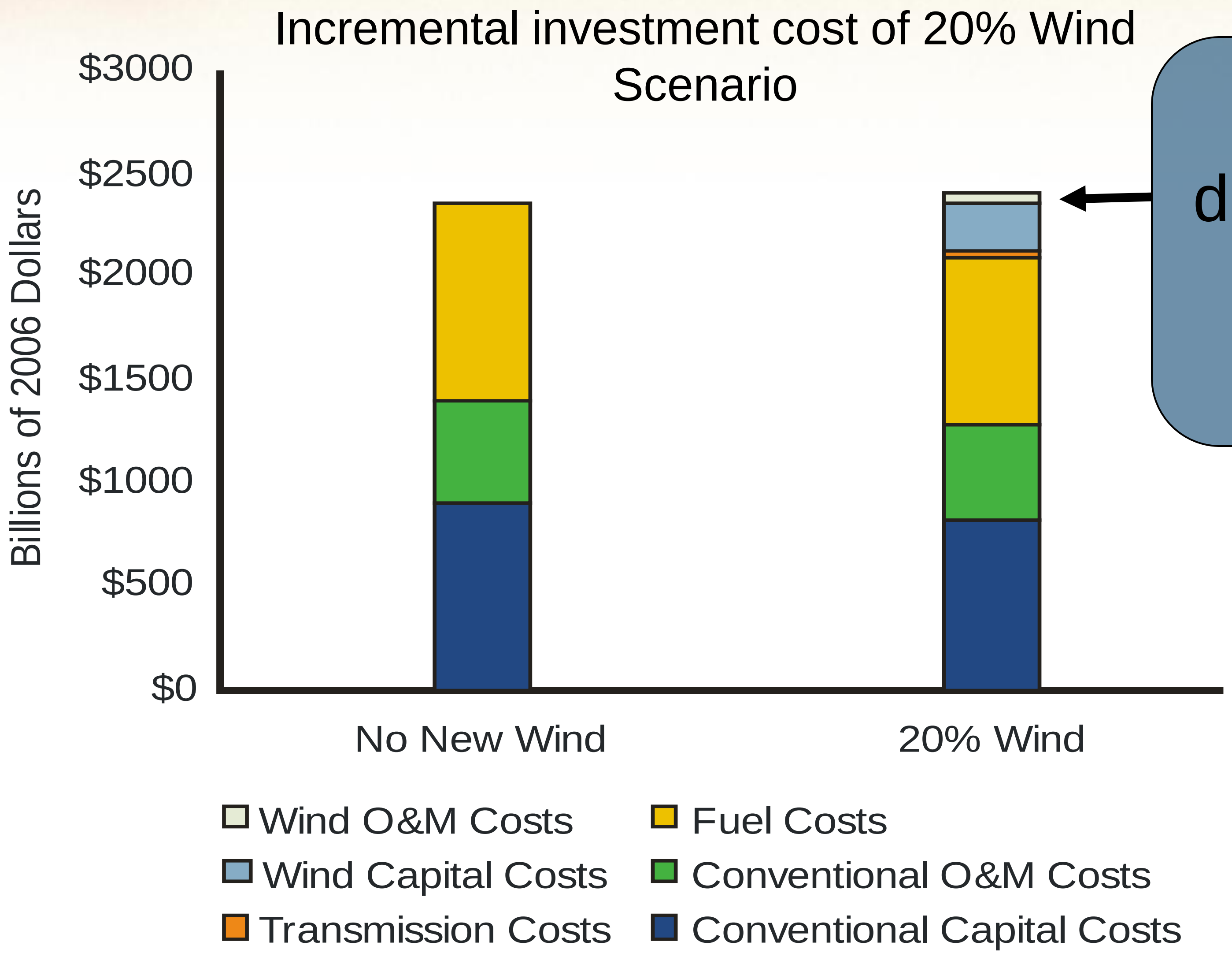
Need for New Transmission: Existing and New in 2030



Laboratories

Economic Costs of 20% Wind Scenario



2% investment difference between 20% Wind and No New Wind

$60 Billion additional Transmission cost

$43 Billion net additional cost

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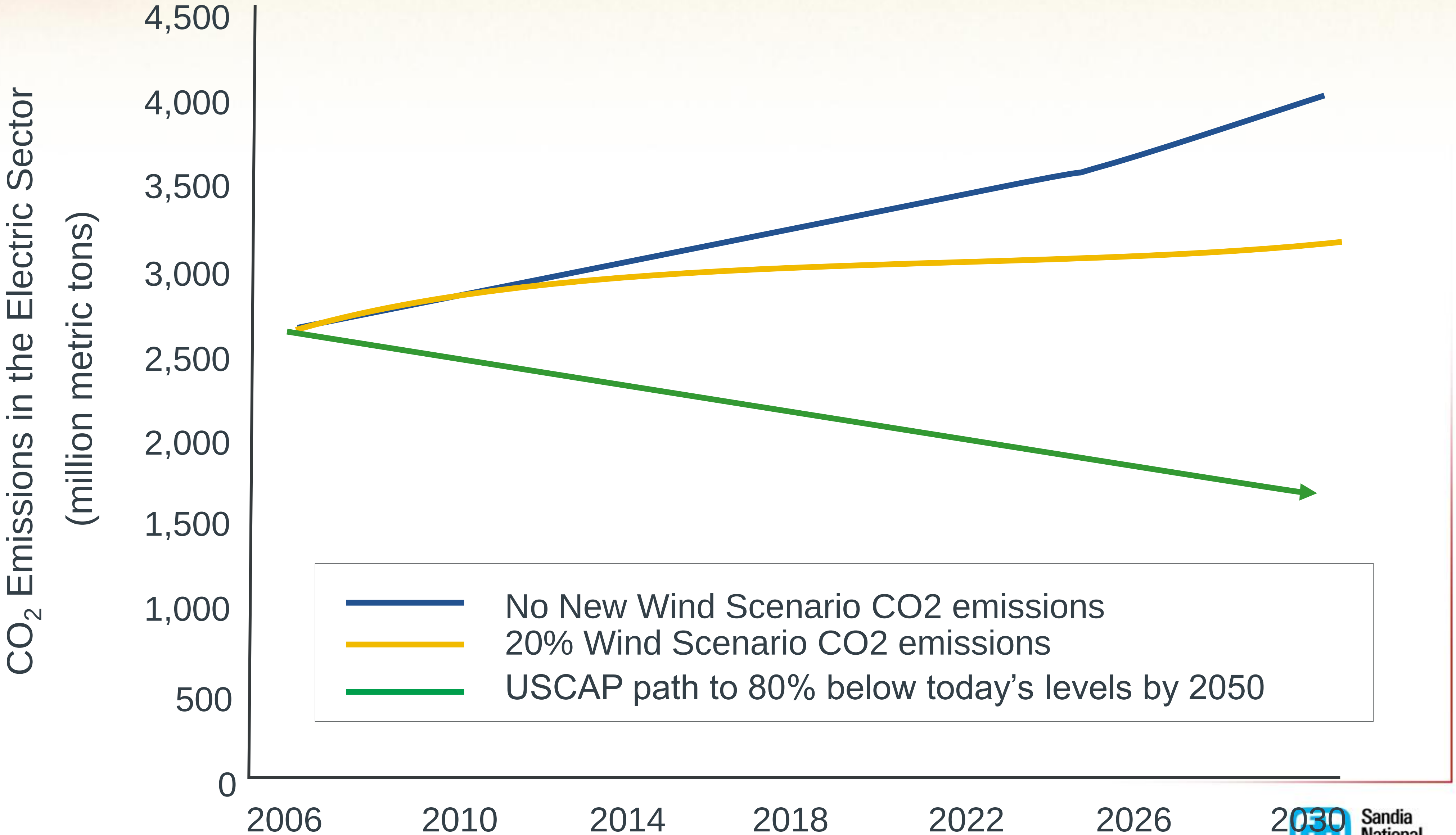
Most area
available
for farming or
grazing

CO_2 Emissions from the Electricity Sector



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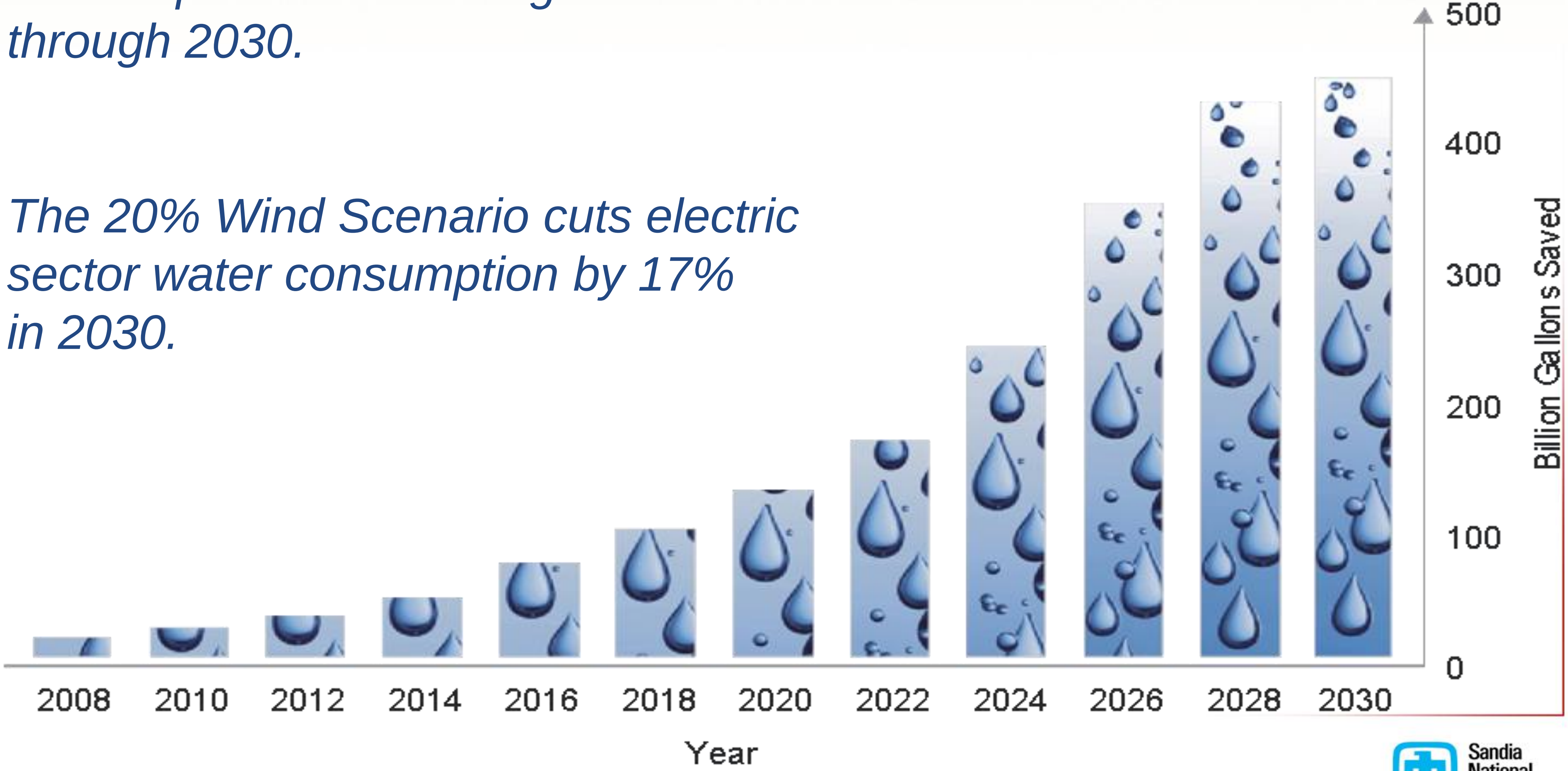
Significant Water Use Savings

Cumulatively, the 20% Wind Scenario would avoid the consumption of 4 trillion gallons of water through 2030.

The 20% Wind Scenario cuts electric sector water consumption by 17% in 2030.



