SAND2007-7089C

Technology Overview:

The Fundamentals of Wind Energy

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Albuquerque, NM, USA

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Carlsbad, CA

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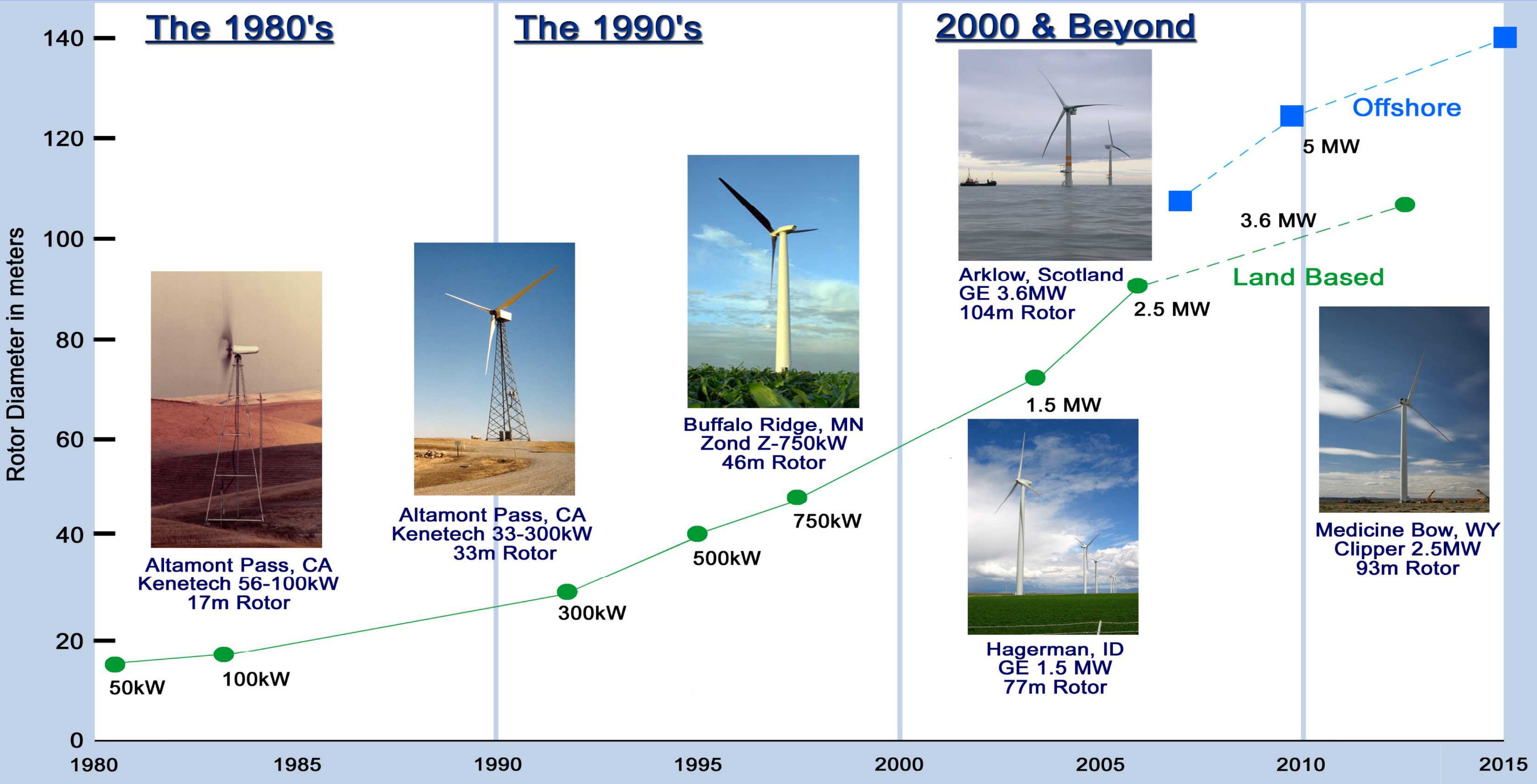
…based on previous presentation by Sandy Butterfield
National Wind Technology Center - Chief Engineer

- Turbine design evolution
- Typical modern wind turbine
- Performance
  - Aerodynamics
  - Power & Energy
  - Availability & Capacity factor
- Component Technology
  - Drive Train
  - Blades
  - Electrical Generation
- Offshore turbines

Evolution of U.S. Commercial Wind Technology



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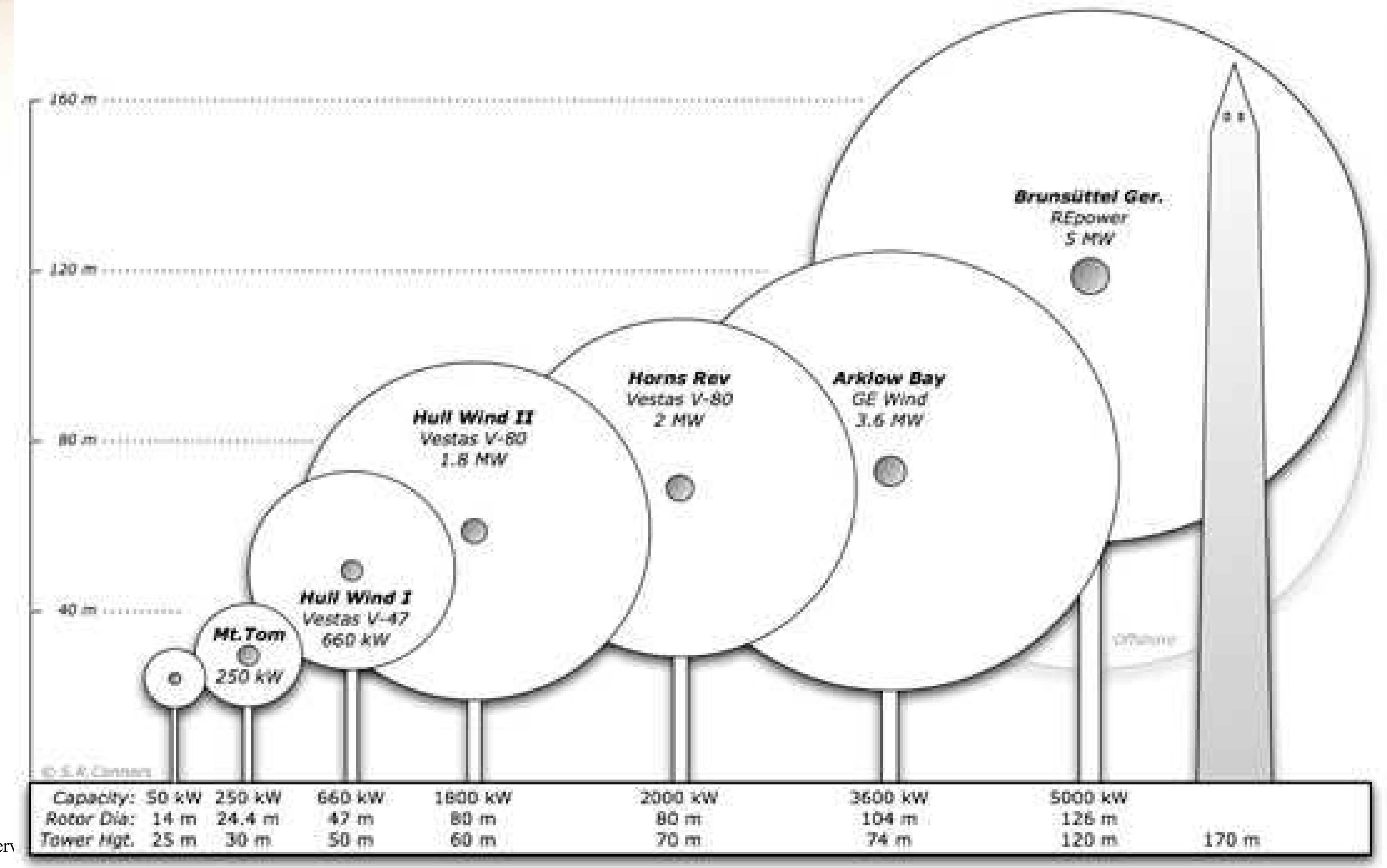
Wind Turbine Size



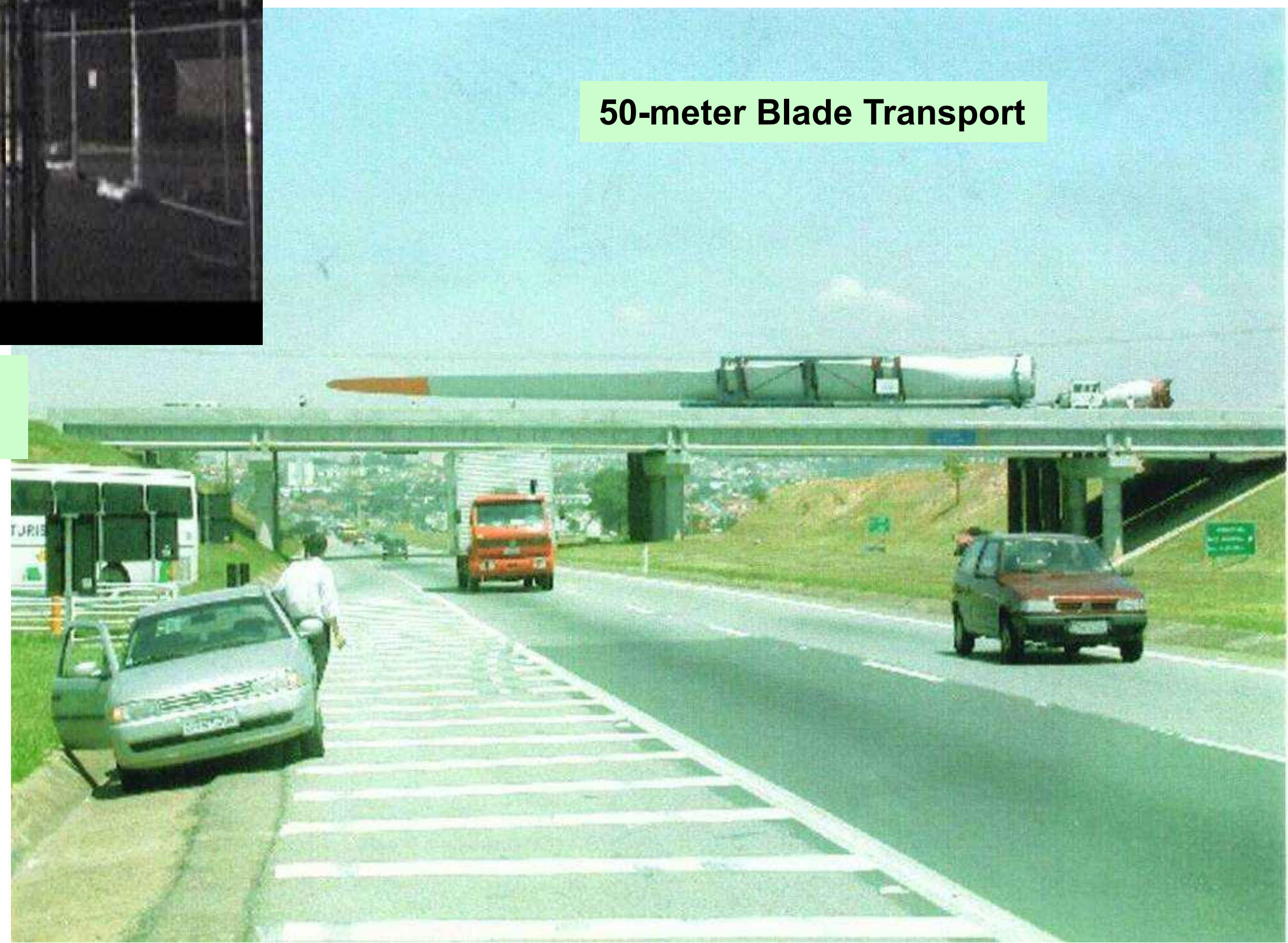
Logistics become difficult as size increases

2004

45-meter Blade Fatigue Test

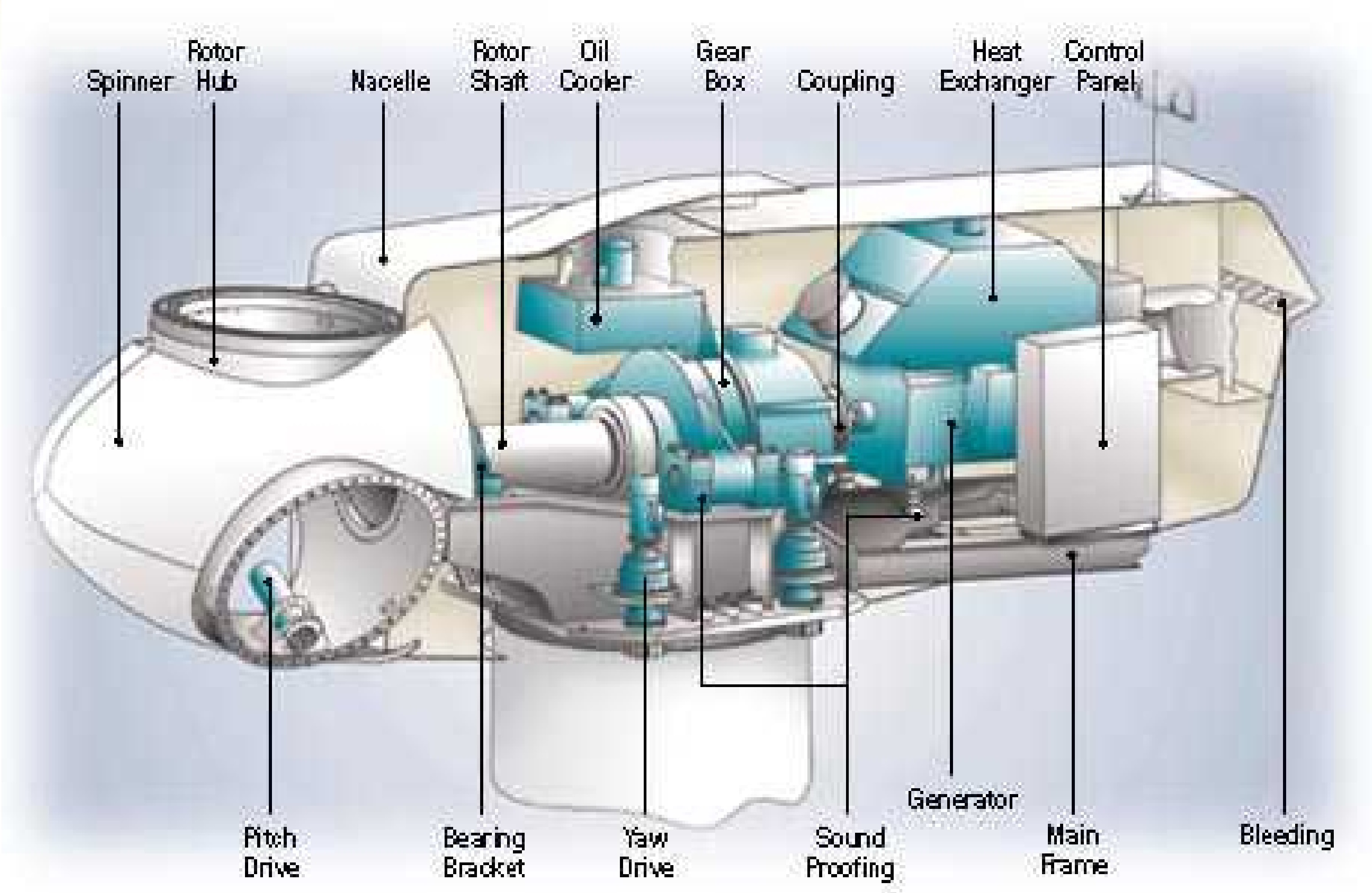
Single-axis Flap Fatigue Test Using B-REX Test System.

45-meter Blade Root Mount



50-meter Blade Transport

Typical Modern Turbine



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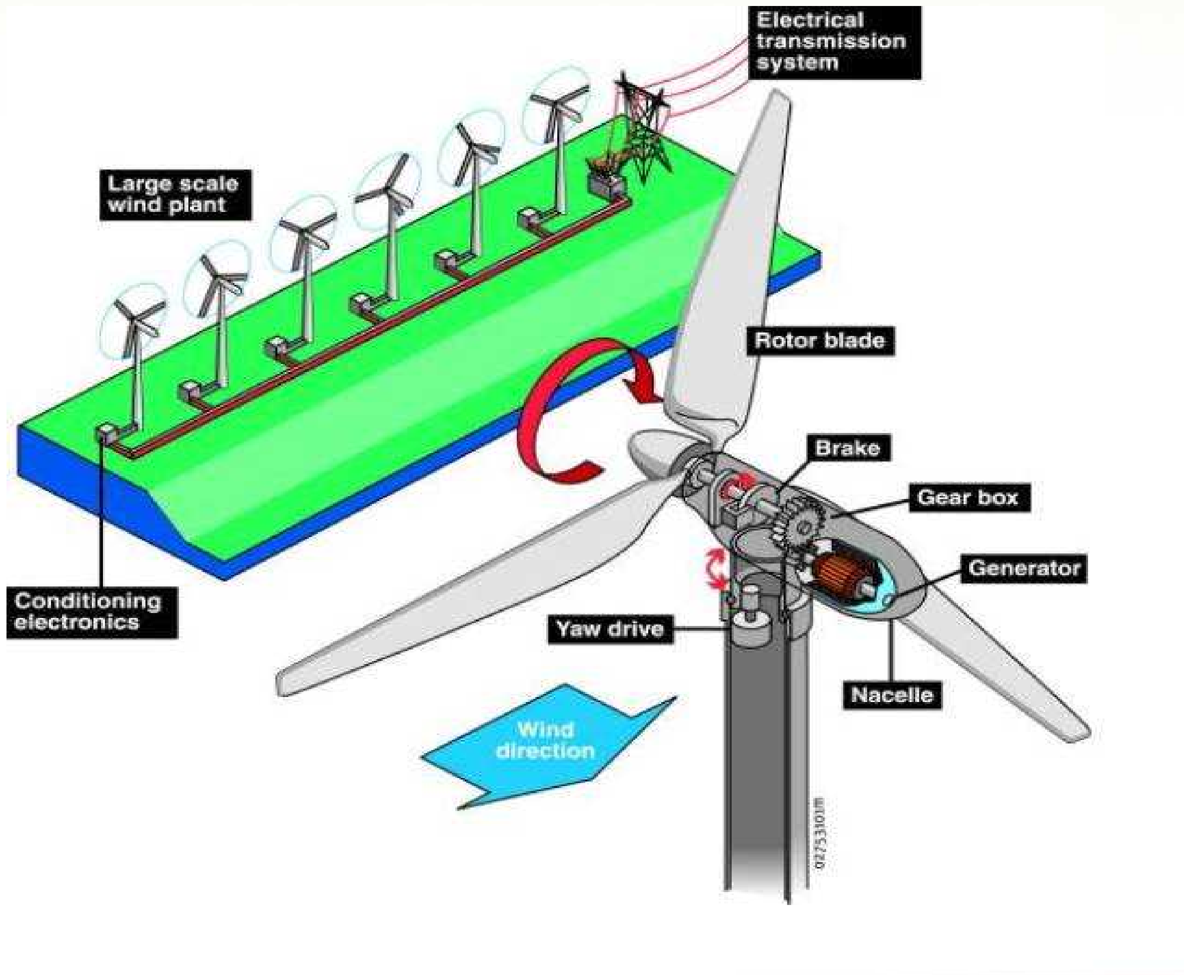
Typical Wind Farm Components

- Turbine
- Foundations
- Electrical Collection System
- Power quality conditioning
- Substation
- SCADA
- Roads
- Maintenance facilities



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Wind Power Basics

Air Density · **Rotor Area** · **Wind Speed**

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

Wind Power output is proportional to wind speed cubed.

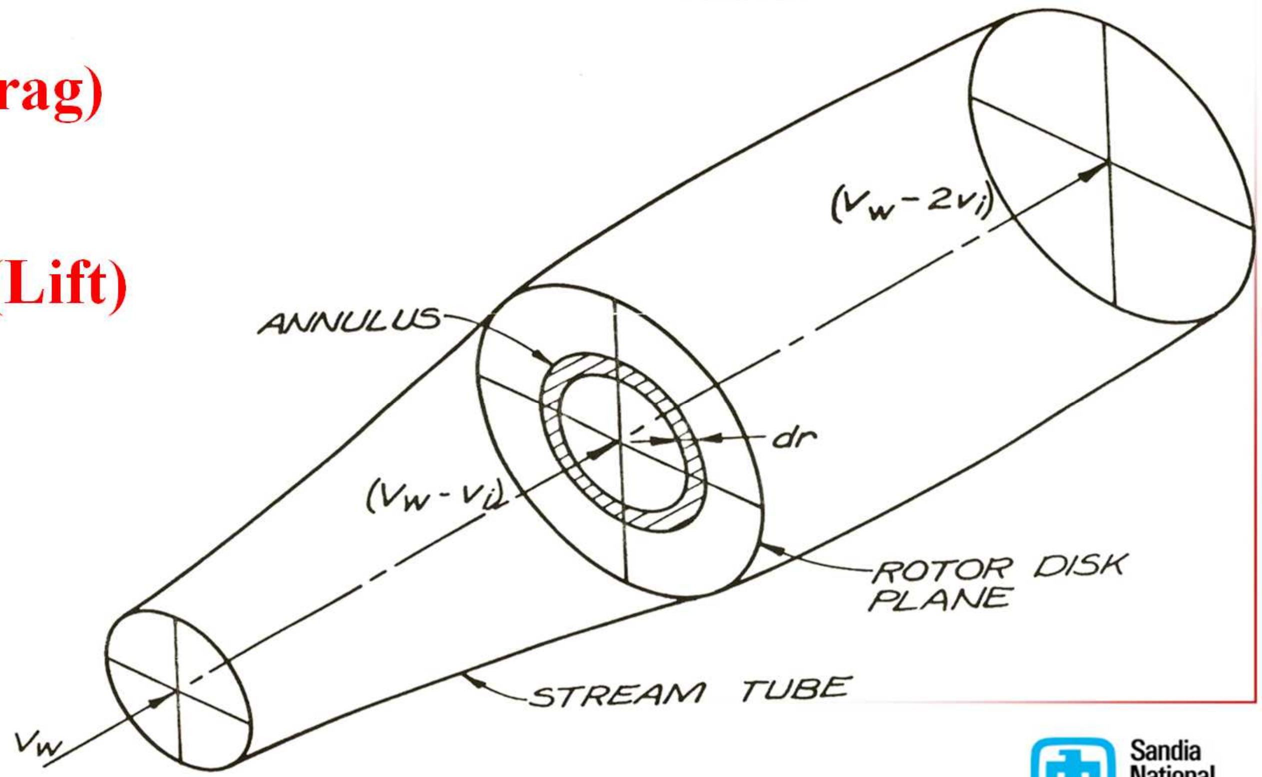
$$C_{P\max} \cong 0.3 \text{ (Drag)}$$

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

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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Visualizing the flow through the rotor

NASA Ames 80’ by 120’
Wind Tunnel Test

Tip Speed Ratio
is

$$\frac{\text{Tip-speed}}{\text{Wind-speed}}$$

Field Test

Smoke Test

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Aerodynamic Efficiency for Various Rotor Designs

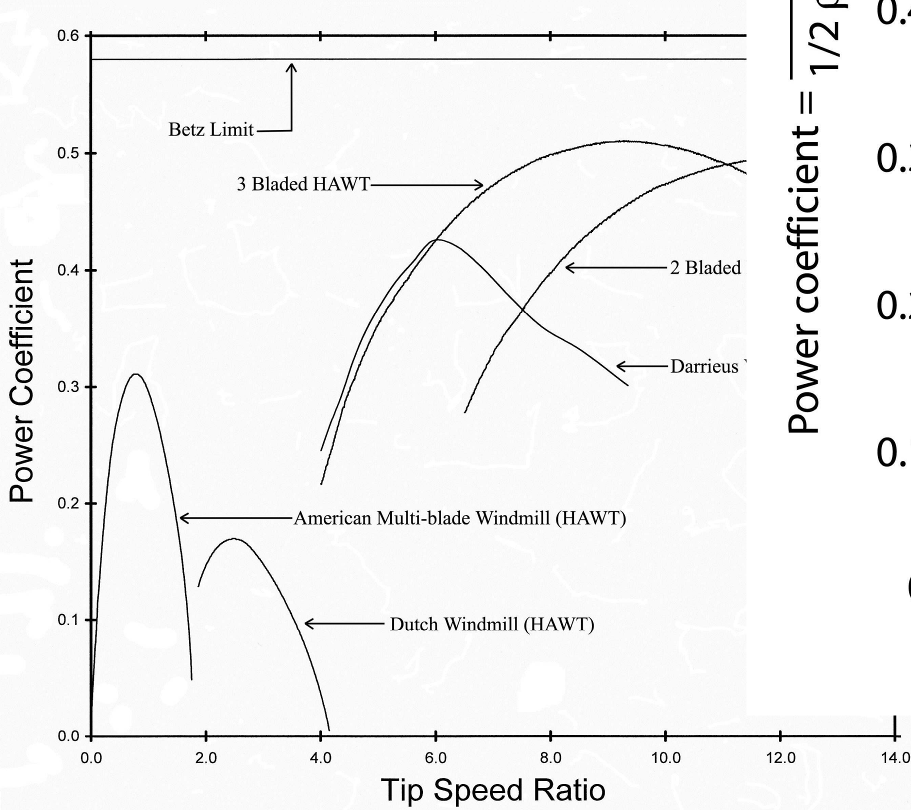
•Low solidity/high tip speed ratio = high efficiency