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Summary: Costs & Benefits

Incremental direct cost to society	$43 billion 50 cents/month/ household
Reduction in emissions of greenhouse gasses and avoided carbon regulation costs	825 million tons of CO_2 $50 to $145 billion
Reduction in water consumption	8% through 2030 17% in 2030
Jobs supported and other economic benefits	500,000 total with 150,000 direct jobs $2 billion in local annual revenues
Reduction in nationwide natural gas use and likely savings for all gas consumers	11% $86-214 billion

Sources: DOE, 2008 and Hand et al., 2008

Note: All dollar values are in NPV

Technology Fundamentals

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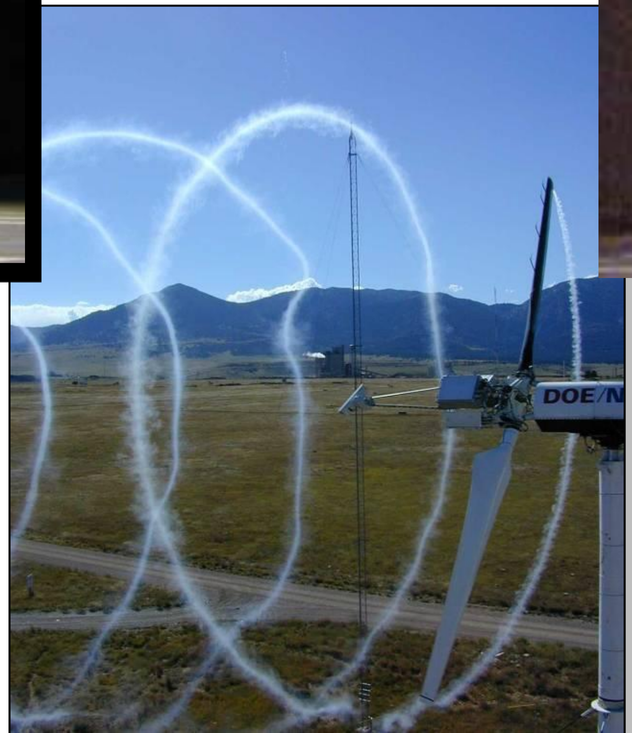
Measuring and Modeling Dynamic Stall and Unsteady Aerodynamics

Visualizing the flow through the rotor

NASA Ames 80’ by 120’ Wind Tunnel Test



Smoke Test

Field Test

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Wind Power Basics

Air Density → ρ, **Rotor Area** → A, **Wind Speed** → V_∞, **Efficiency** → C_P

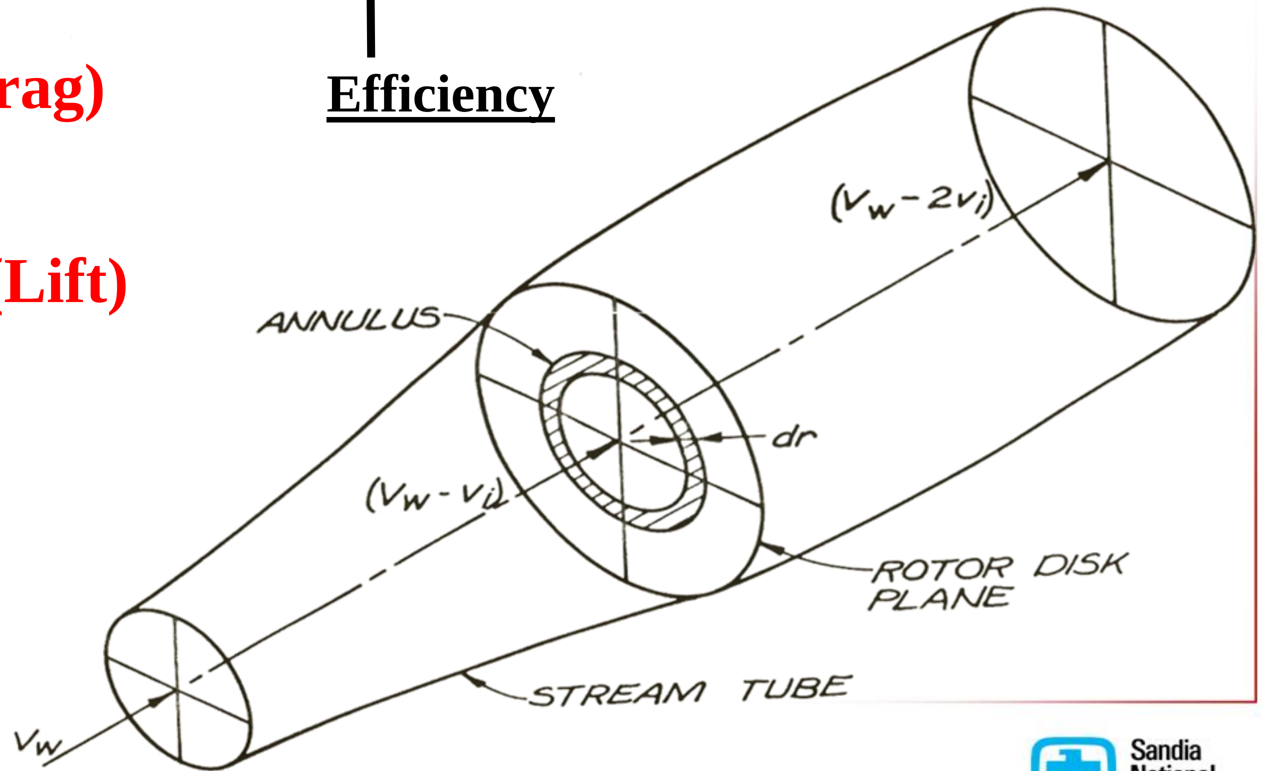
$$WindPower = \frac{1}{2}\rho A C_P V_\infty^3$$

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



Courtesy Jim Green, NREL

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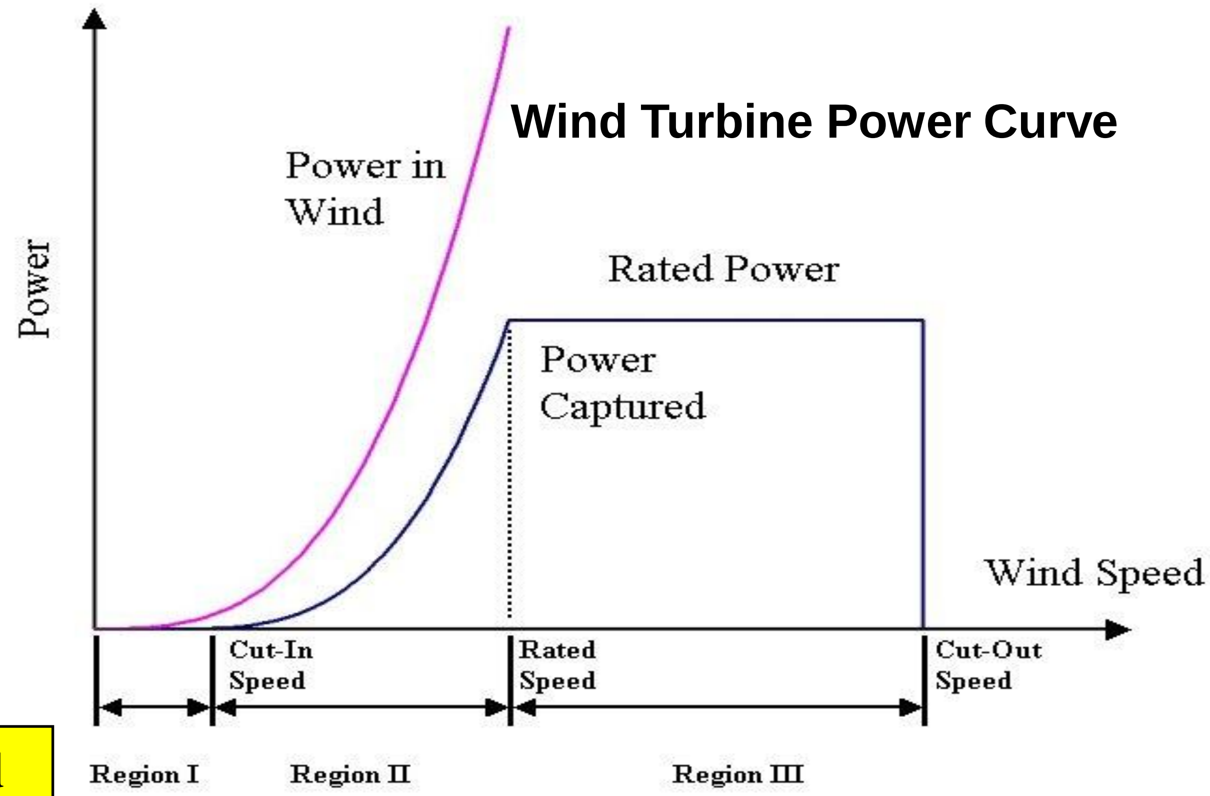
Turbine Power: What is available and what is useable?

Regions of the Power Curve

Region I – not enough power to overcome friction

Region II – Operate at maximum efficiency at all times

Region III – Fixed power operation



"Rated Power" governs the size and cost of the entire turbine infrastructure

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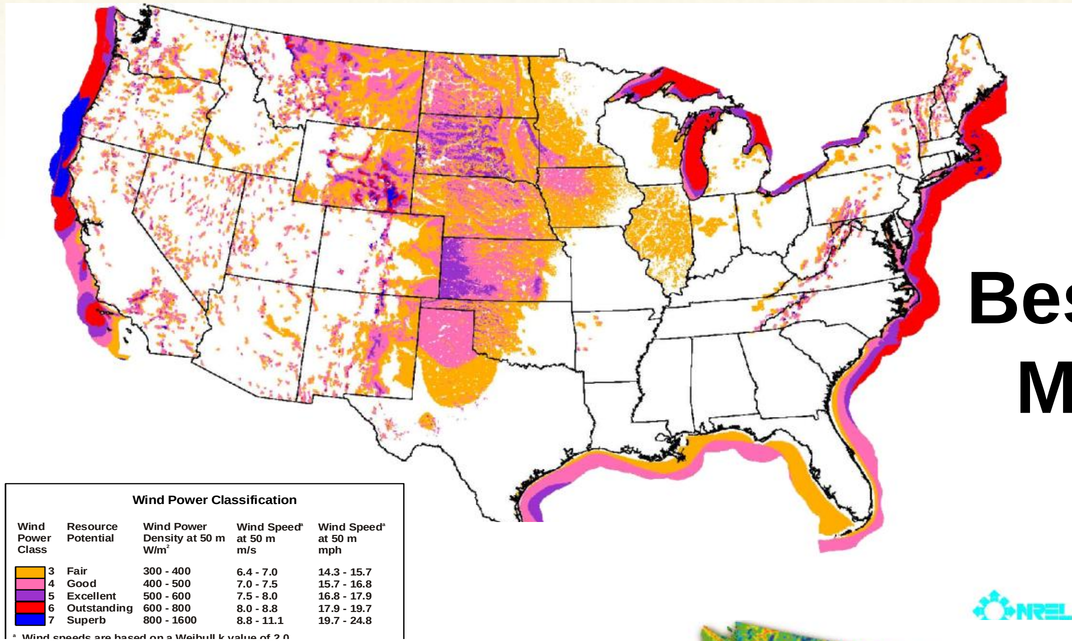
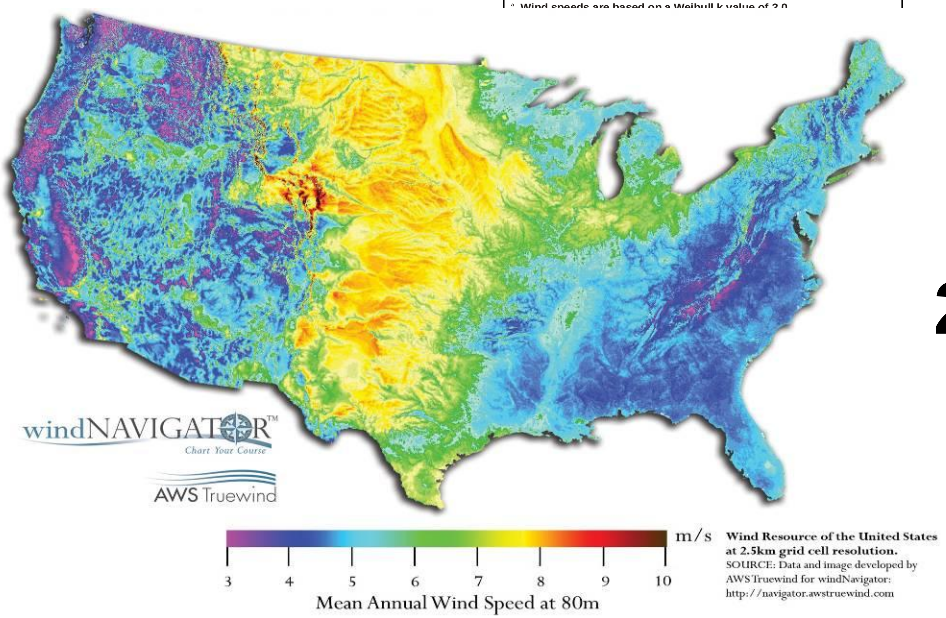
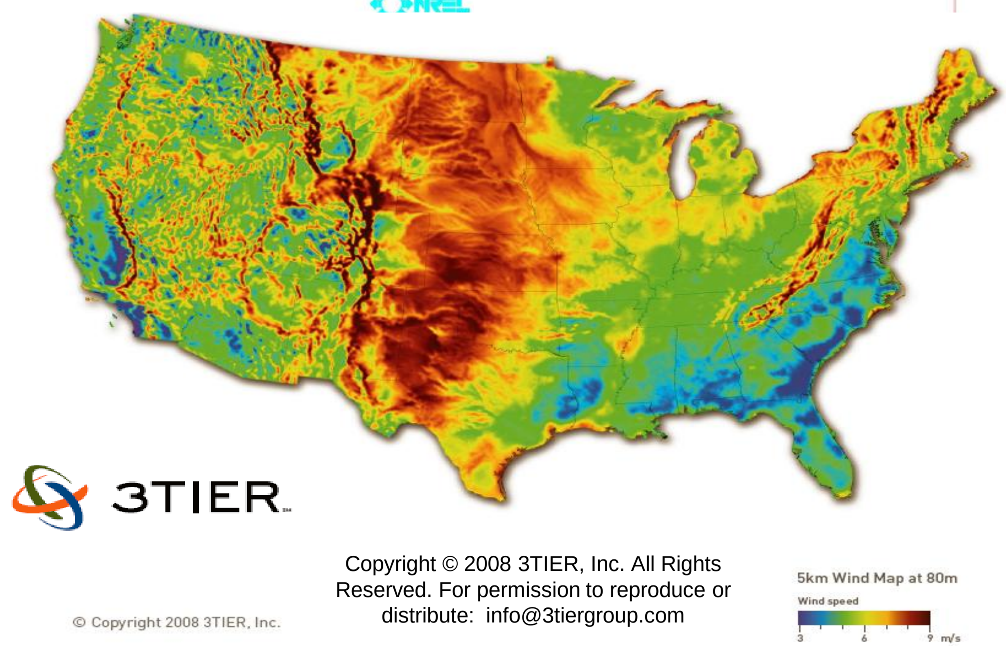
U.S. Wind Resource Maps (50 meter elevation)