•High solidity/low tip speed ratio = high torque

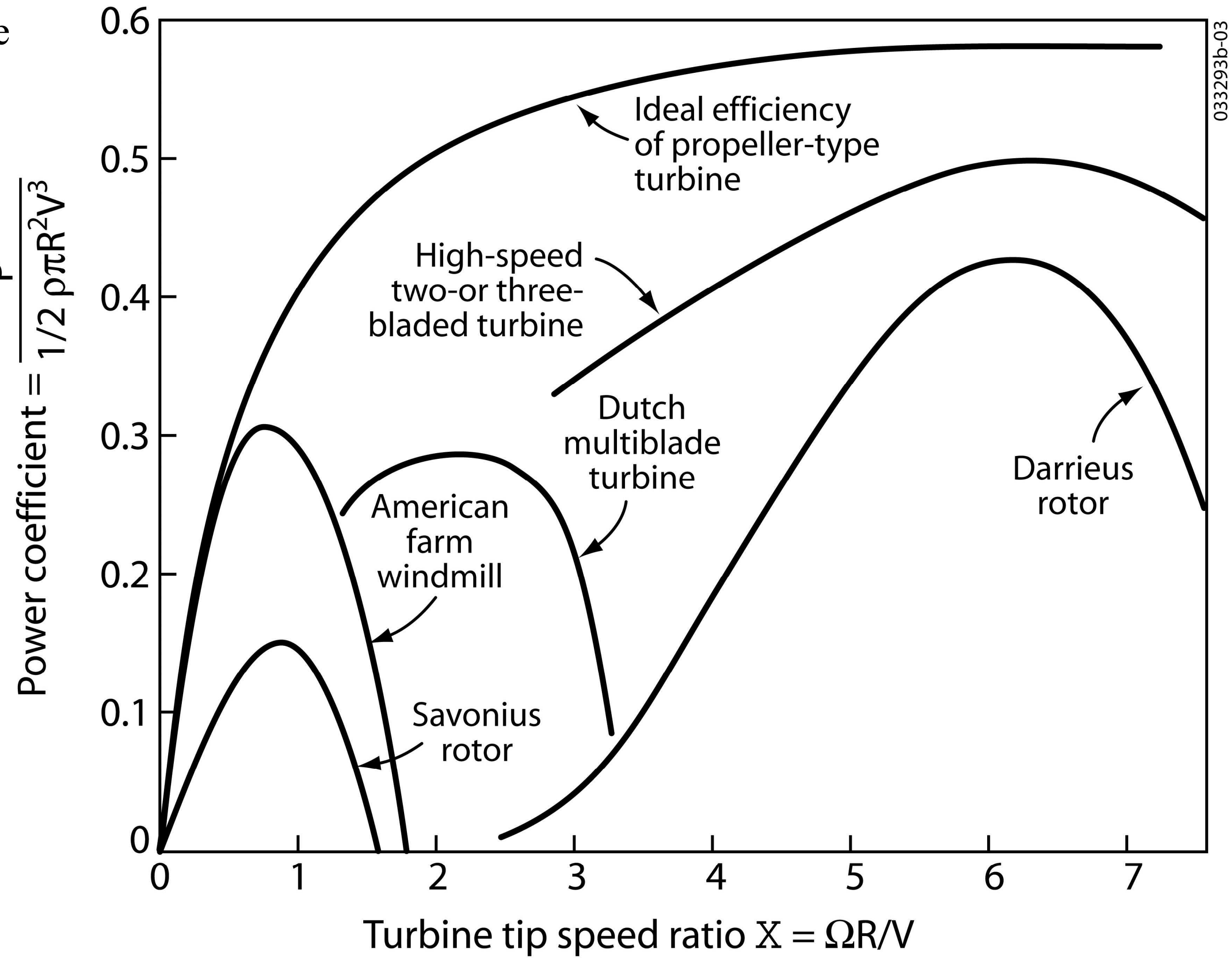
Where: Solidity = blade area / swept area

TSR = tip speed/wind speed

New data ~2005



Old estimates ~1975



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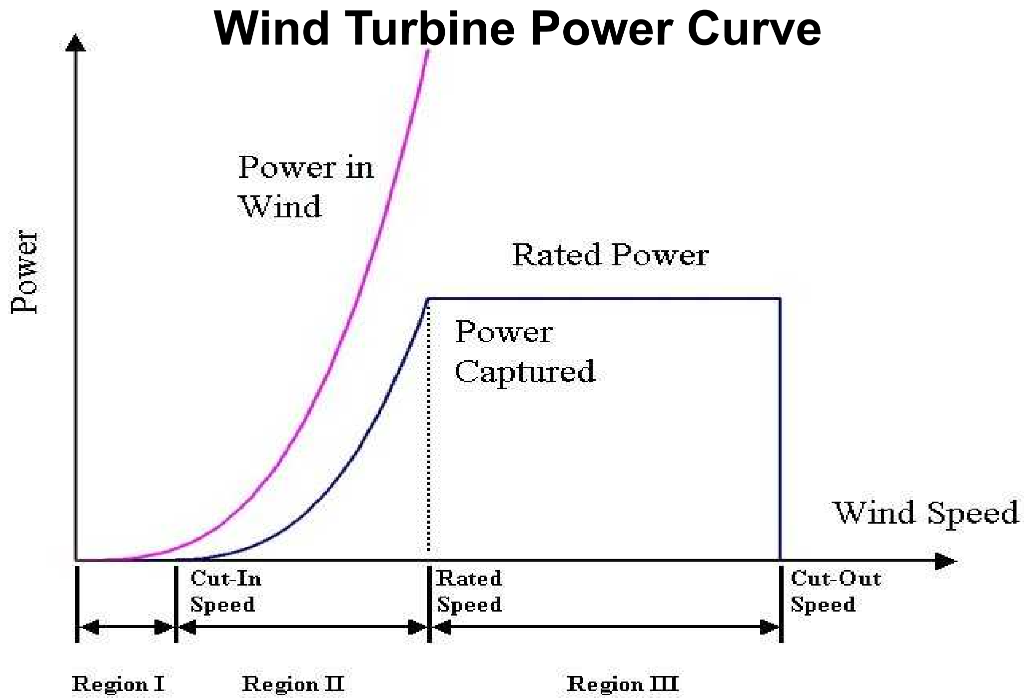
Turbine Power Basics

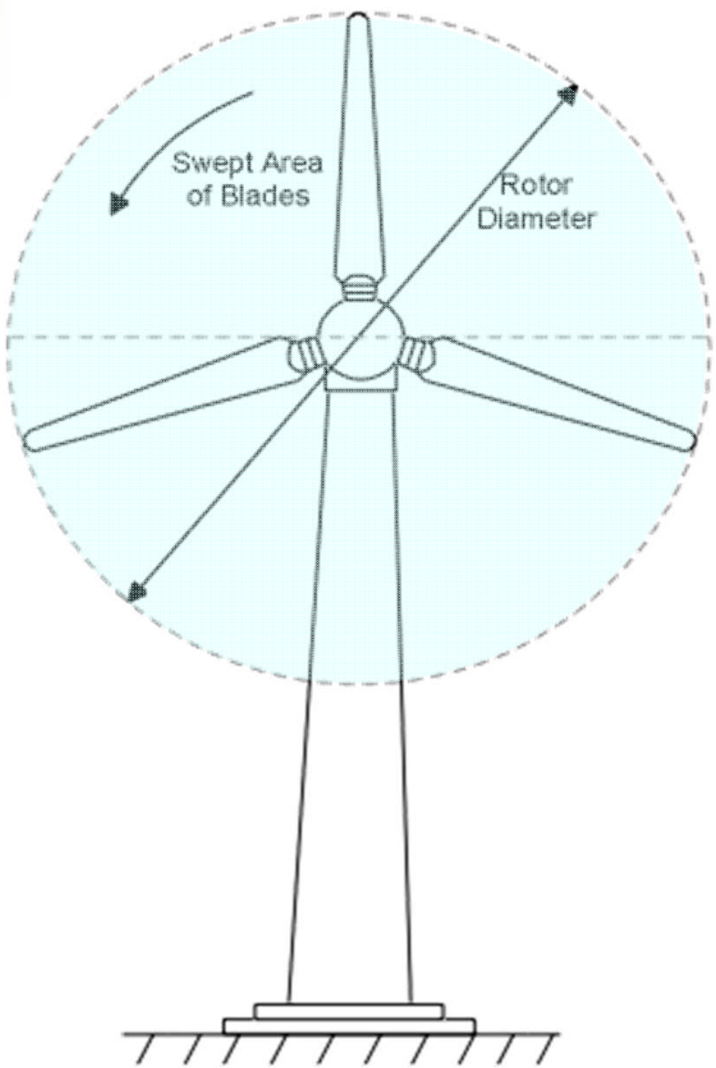
Three Regions of the Power Curve

Region I – not enough power to overcome friction

Region II – Operate at maximum efficiency at all times
Constant Tip Speed Ratio (TSR)

Region III – Fixed power operation





The Wind Resource can be described using Probability Distributions

- **Rayleigh**
- **Weibull**
- **Measured**

$$P_R(V_0) = 1 - \exp\left[-\pi\left(V_0/2V_{ave}\right)^2\right]$$

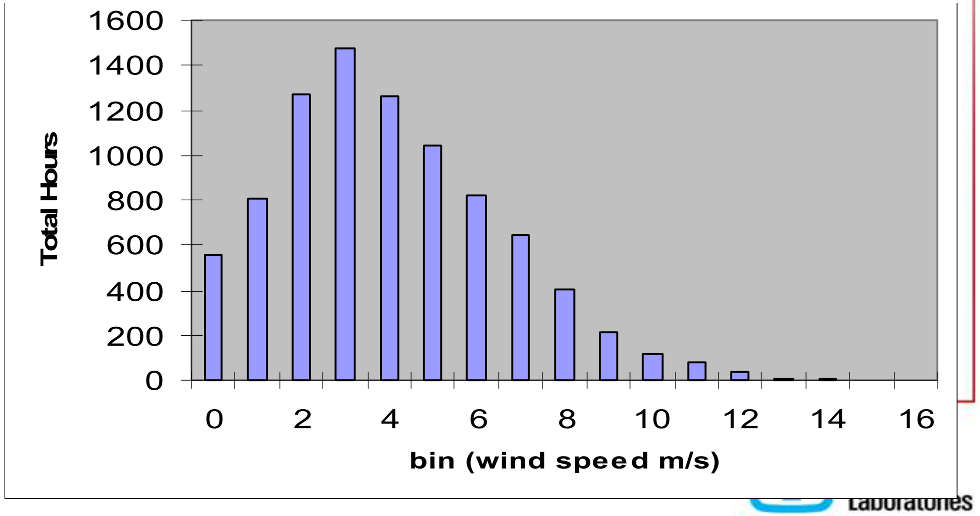
$$P_w(V_0) = 1 - \exp\left[-\left(V_0/C\right)^k\right]$$

with $$V_{ave} = \begin{cases} C\,\Gamma\left(1+\frac{1}{k}\right) \\ C\sqrt{\pi}/2, \text{ if } k=2 \end{cases}$$

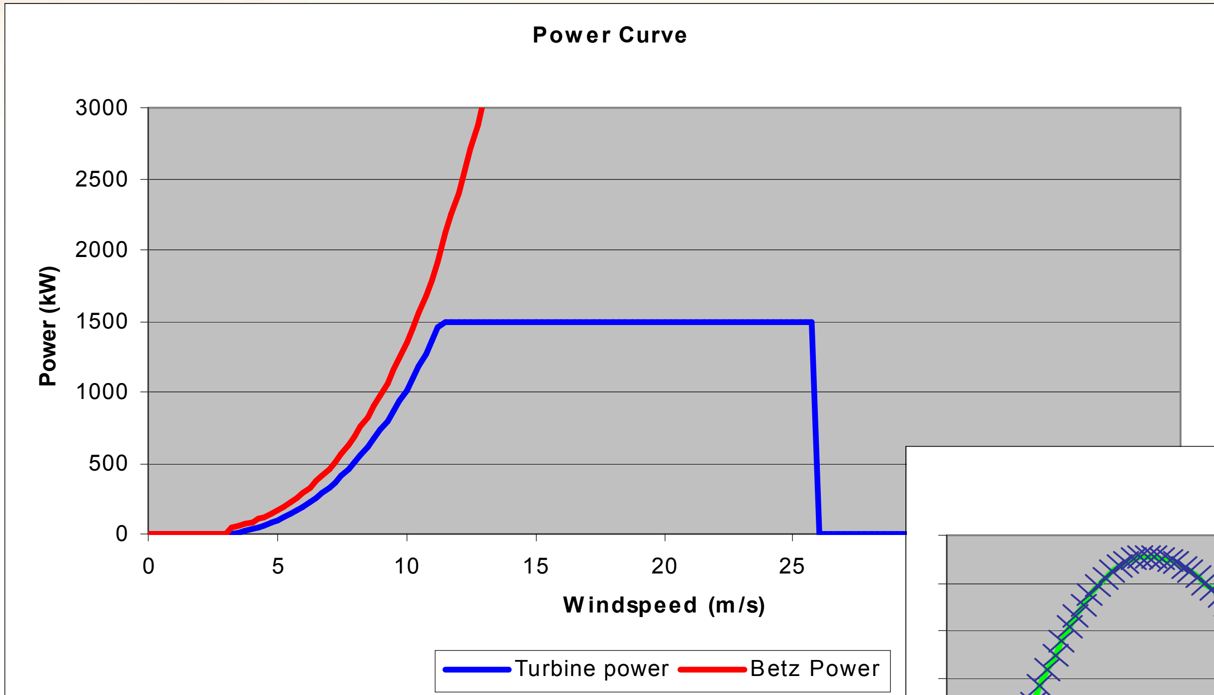
where

- $P(V_0)$ is the cumulative probability function, i.e. the probability that $V<V_0$
- V_0 is the wind speed
- *Vave* is the average value of V
- C is the scale parameter of the Weibull function
- k is the shape parameter of the Weibull function
- Γ is the gamma function

Both *C* and *k* can be evaluated from field data.

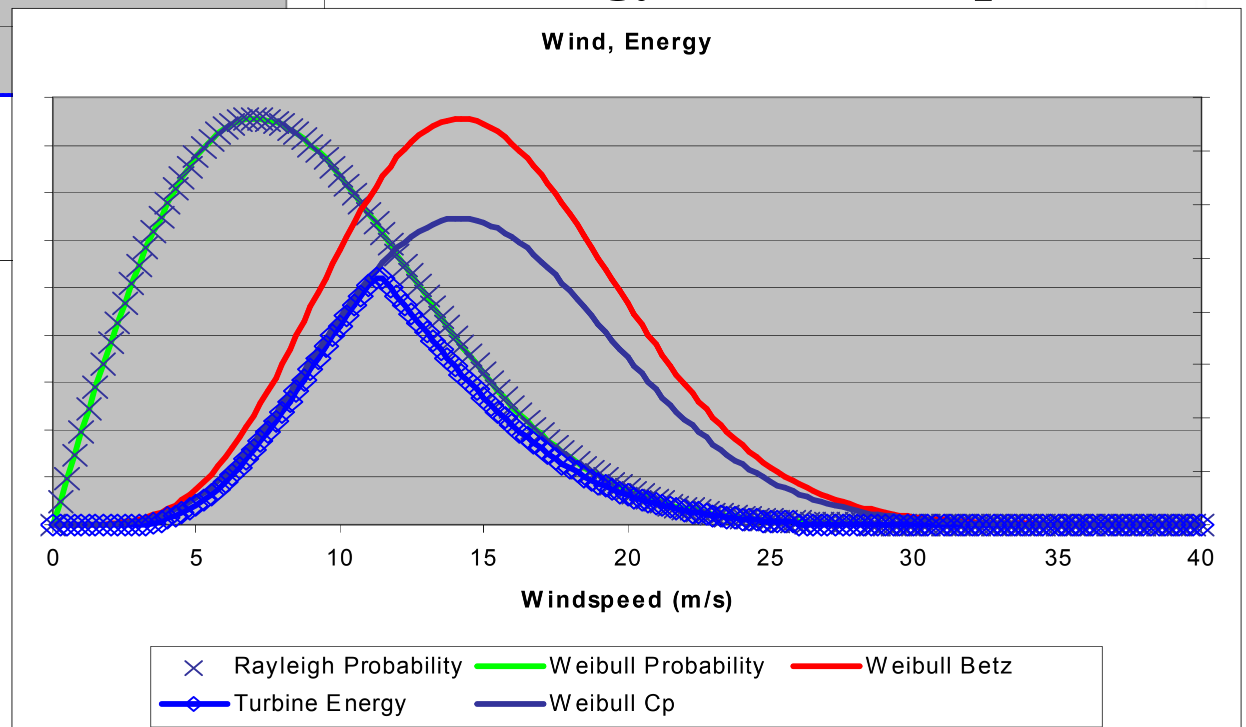


Multiplying the power curve by the annual distribution of wind speed yields annual energy



*Operating at rated power allows some energy to pass through.

Energy vs. Wind Speed

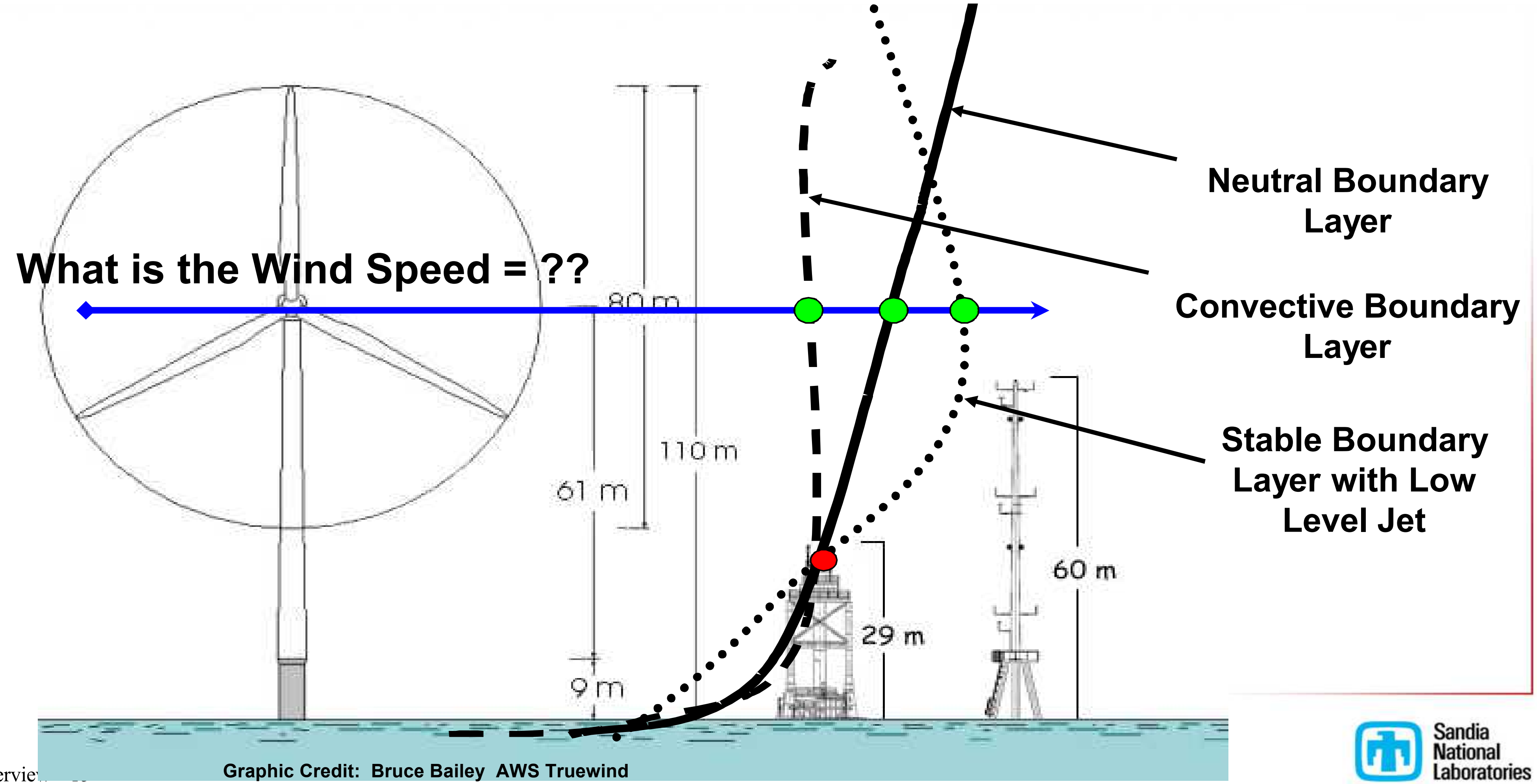


Power vs. Wind Speed

15 mph (6.8 m/s) average wind speed

Understanding Wind Shear

- **Long term wind measurements typically made lower than hub height.**
- **How do we correct for to hub height?**
- **Earths boundary layer changes with time and location – stable vs. unstable, wind shear variations**



Graphic Credit: Bruce Bailey AWS Truewind

Equations for Long Term Average Wind Shear

- **Logarithmic**
- **Power Law**

Where:

- $V(z)$ is the wind speed at height z
- z is the height above ground
- Zr is a reference height above ground used for fitting the profile
- Zo is the roughness length
- *α is the wind shear (or power law) exponent (assume 1/7)*

$$V(z) = V(z_r) \cdot \frac{\ln(z/z_0)}{\ln(z_r/z_0)}$$

$$V(z) = V(z_r) \cdot \left(\frac{z}{z_r}\right)^a$$

Simple Energy Calculations

Step One

Estimate Wind Resource

- **Rayleigh Distribution**
- **Average Wind speed**
- **Time at each wind bin**

Step Two

Choose Turbine

- **Published Power Curve**
- **Adjust wind data to hub height**
- **Adjust for air density (altitude)**

Step Three

Estimate Annual Energy

- **Convolve Power Curve & wind distribution across wind speeds**
- **Sum across wind speed bins for total energy**

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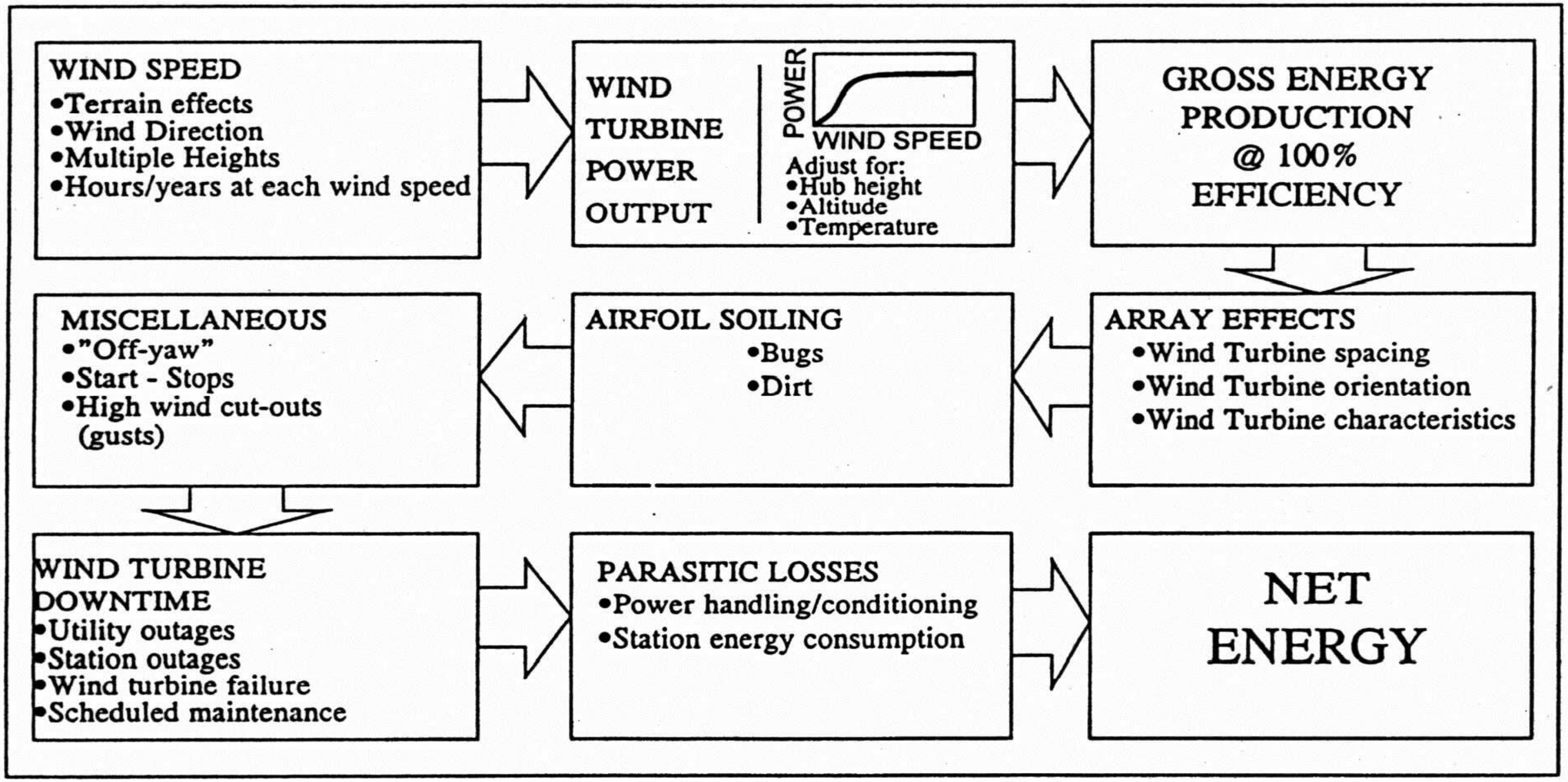
Net Energy Calculations