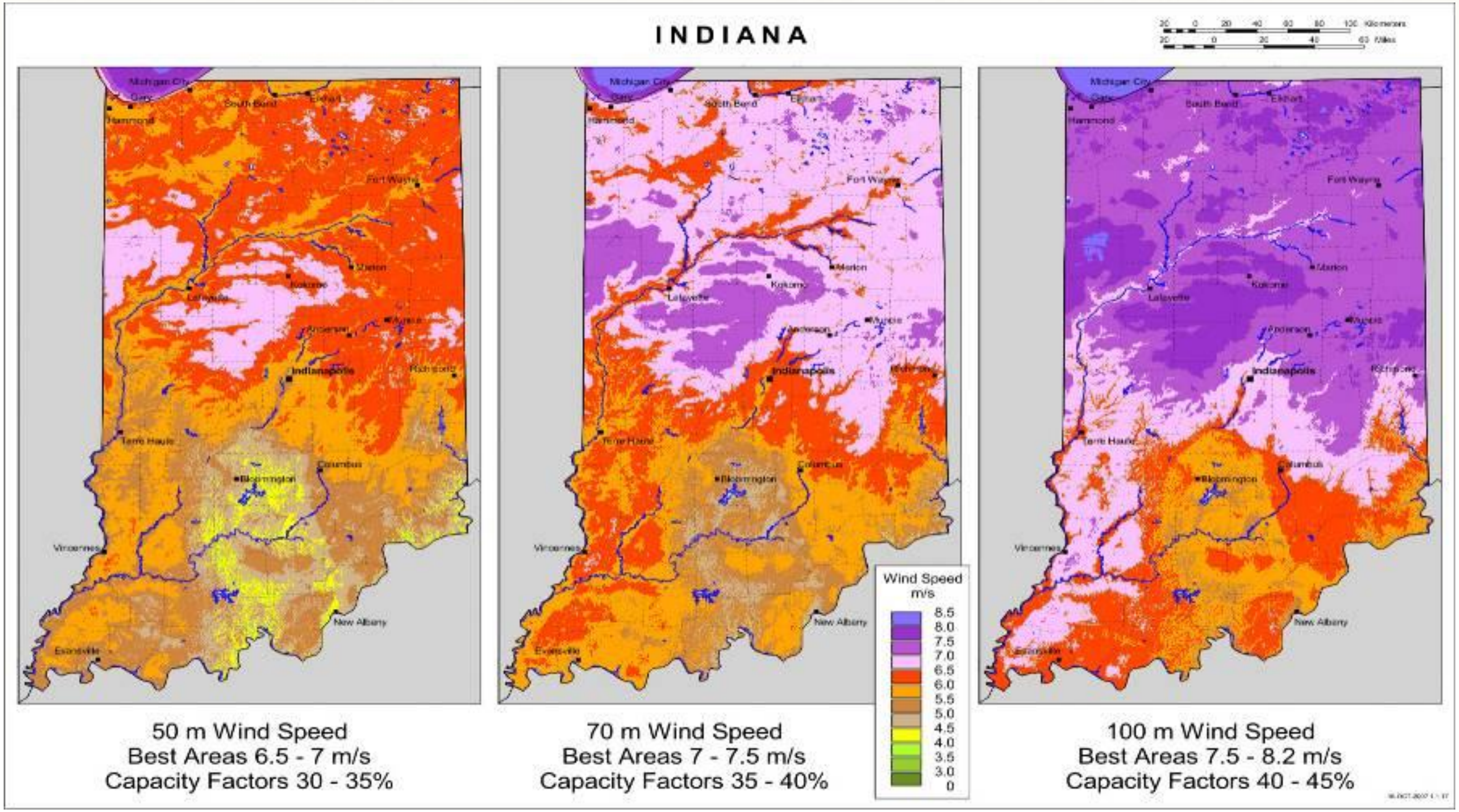
Best National Map ~ 2002



2008



The wind resource is much better as you go higher above ground



50 meters **70 meters** **100 meters**

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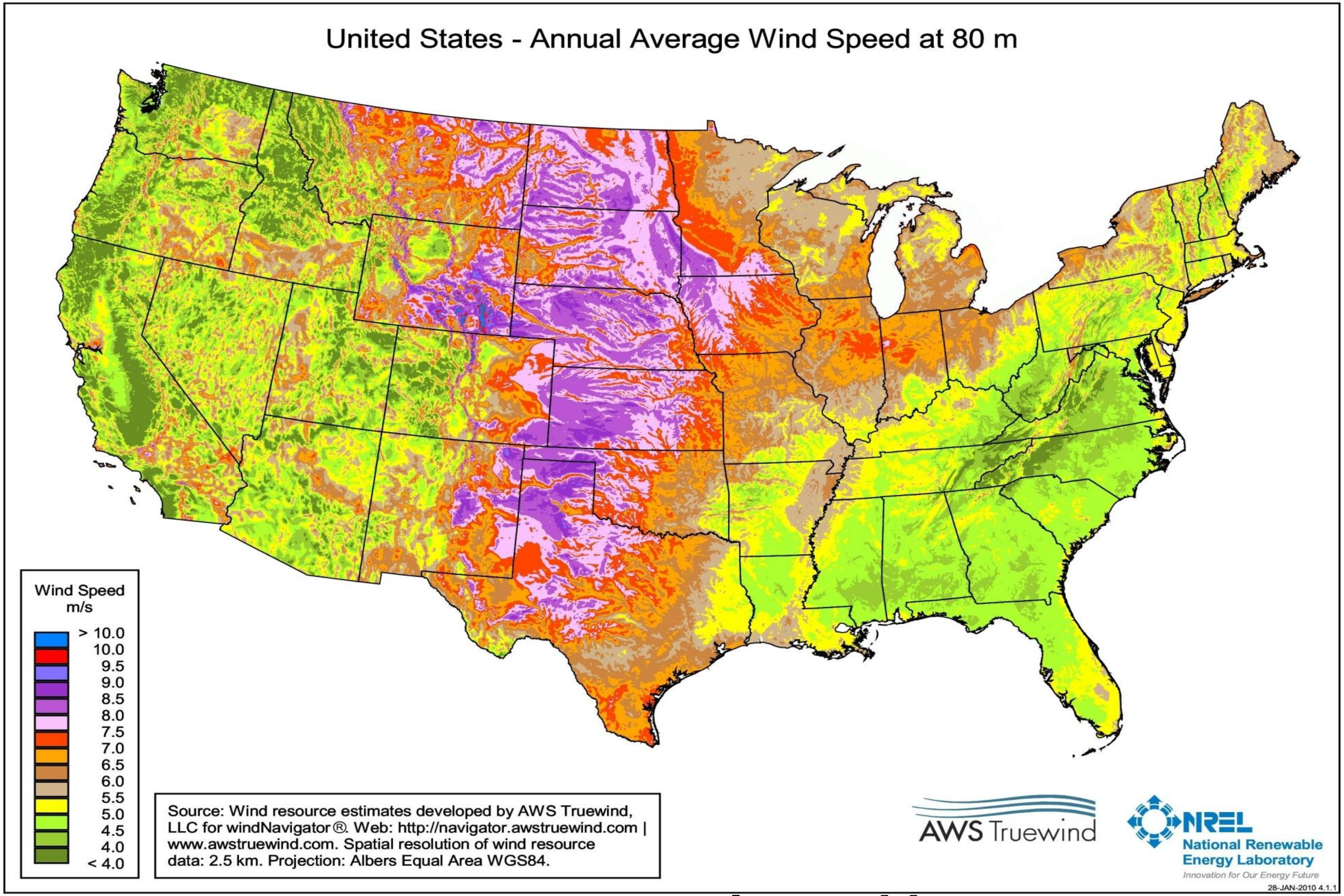
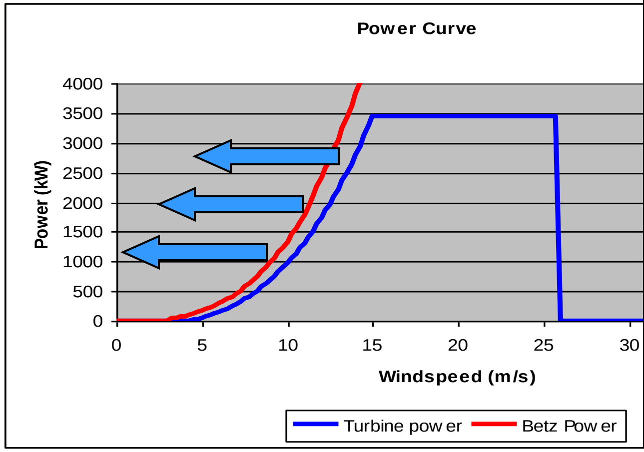


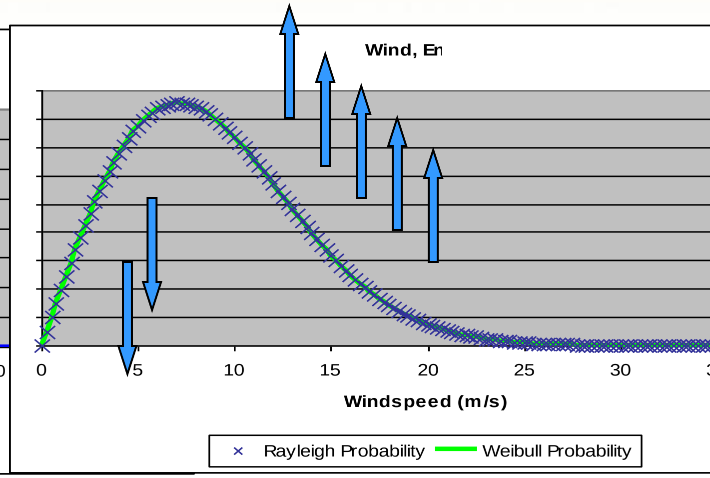
New 80m map – released in 2010

Performance Enhancement Options

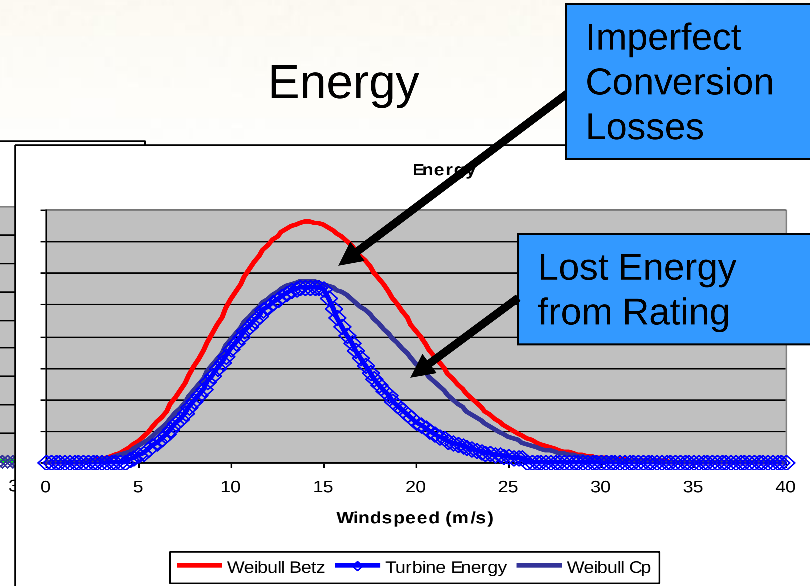
Power



Resource



Energy



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 (constrained base diameter)