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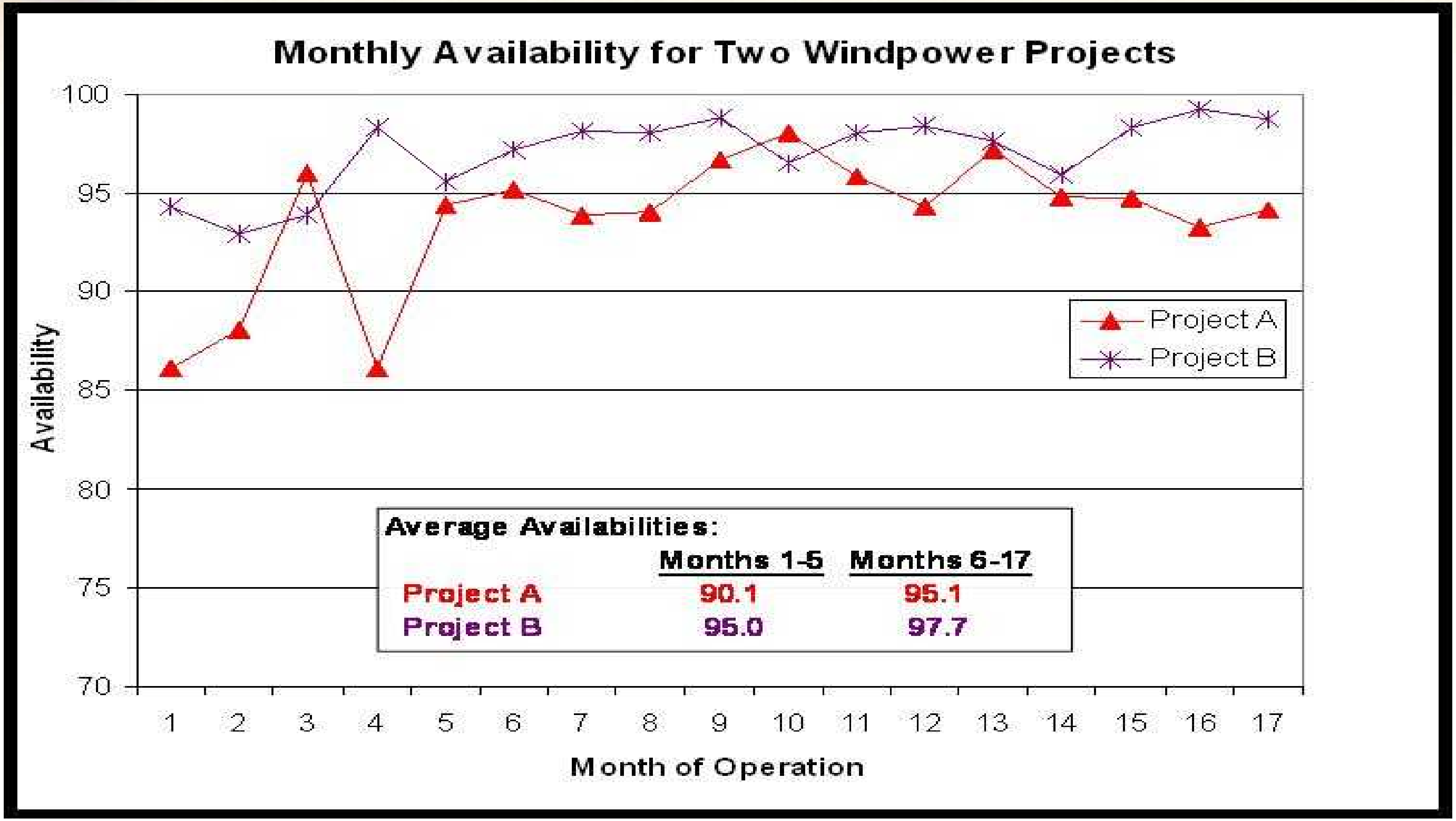
Availability



Simple Definition:

- **Availability = turbine available time/total time**

More detailed definitions are commonly used in contracts

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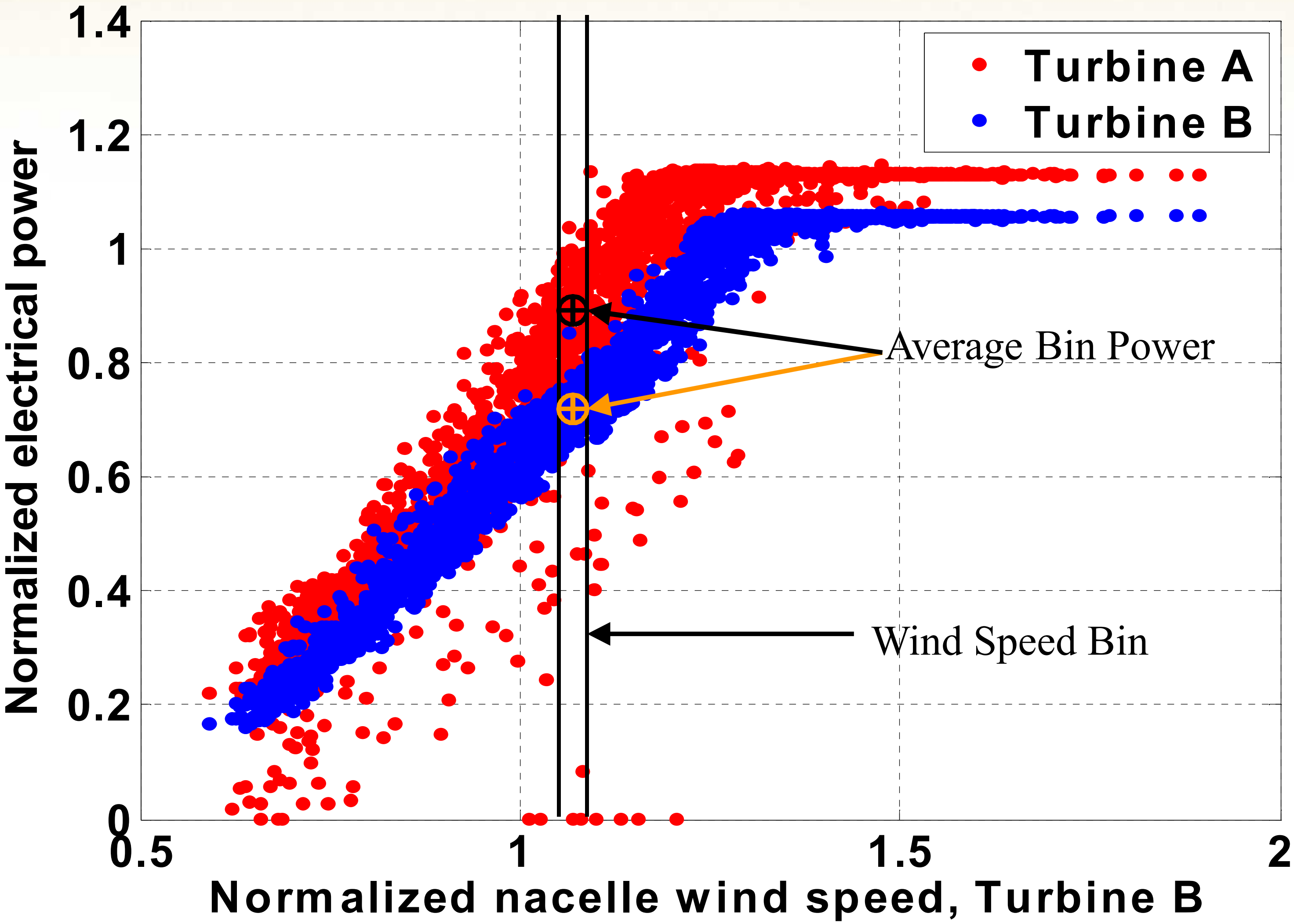
Typical Measured Power Curves



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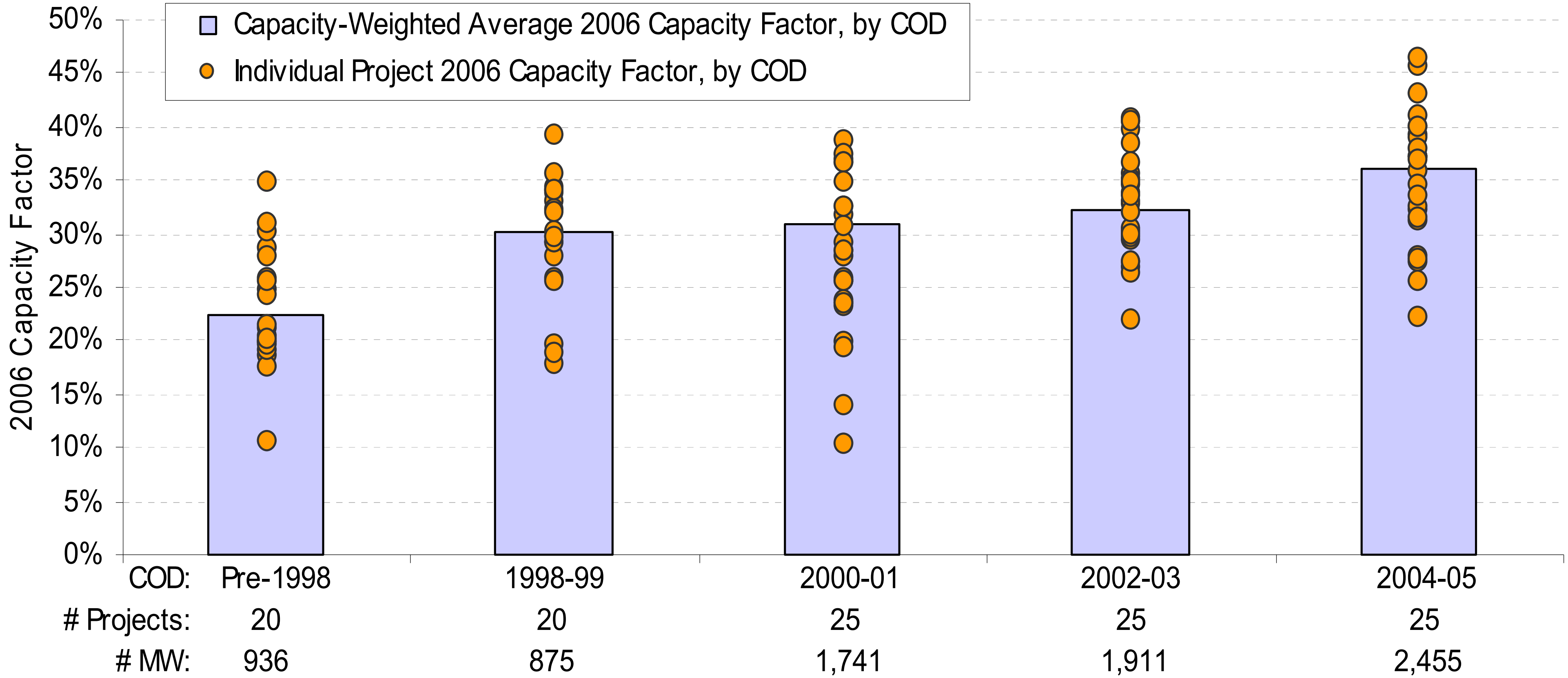
Reported Capacity Factors