Greater Output

The cost benefits are constrained by the *squared-cubed* law

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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Wind Turbine Rotor Design Challenge

- Numerous existing manufacturers of large composite structures in Military and Aerospace
- Technology/Expertise does not generally transfer

High-end military	Commercial Aerospace	Wind Turbine Blade
~ $1000/lb	~ $100/lb	~ $6/lb
10^6 cycles	10^6 cycles	10^8 cycles

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Technology Challenges from the 20% Report

Challenges:

- Cost of Energy (Capital Cost / Energy Production)
- Reliability and Maintenance Cost
- Public acceptance and Investor Confidence

Potential Impact from Rotor Enhancements:

- Greater energy capture on a given tower/drivetrain
- Lower tower-top mass for given rotor size
- Lower Cost of Energy (COE)
- Increased deployment of wind power

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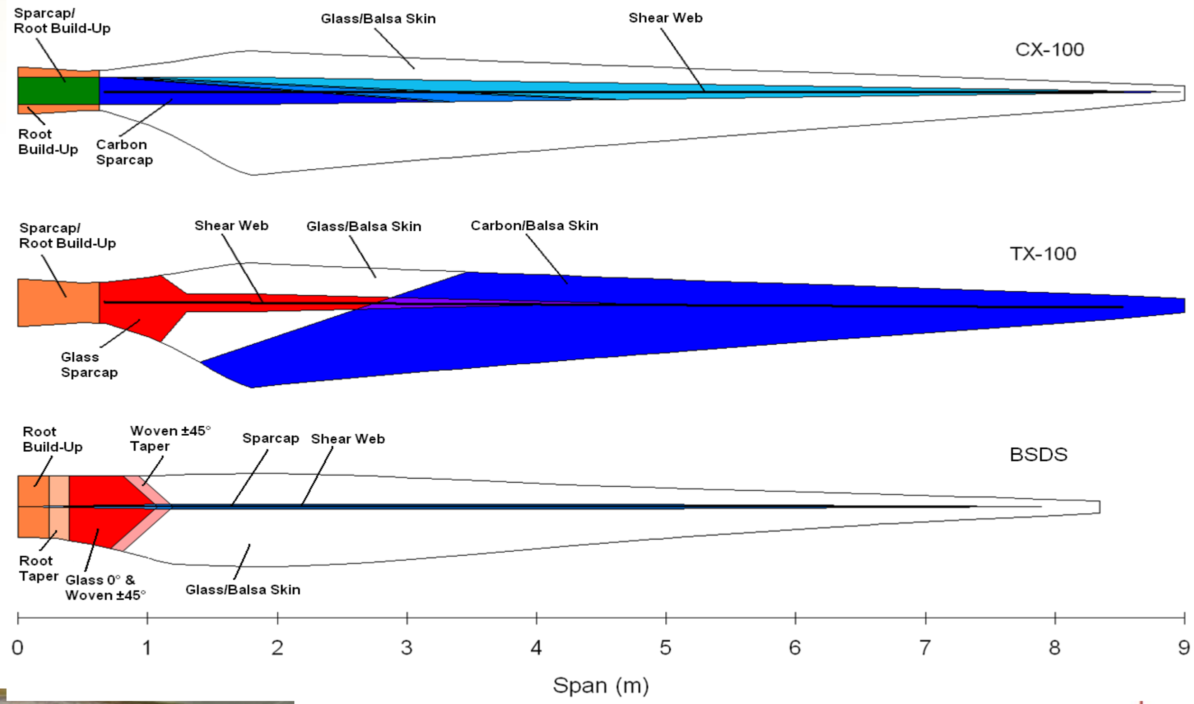
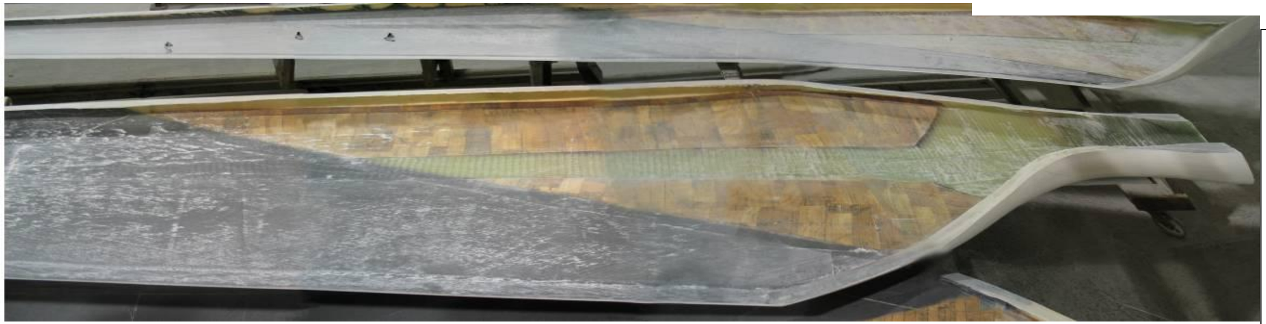
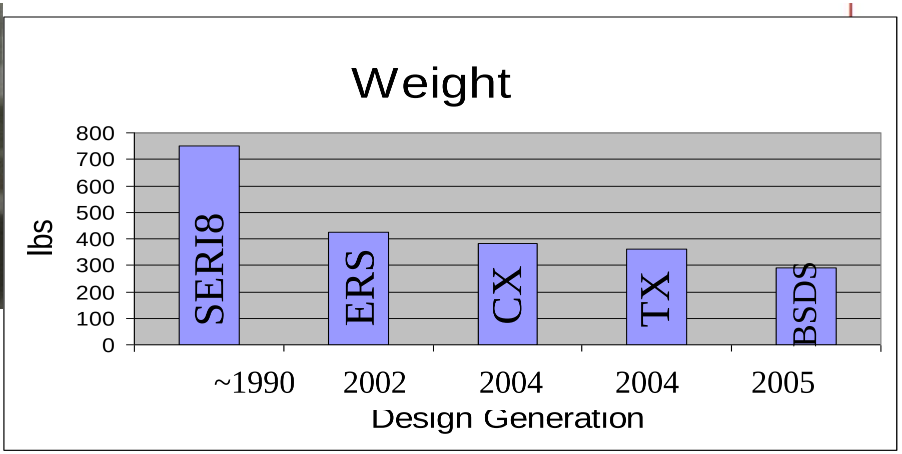
Technology Advancements Under Sandia's Blade Program

- **Prototype Sub-scale Blades Manufactured (9 meters)**
  - **CX-100**
    - Carbon spar cap
    - Glass skin and shear web
  - **TX-100**
    - Carbon triax in skin for passive bend-twist coupling
  - **BSDS** (Blade System Design Study)
    - Flatback airfoils
    - Carbon spar cap
    - Constant spar cap thickness





TX-100 skin w/ off-axis carbon fiber

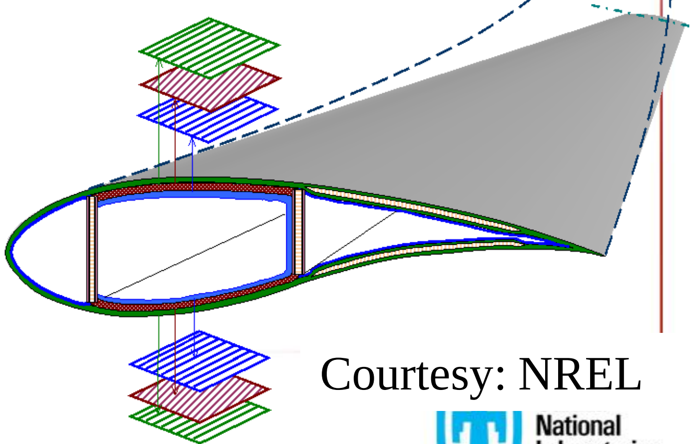


Previous Load Control Concepts

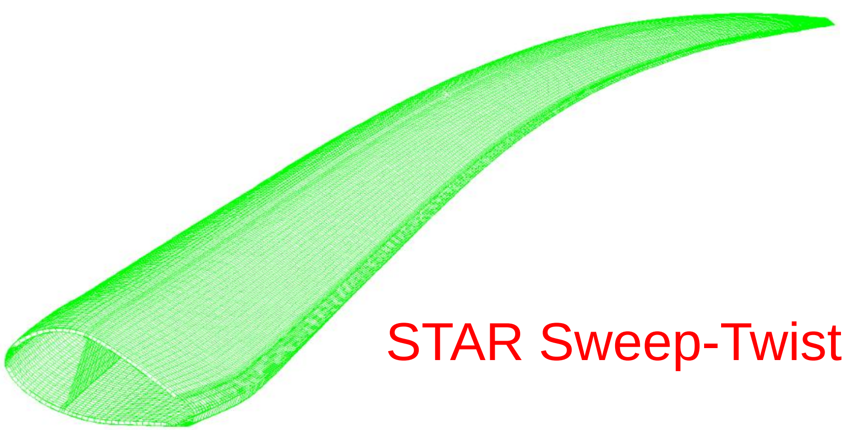
Past work has investigated blade load control

- Individual blade pitch (rather than collective)
  - Pitches entire blade (slow response)
  - Responds to some “average” blade load
  - Current “state-of-the-art” in industry research
- Passive bend/twist or sweep/twist blade load control (load causes blade to twist and reduce load)
  - Response fixed at time of design
  - Unable to tailor to specific site/wind conditions

Passive Bend-Twist Coupled Blade



Courtesy: NREL



STAR Sweep-Twist Coupled Blade

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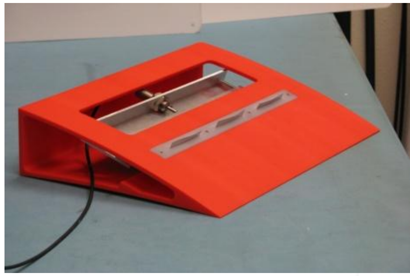
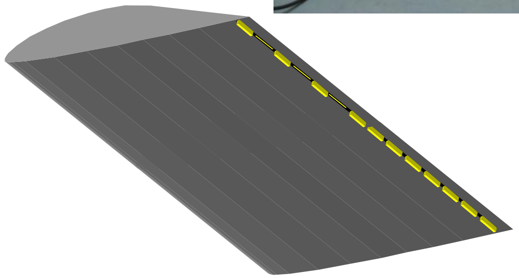
Knight & Carver Swept (STAR) Blade

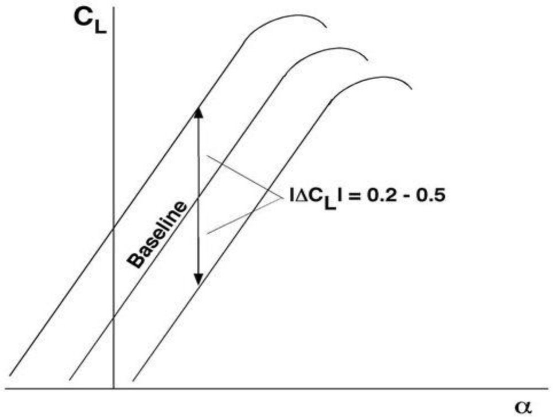
Smart-Blade Approach

Investigate use of distributed active aerodynamic load control devices to reduce locally fluctuating blade loads