Source: Berkeley Lab database

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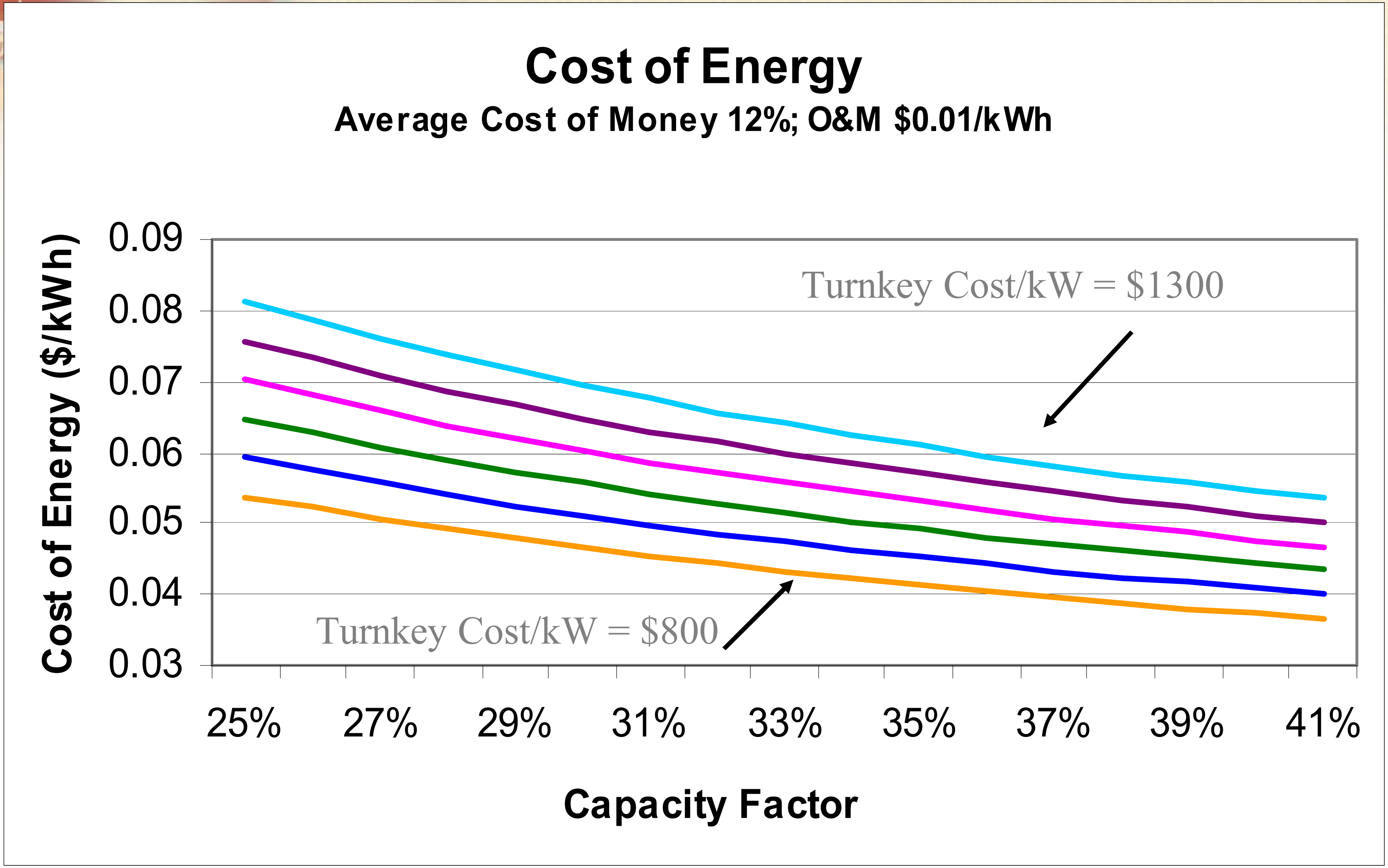
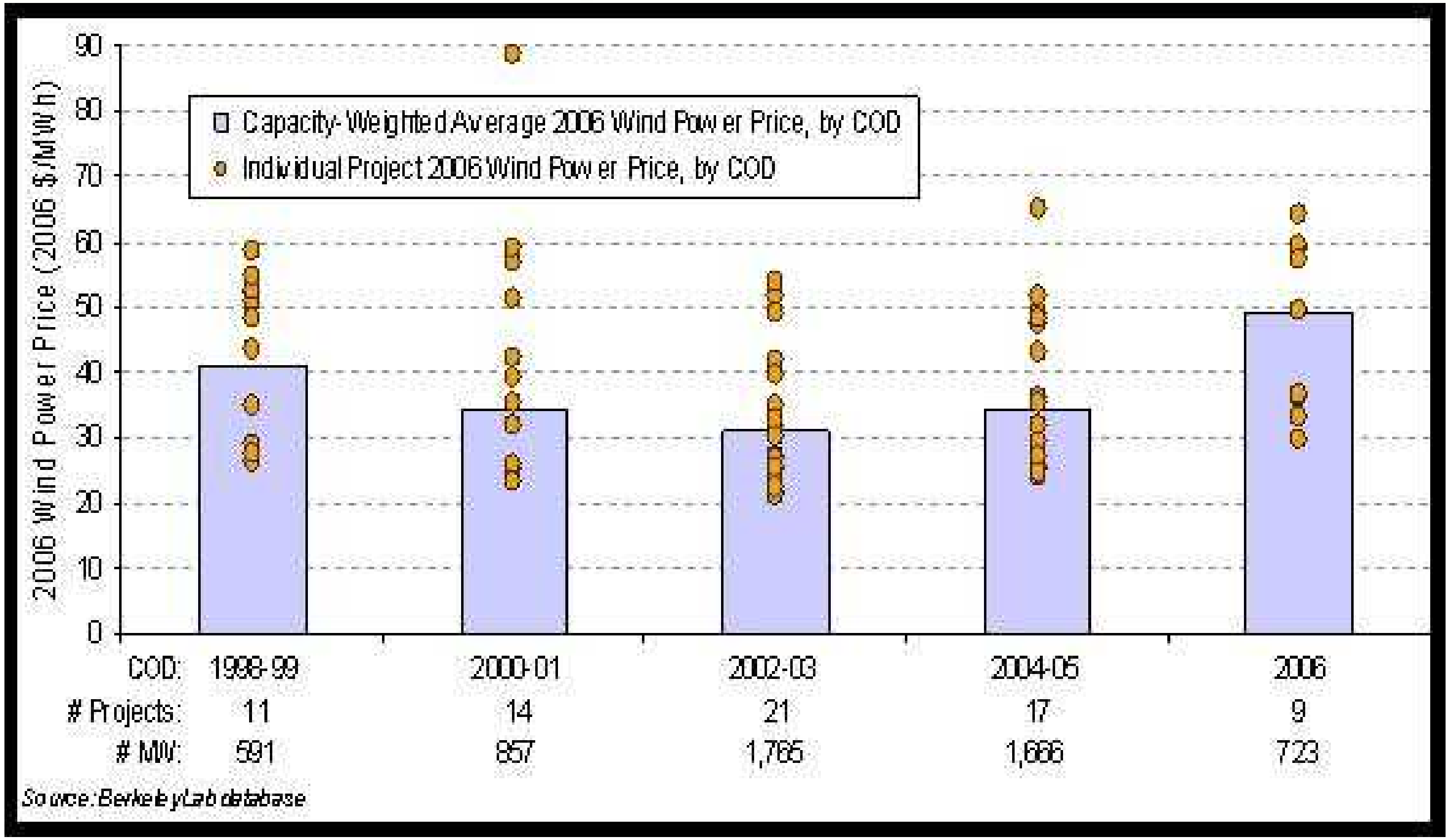


CF = Generated Energy in a period of time / (Rated Power x Time period)

Cost of Energy: Sales Prices



Rising prices are caused by:

- Weak Dollar
- Growing commodity prices
  - steel
  - copper
  - concrete
- Limited availability of machines

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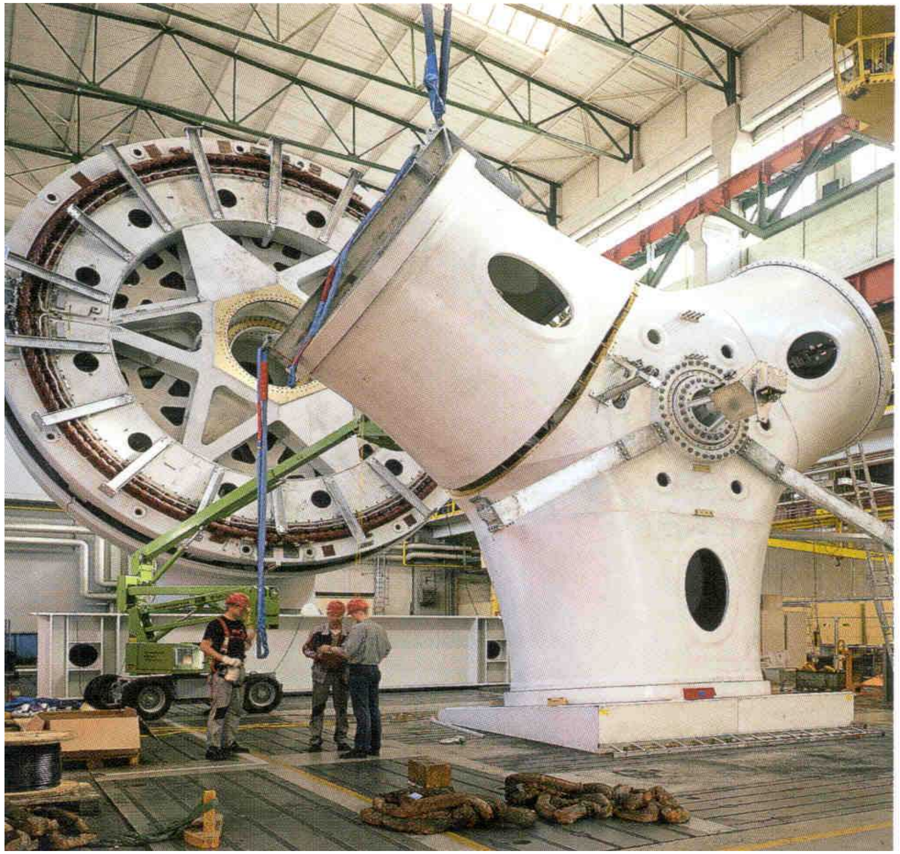
Drive Train Technology

Enercon 4.5MW 112 meter rotor



Direct Drive

440 metric tonnes

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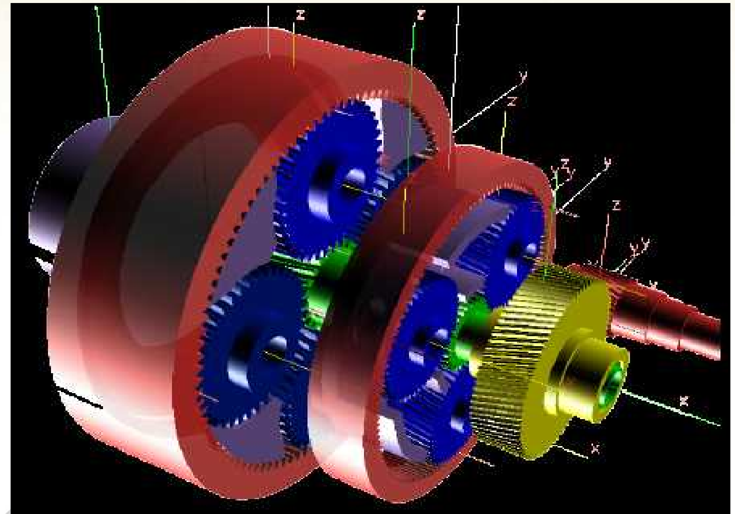
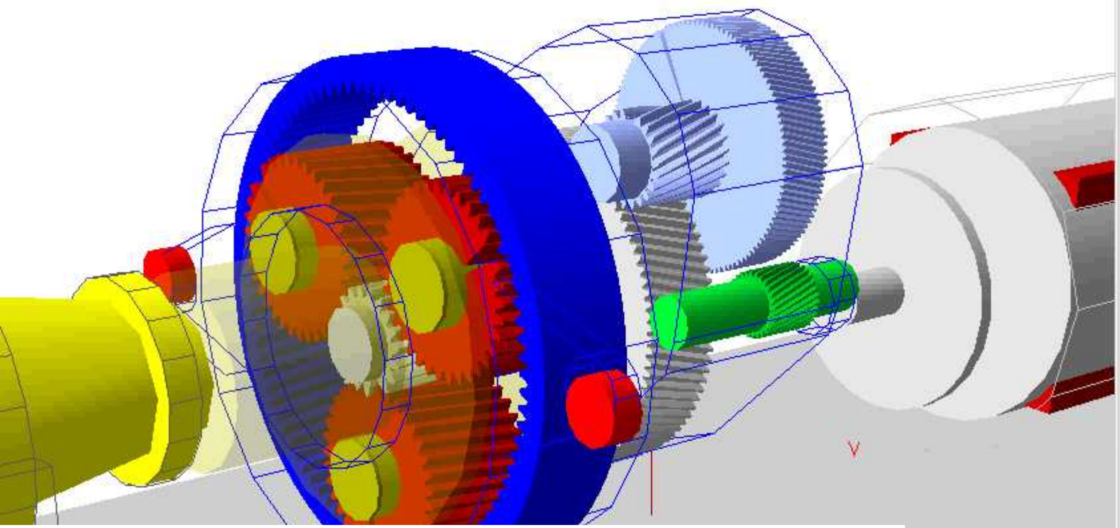
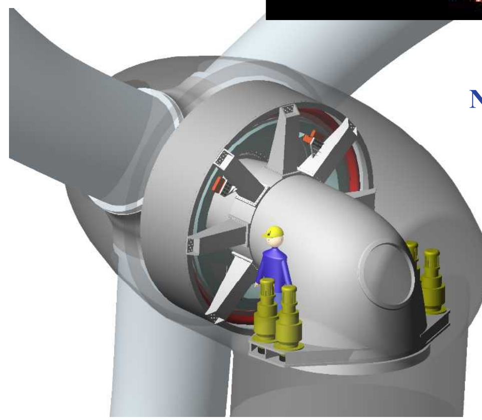
Drivetrain Technology



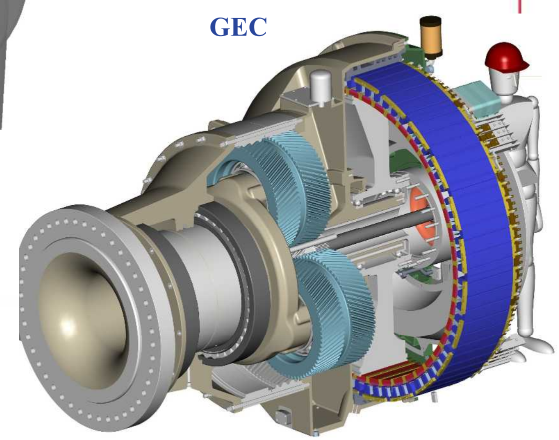


Multibody-System-Simulation
SIMPACK User Meeting 2004 – Wartburg / Eisenach
Dipl.-Ing. Tobias Schulze, 09./10. November 2004

NPS



GEC



2.5 MW Clipper Drive Train

- Light weight
- Multiple torque path
- Modular
- Efficient Permanent Magnet Generators
- Power conditioning

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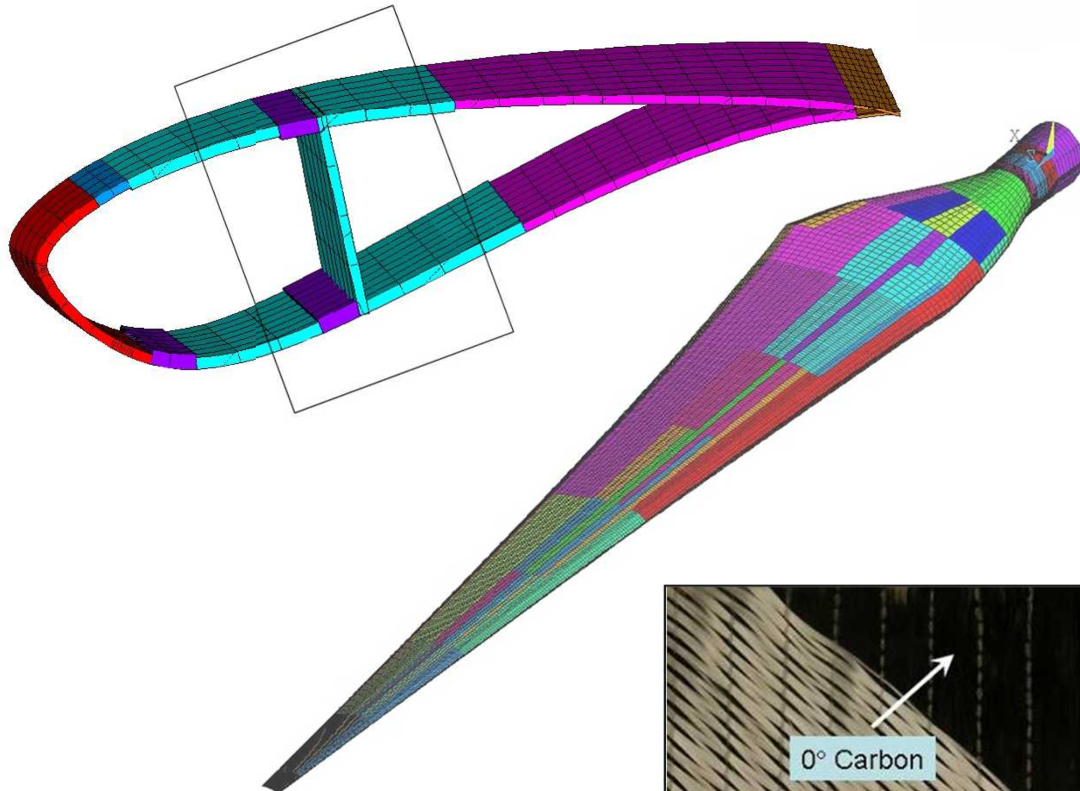
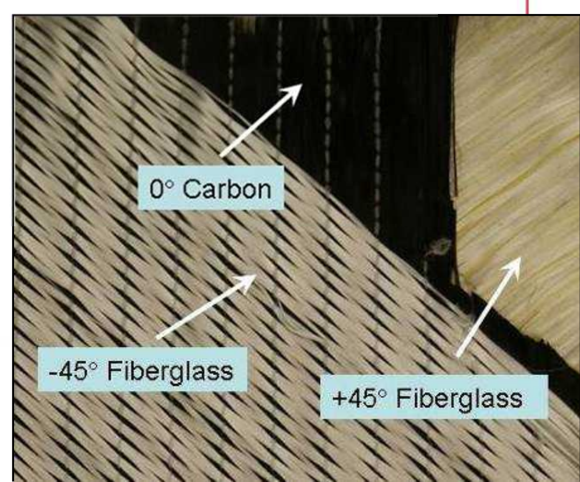
Blade Technology

- **Composite construction**
- **Based histrically on boat-building technology**
- **New high-tech materials are emerging (Carbon fibers)**
- **Massive construction**

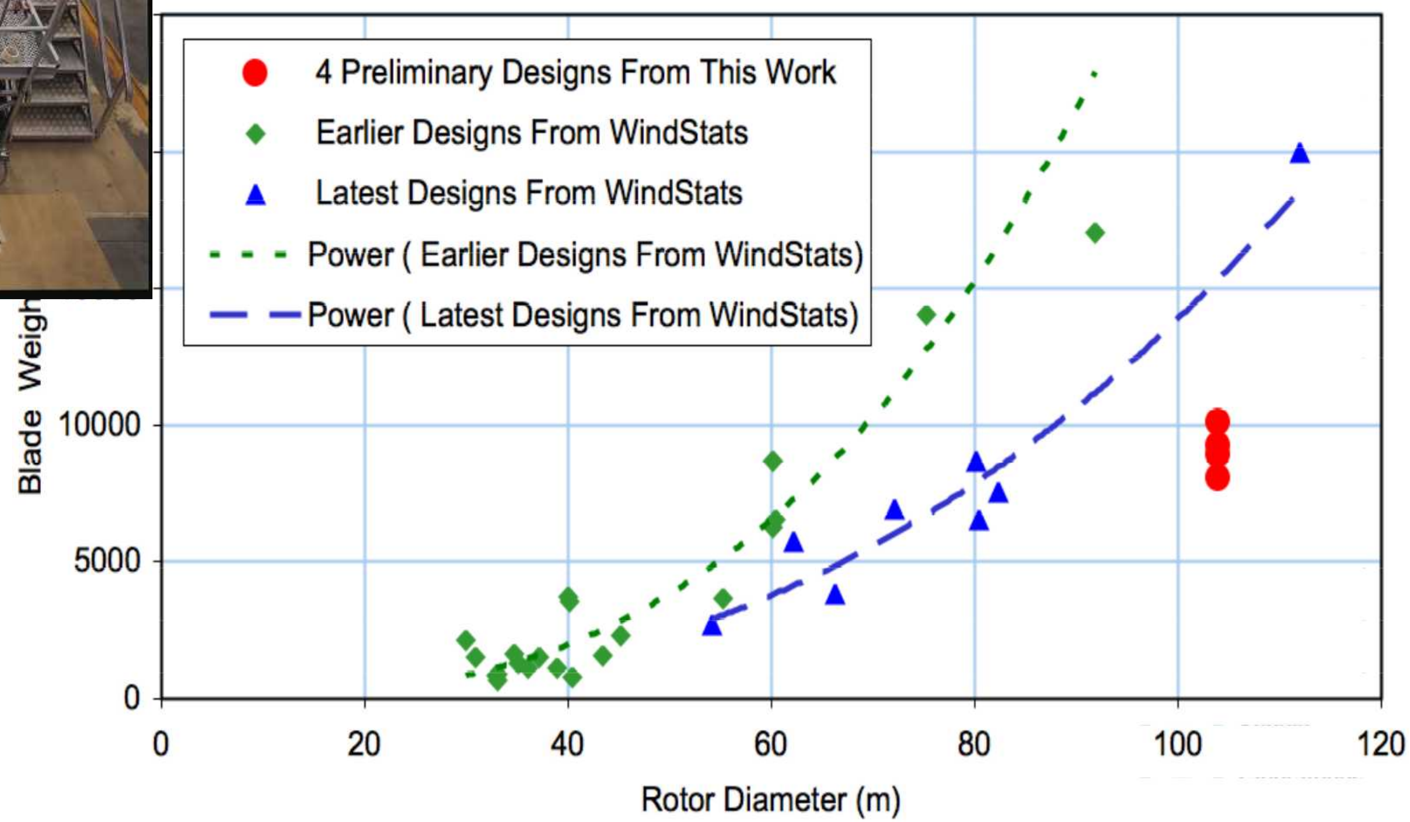




SAERTEX Glass/Carbon Triax used in SNL 9 m Blades

Courtesy LM Glassfiber

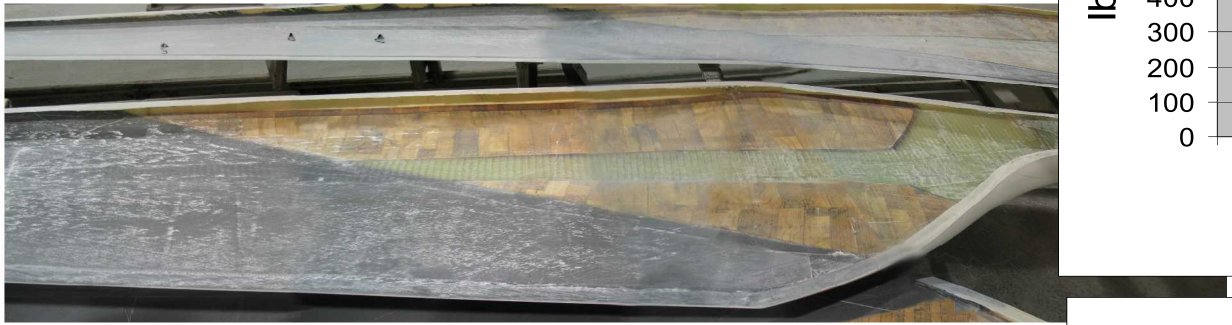
Blade manufacturers have reduced weight as turbines have grown in size



Improved Subscale Blades (9m)

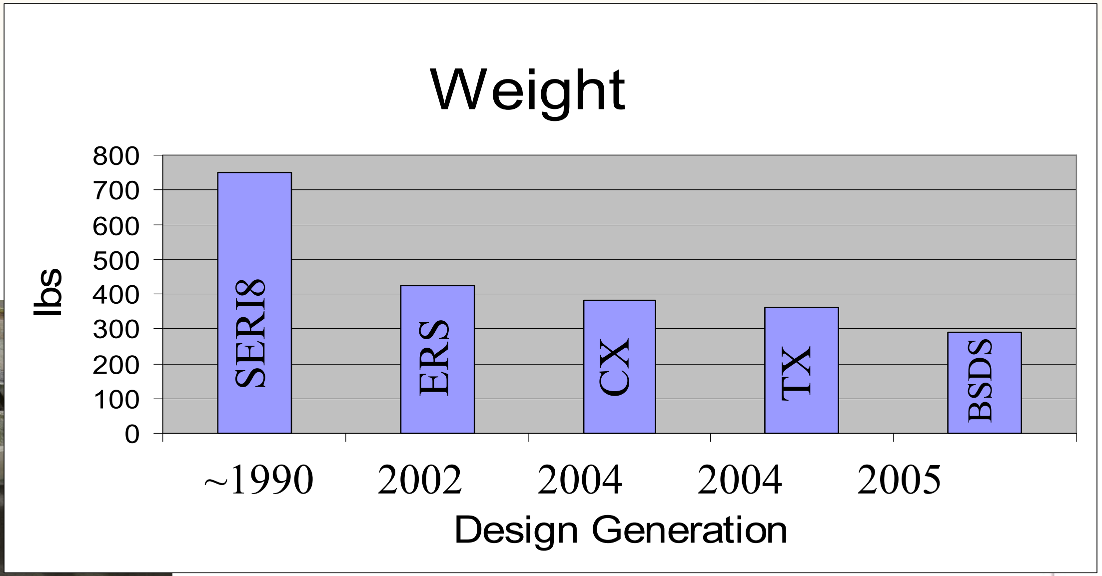
Research blades are lighter and stronger