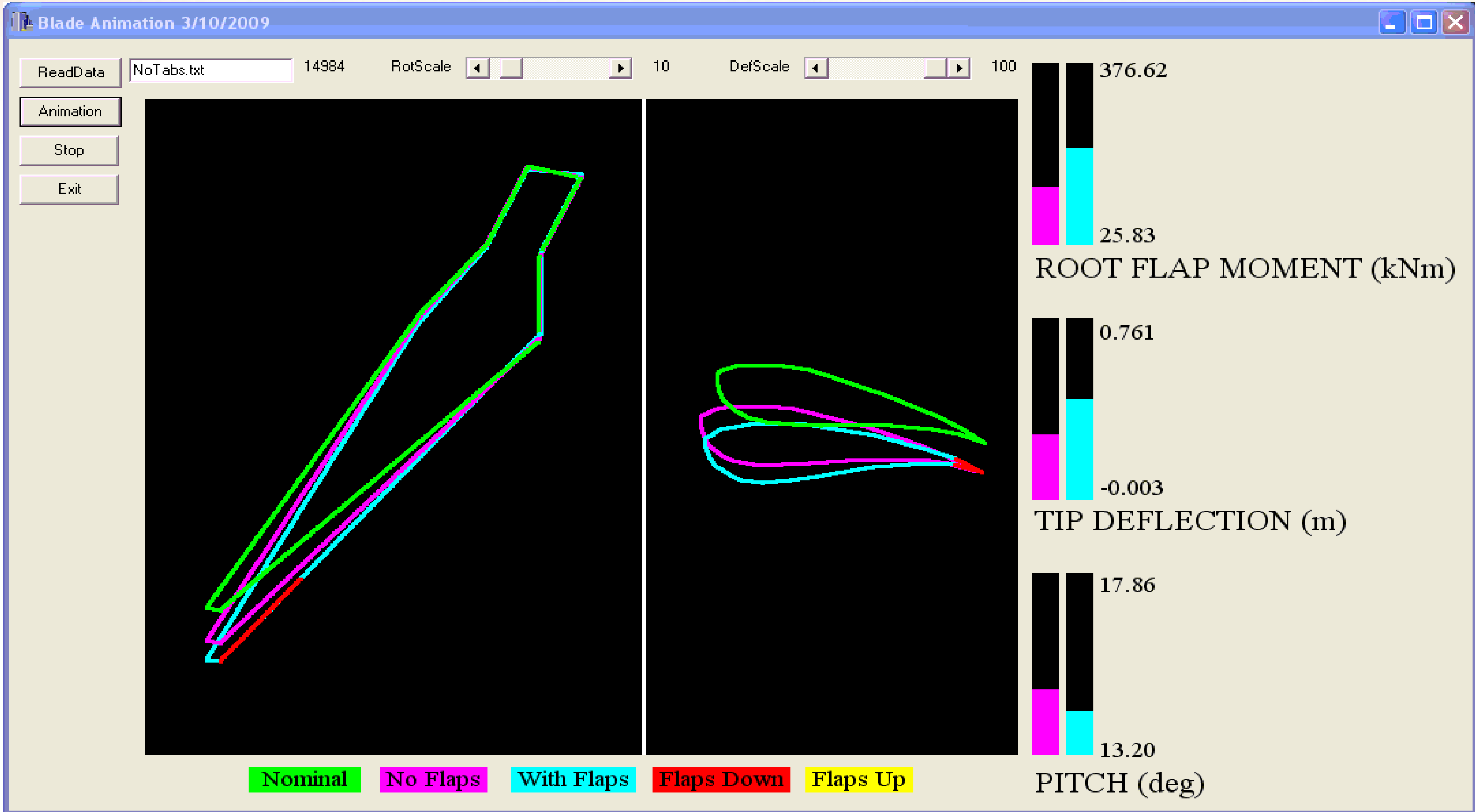
- **Improved load control capability**
  - Respond to loads at locations along blade
  - Respond to site-specific conditions
- **Utilize full system dynamic simulations**
  - Analyze system response
  - Develop control system
- **Develop prototype control devices**
  - Microtabs, microflaps, morphing trailing edges
  - Fast response, low loads
  - Study impact on flow field (UC Davis)
    - Analytical (2-D and 3-D CFD)/experimental





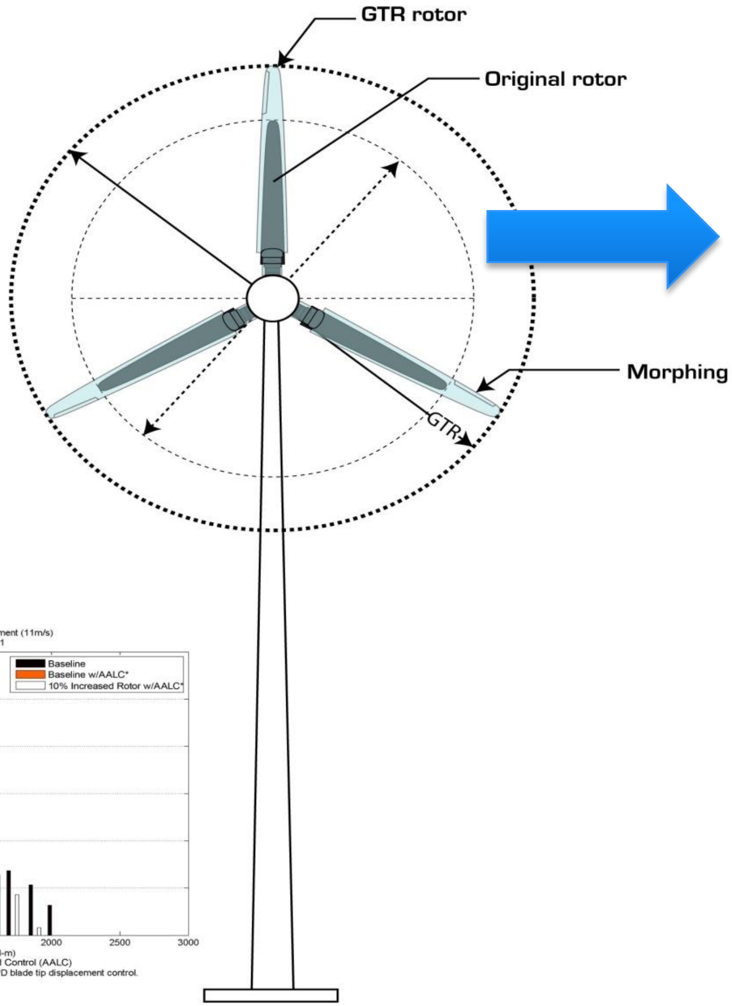


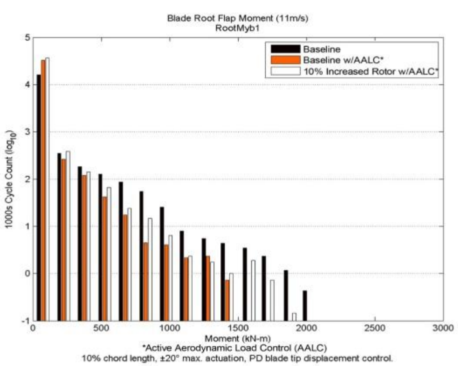
Load Control Decreases Blade Motion & Fatigue

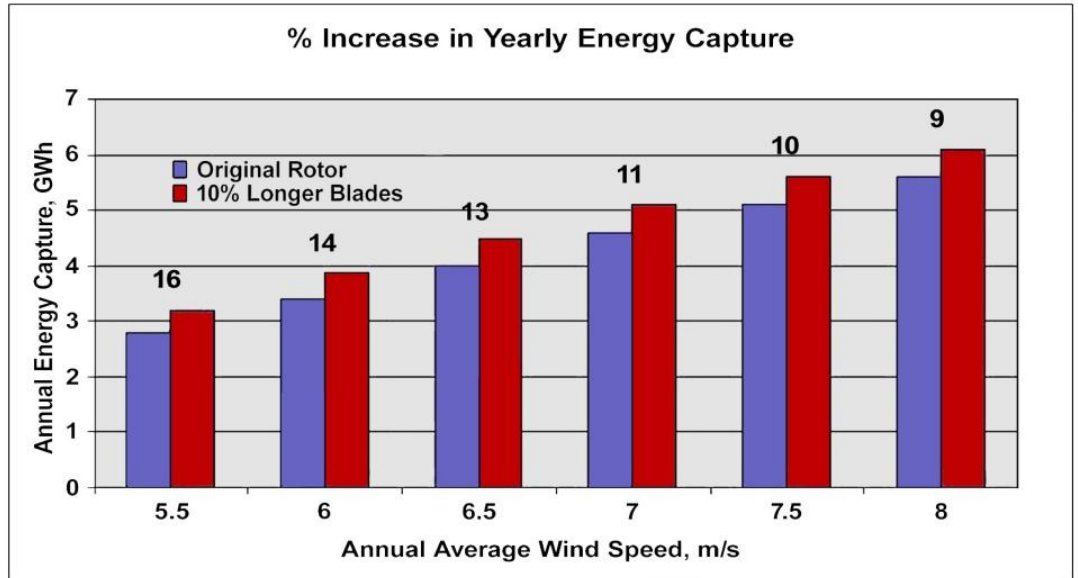


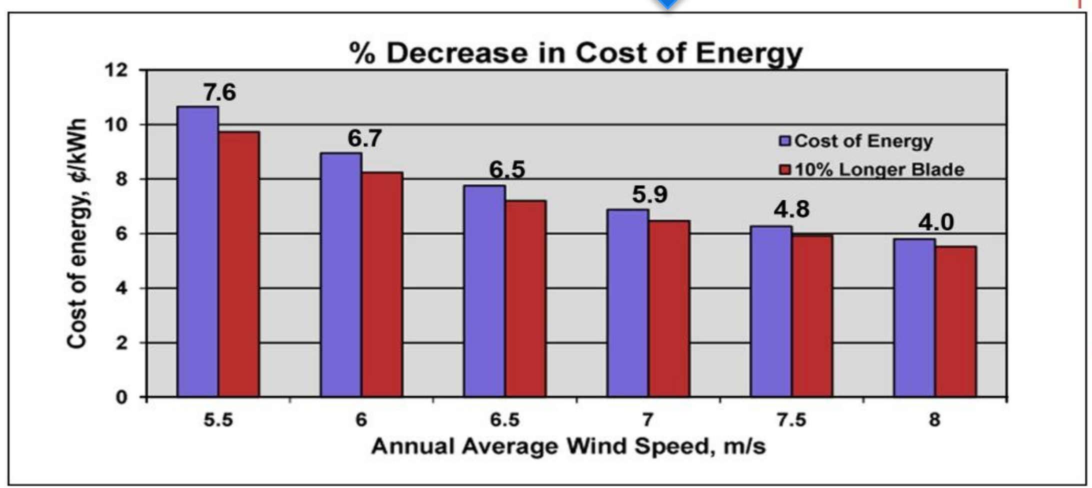
Grow the Rotor (GTR) Concept

Comparable Blade Flap Fatigue Damage – 1.5MW

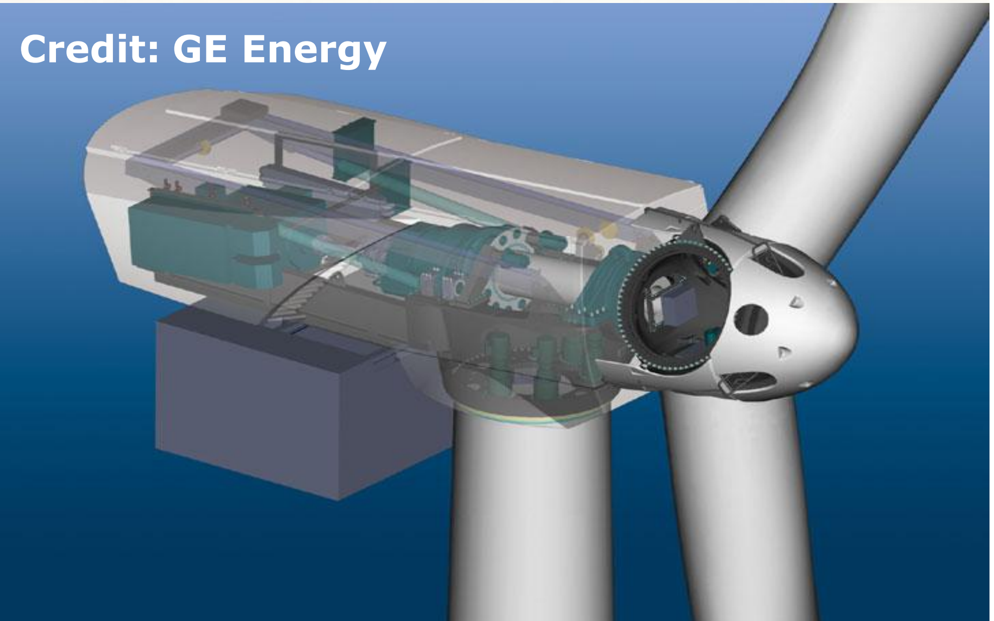




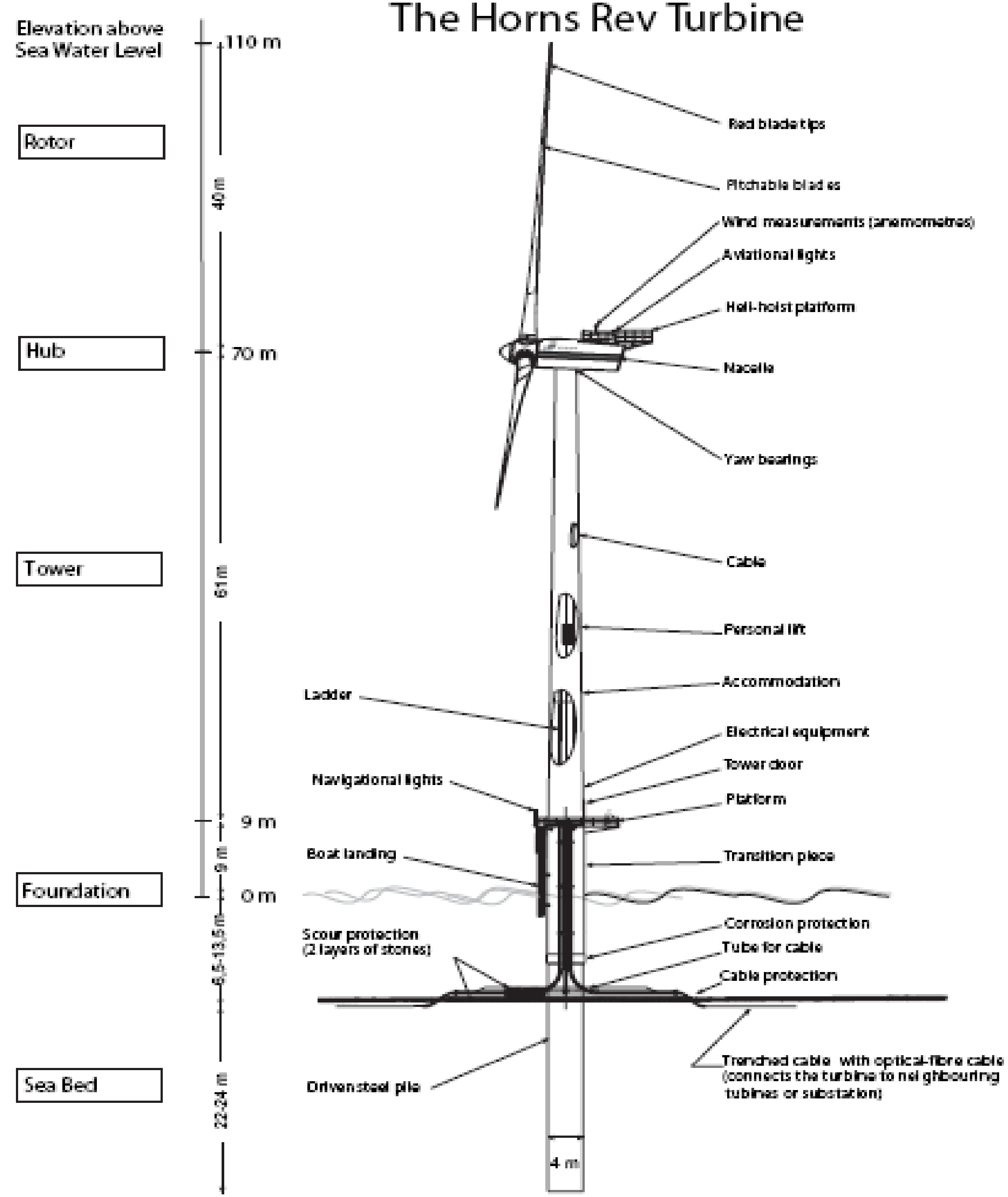




Typical Offshore Wind Turbine



The Horns Rev Turbine



Principal Components and Dimensions of an Offshore Wind Turbine

Graphic courtesy of Horns Rev wind project, Denmark (http://www.hornsrev.dk). Copyright Elsam A/S.

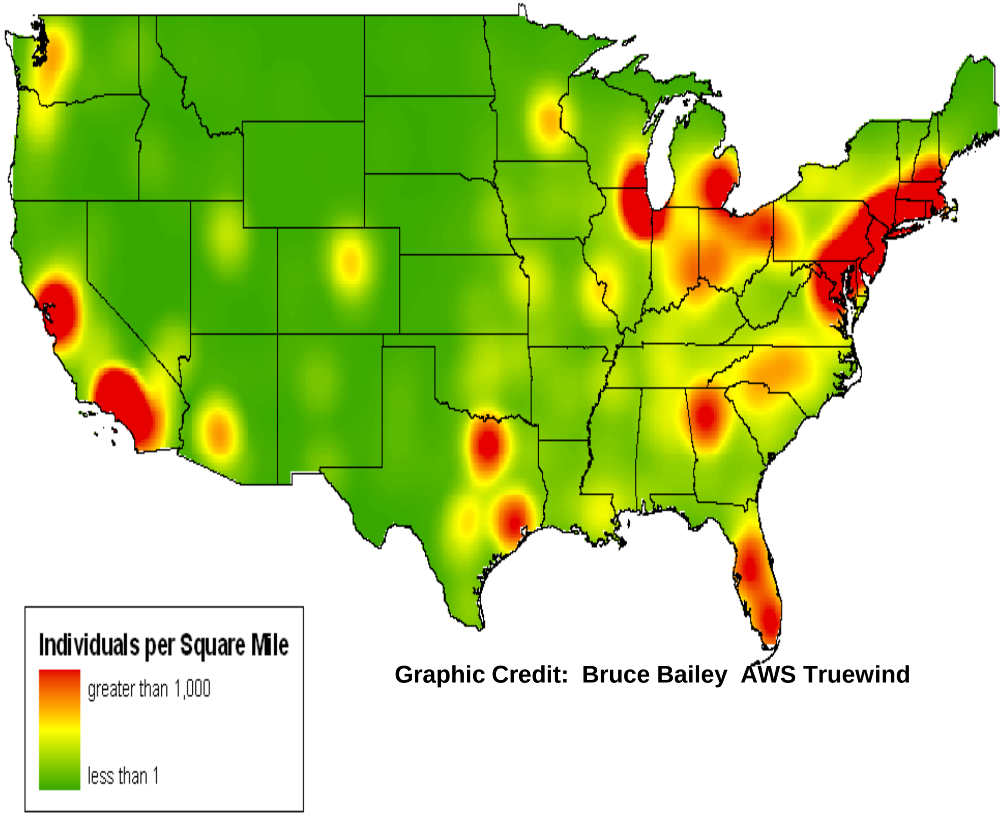
Why Offshore Wind ?

Land-based sites are not close to population centers

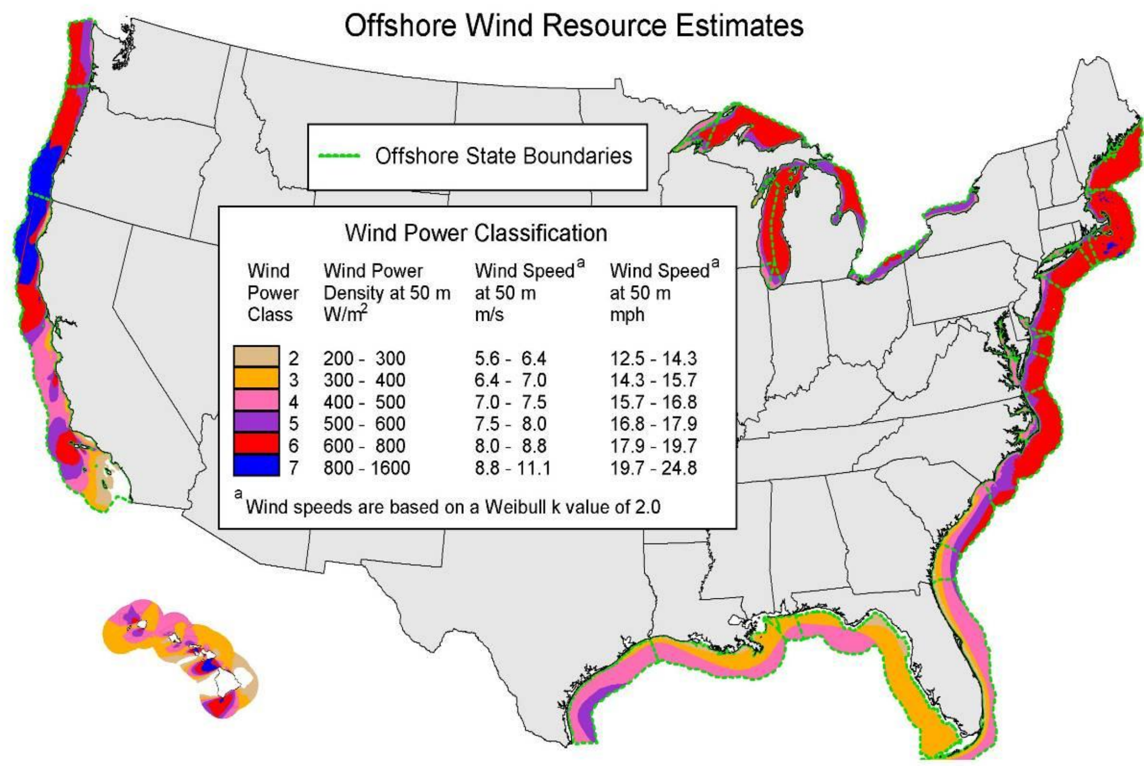
Cities are close to offshore wind sites

28 coastal states use 78% of the electricity in US

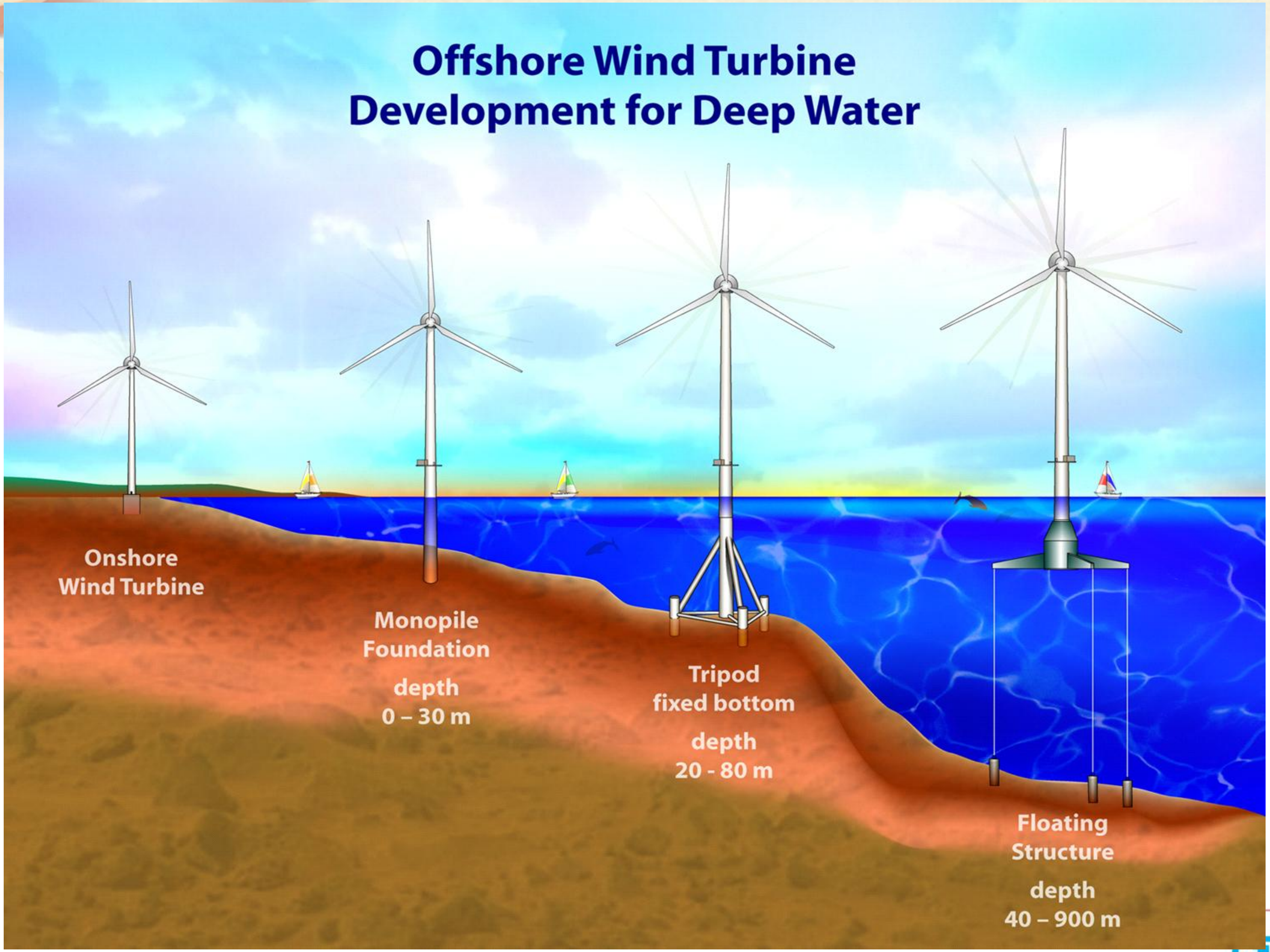
US Population Concentration



U.S. Offshore Wind Resource



Graphic Credit: Bruce Bailey AWS Truewind



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Floating Wind Turbines

Technical data

• WTG:	2,3 MW
• Turbine weight:	138 tonnes
• Turbine height	65 m
• Rotor diameter:	82,4 m
• Draft hull:	100 m
• Displacement:	5300 m^3
• Diameter at water line:	6 m
• Diam. submerged body:	8,3 m
• Water depths:	120-700 metres
• Mooring:	3 lines

StatoilHydro

Statoil/Hydro (Norway) tested a floating system in 2009.

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Grid Integration and Transmission

Wind Grid Integration and Transmission Challenges

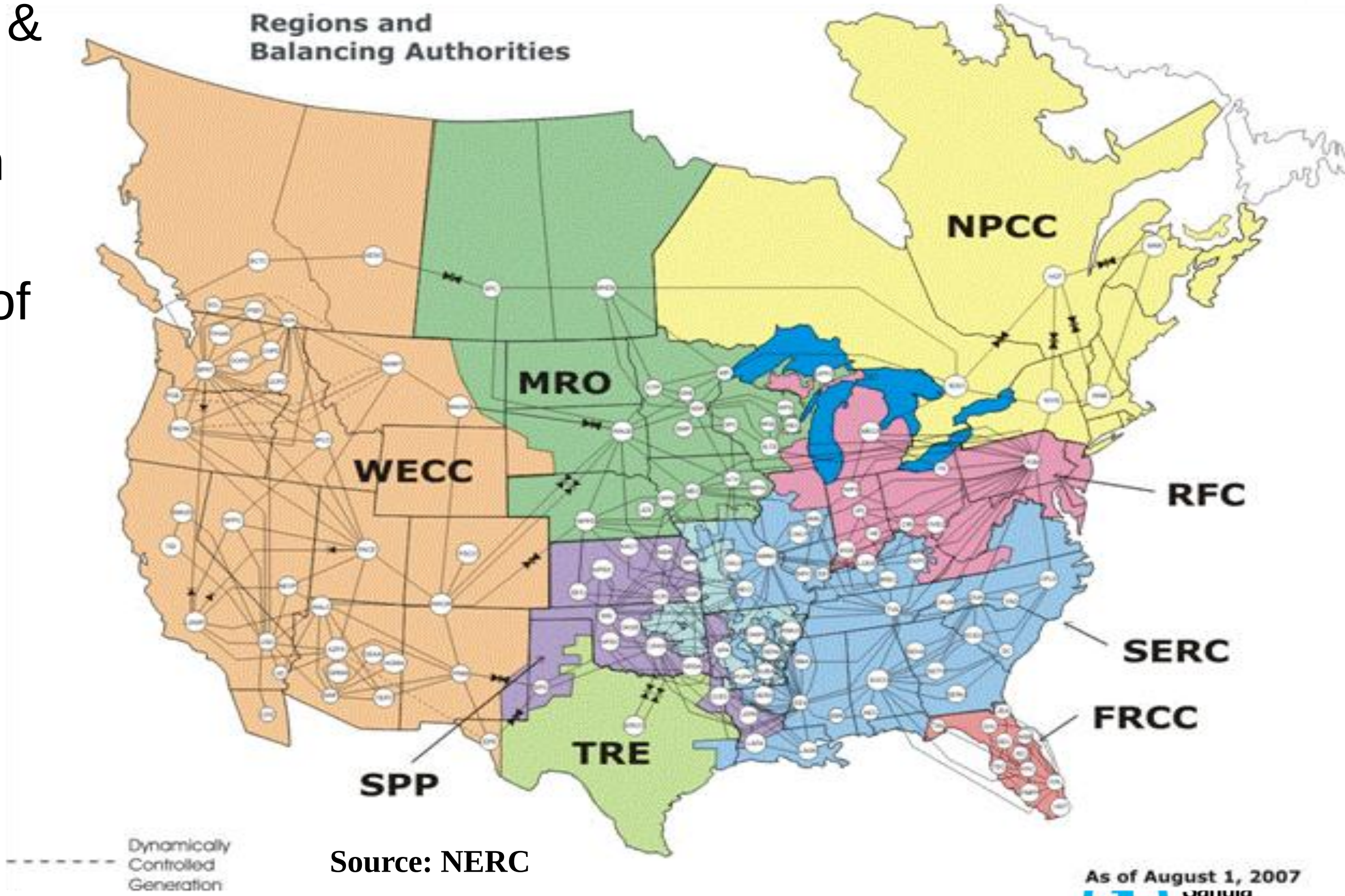
- **Inability to dispatch**
  - Weather determines output
- **Variability**
  - Makes it more difficult to balance load
- **Uncertainty**
  - Can be forecasted to a large extent
- **Different electrical characteristics**
  - Lower inertia, voltage tolerance, reactive controls
  - Still compatible with the grid

Wind Turbine Technology Advancements

- **Low-Voltage Ride-Through**
  - Wind plants can contribute to system stability during a disturbance
- **Voltage Control Capability**
  - Capable of supplying reactive power at the point-of-interconnection
- **SCADA Integration**
  - Ability to provide frequency response
- **Wind Forecasting**
  - Reduces wind output uncertainty by using wind forecasts that incorporate meteorological data
  - Allows operators to anticipate wind generation levels and adjust other generators output

Balancing Area Size and Flexibility

- **BA functions**
  - Balance demand (load) & supply (generation)
  - Support interconnection frequency
  - Maintain desired level of interchange with other BAs
- **Larger BAs are generally more efficient**
  - More flexibility
  - BA consolidation being explored in some areas



Source: NERC

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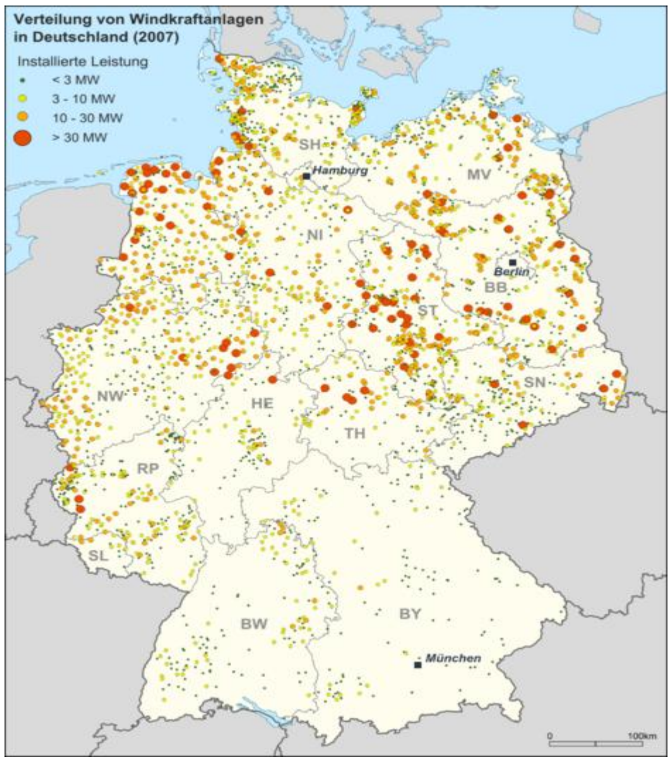
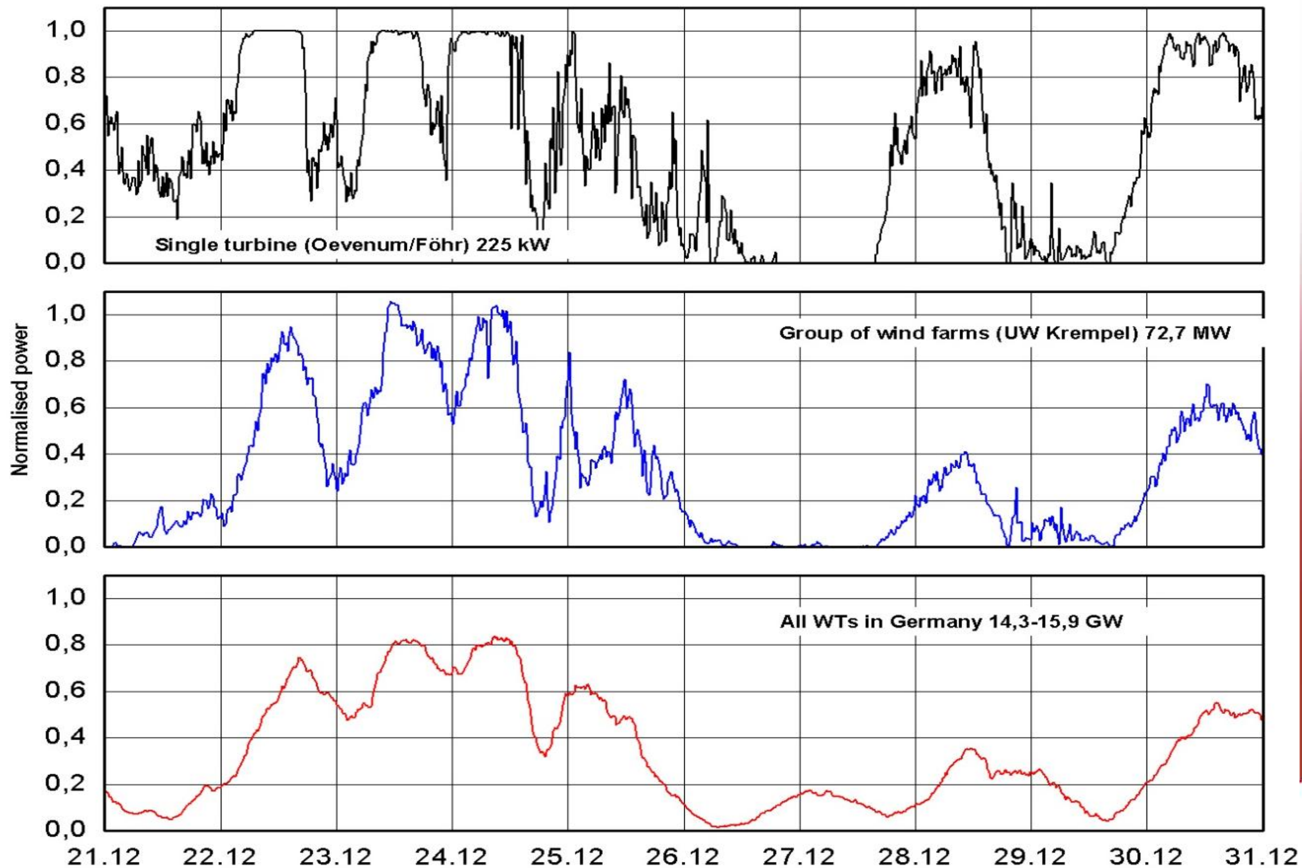
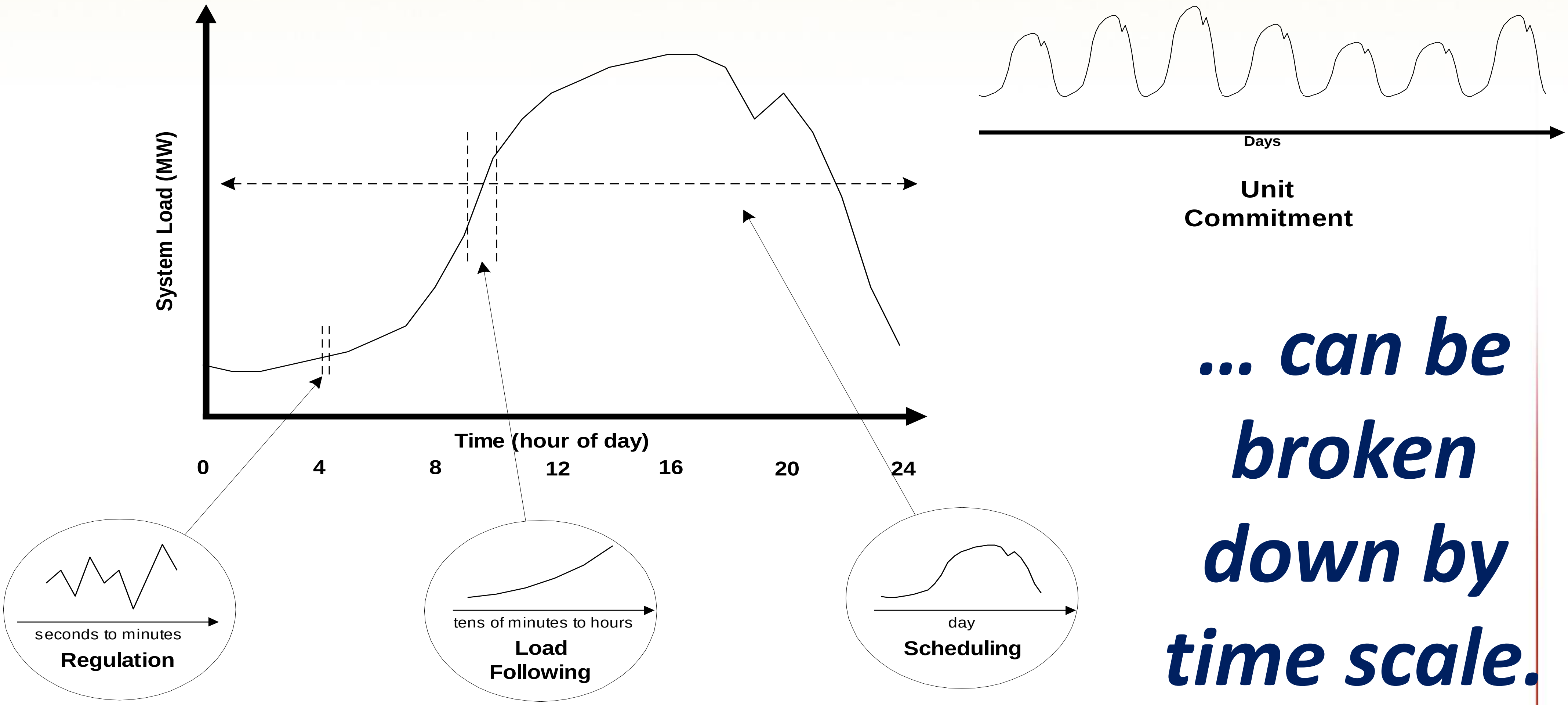
Geographic Diversity

- **Substantially reduces short-term and long term variability**





Cost of Wind Integration…



… can be broken down by time scale.

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Cost of Wind Integration is <0.5 cents/kWh

Source: UWIG

Date	Study	Wind Capacity Penetration (%)	Regulation Cost ($/MWh)	Load Following Cost ($/MWh)	Unit Commit-ment Cost ($/MWh)	Gas Supply Cost ($/MWh)	**Tot Oper. Cost Impact ($/MWh)**
May 03	Xcel-UWIG	3.5	0	0.41	1.44	na	**1.85**
Sep 04	Xcel-MNDOC	15	0.23	na	4.37	na	**4.60**
June 06	CA RPS	4	0.45*	trace	na	na	**0.45**
Feb 07	GE/Pier/CAIAP	20	0-0.69	trace	na***	na	**0-0.69*** **
June 03	We Energies	4	1.12	0.09	0.69	na	**1.90**
June 03	We Energies	29	1.02	0.15	1.75	na	**2.92**
2005	PacifiCorp	20	0	1.6	3.0	na	**4.60**
April 06	Xcel-PSCo	10	0.20	na	2.26	1.26	**3.72**
April 06	Xcel-PSCo	15	0.20	na	3.32	1.45	**4.97**
Dec 06	MN 20%	31**					**4.41****
Jul 07	APS	14.8	0.37	2.65	1.06	na	**4.08**

*** 3-year average; total is non-market cost**

**** highest integration cost of 3 years; 30.7% capacity penetration corresponding to 25% energy penetration; 24.7% capacity penetration at 20% energy penetration**

***** found $4.37/MWh reduction in UC cost when wind forecasting is used in UC decision**

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Grid Issues: Summary

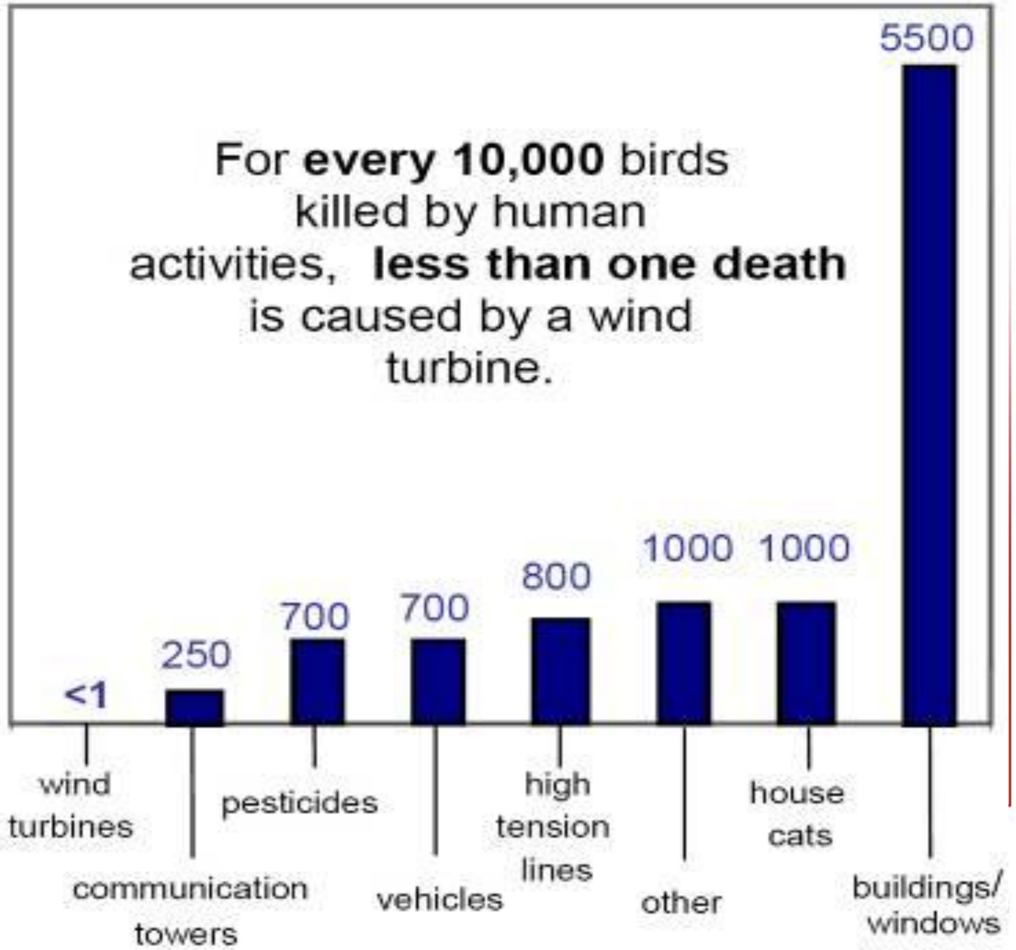
- **Grid Integration of wind has technical and cost impacts**
  - Reasonable 25% penetration level by energy
  - Dedicated “backup generation” or storage **<u>not required</u>**

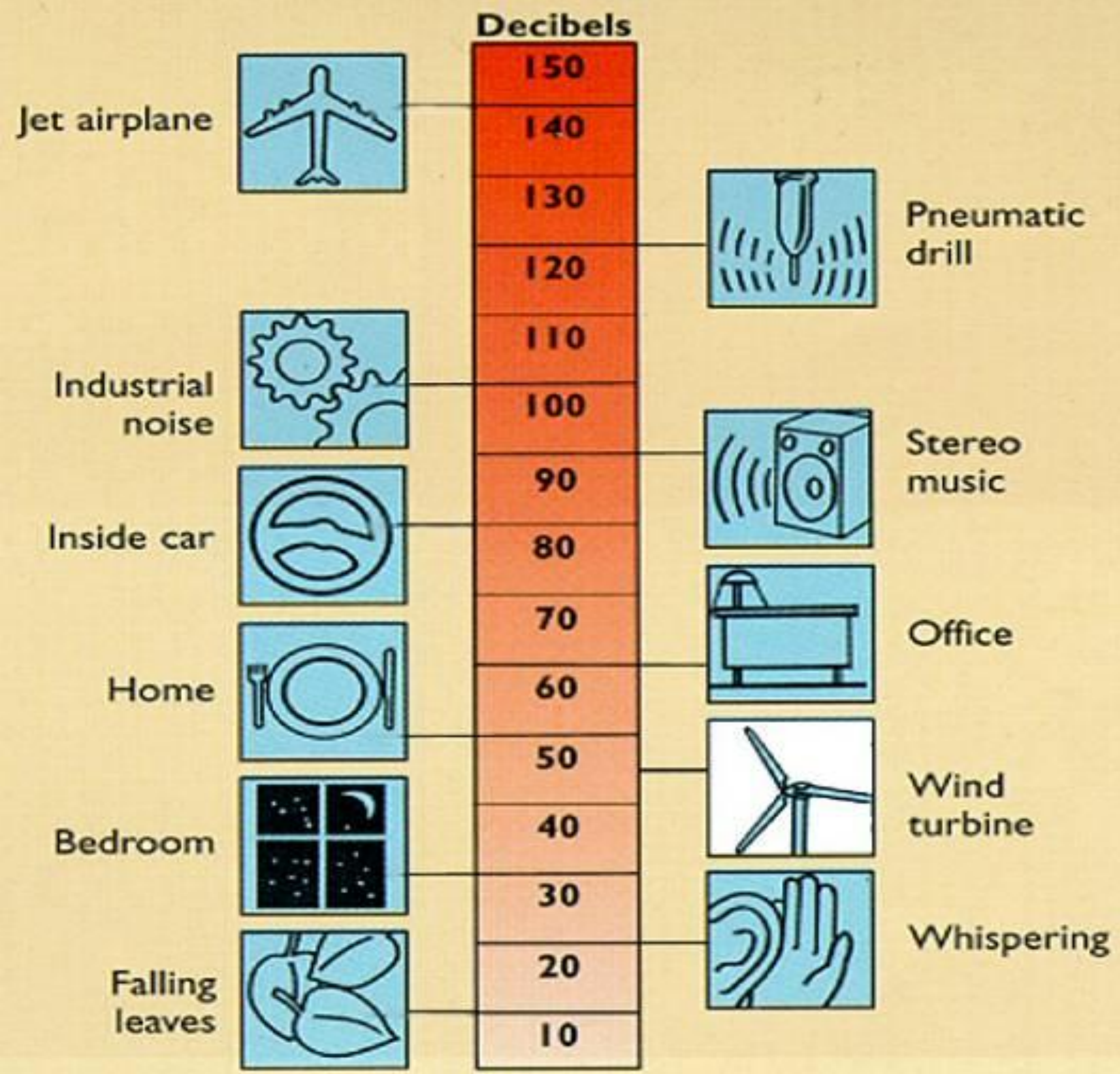
- **Things that can be done to reduce impacts**
  - Geographical diversity
  - Better forecasting and implementation in operations
  - Larger balancing areas
  - More flexibility with generation (and load)
  - Perform detailed wind integration studies

WHAT DO PEOPLE REALLY CARE ABOUT?

Bird Collisions & Mortality

- **Problem documented in Altamont Pass**
  - One of nation's largest concentrations of federally-protected raptors
  - Abundant prey base (migration path)
  - Heavy year-round raptor use





Acoustic Emission: Noise

Mod 1

Boone, NC

AWEA

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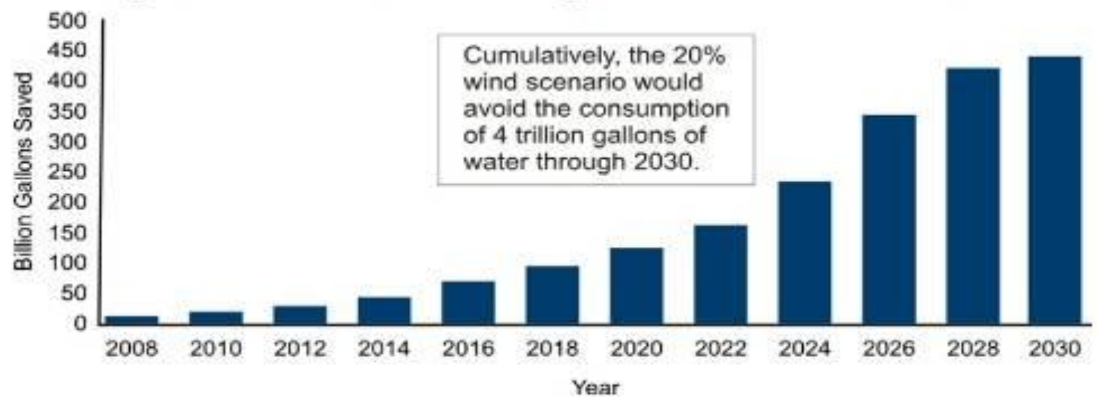
Benefits of Wind Power

- Economic Development
  - Jobs, lease payments, tax revenue
- Cost Stability
- Resource Diversity
  - Domestic, inexhaustible, reduced risk
- Environmental
  - no CO_2, SO_2, NO_x, mercury
  - no mining or drilling
  - no water use

Figure 1-14. National water savings from the 20% Wind Scenario



World-Wide Growth in Energy Demand Will Require all Available Energy Technology Options Integrated into a System

- **A complete portfolio of supply options: renewables, fossil, nuclear**
- **Highly efficient and environmentally benign technologies**
- **Fault-tolerant, self-healing infrastructures**
- **Enhance physical and cyber security and safety**

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Questions?

The view from 250 feet…

… is encouraging

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