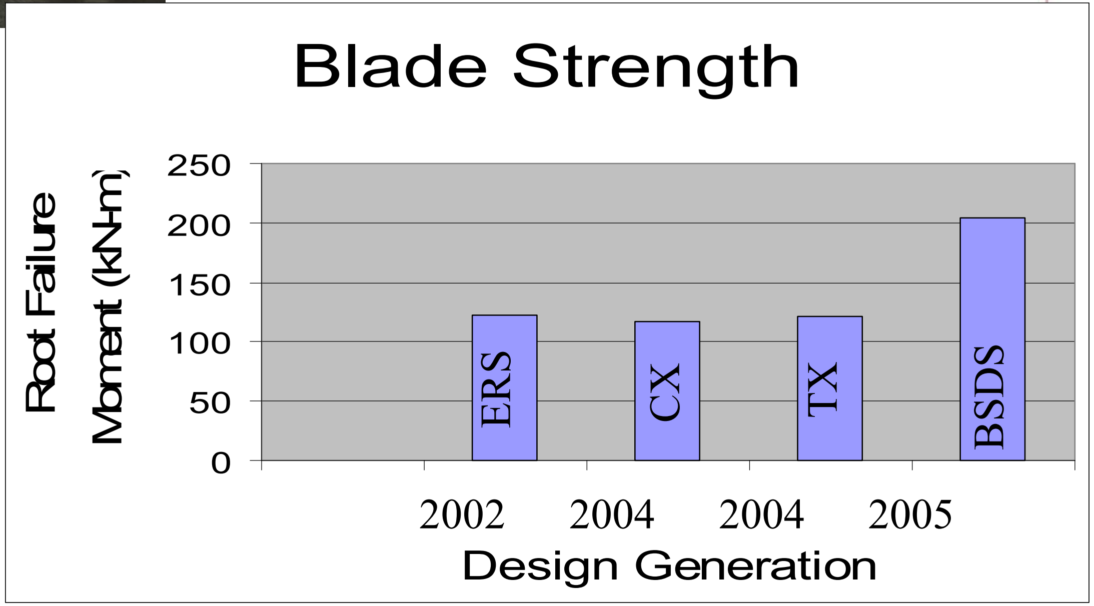
CX



TX

BSDS





Blade Full-Scale Testing is Critical

Courtesy LM Glassfiber

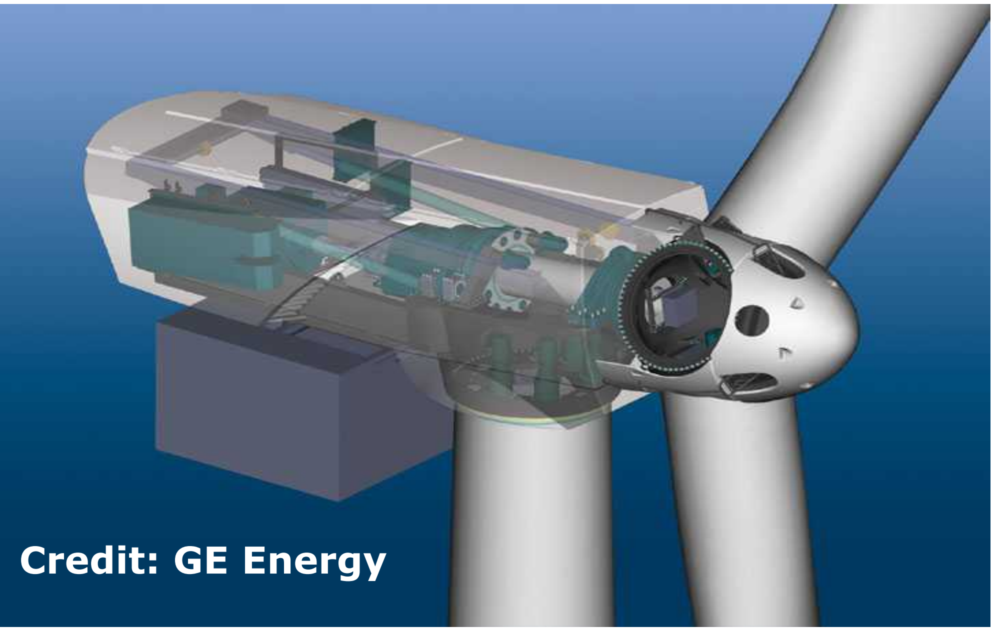
Courtesy NREL/NWTC

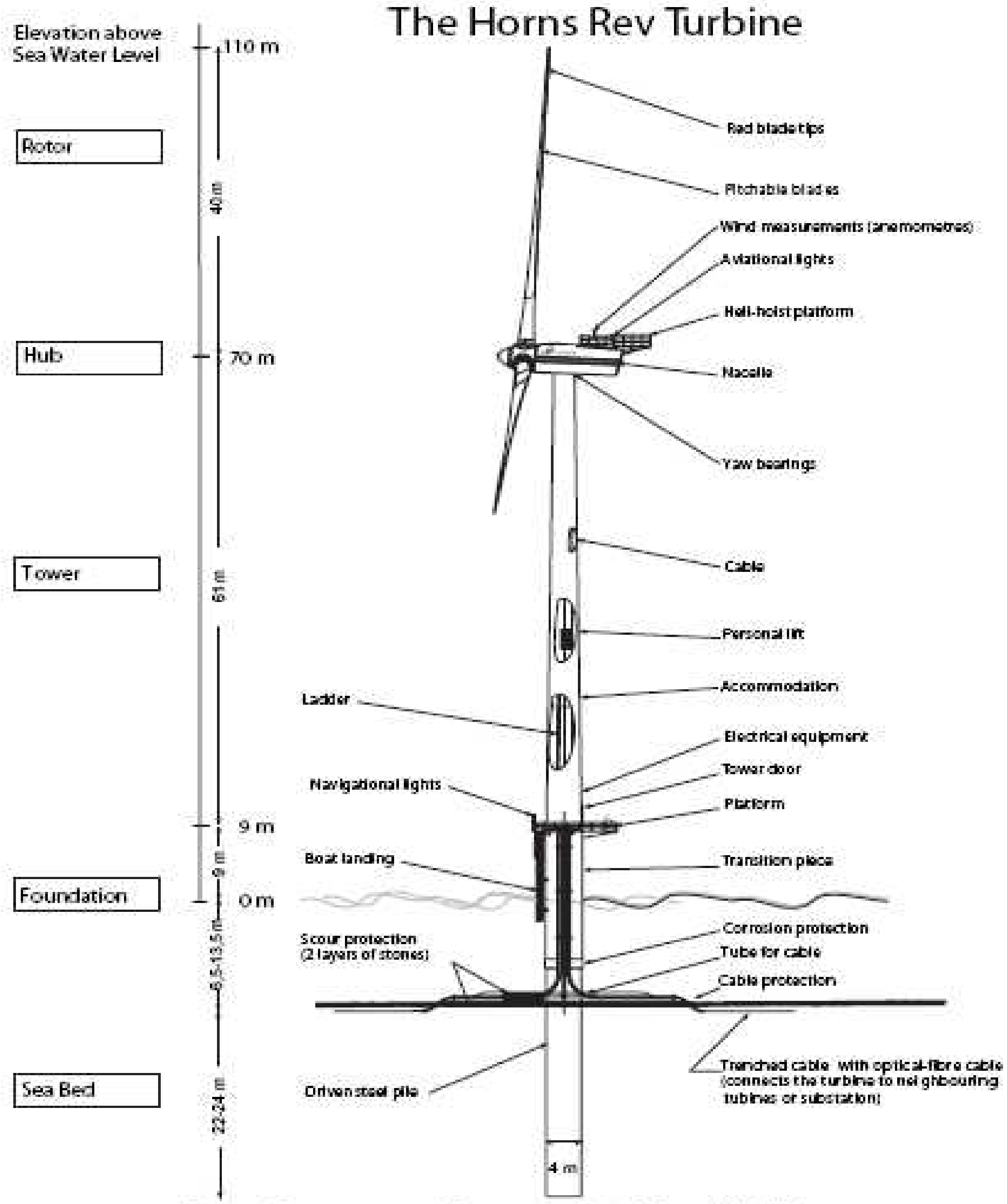
Offshore Wind Turbines

Horn's Reef,
Denmark

®Middelgruden.dk

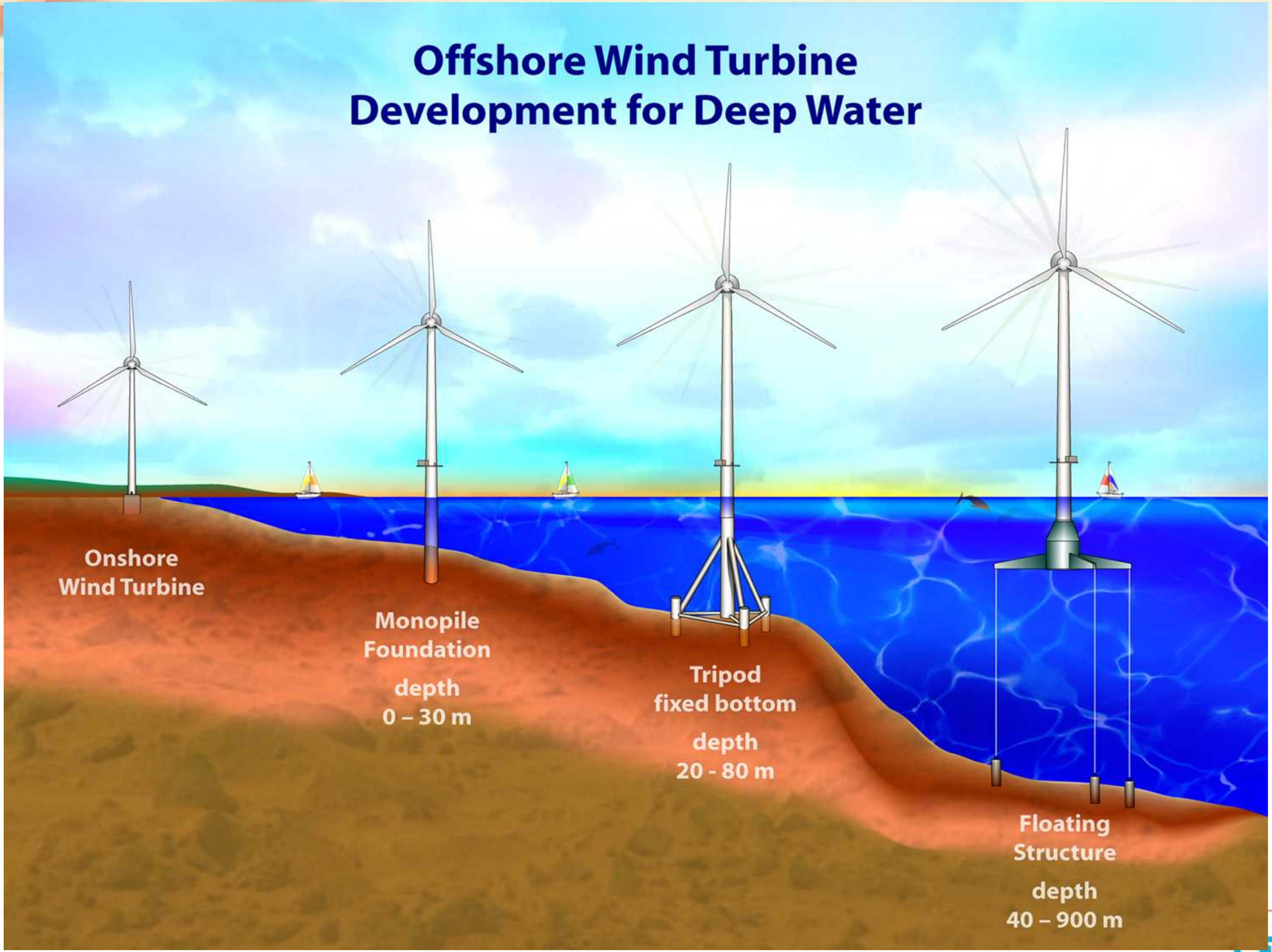
Typical Offshore Wind Turbin





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.



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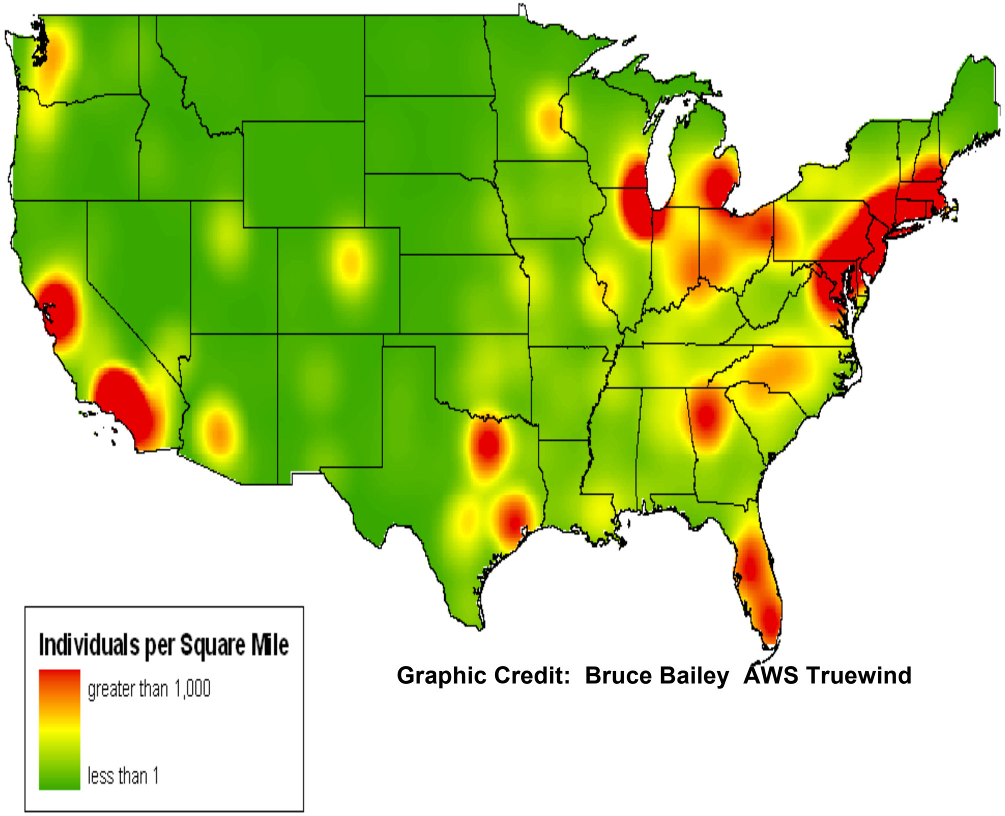
Why Offshore Wind ?

Land-based sites are not close to population centers

Cities are close to offshore wind sites

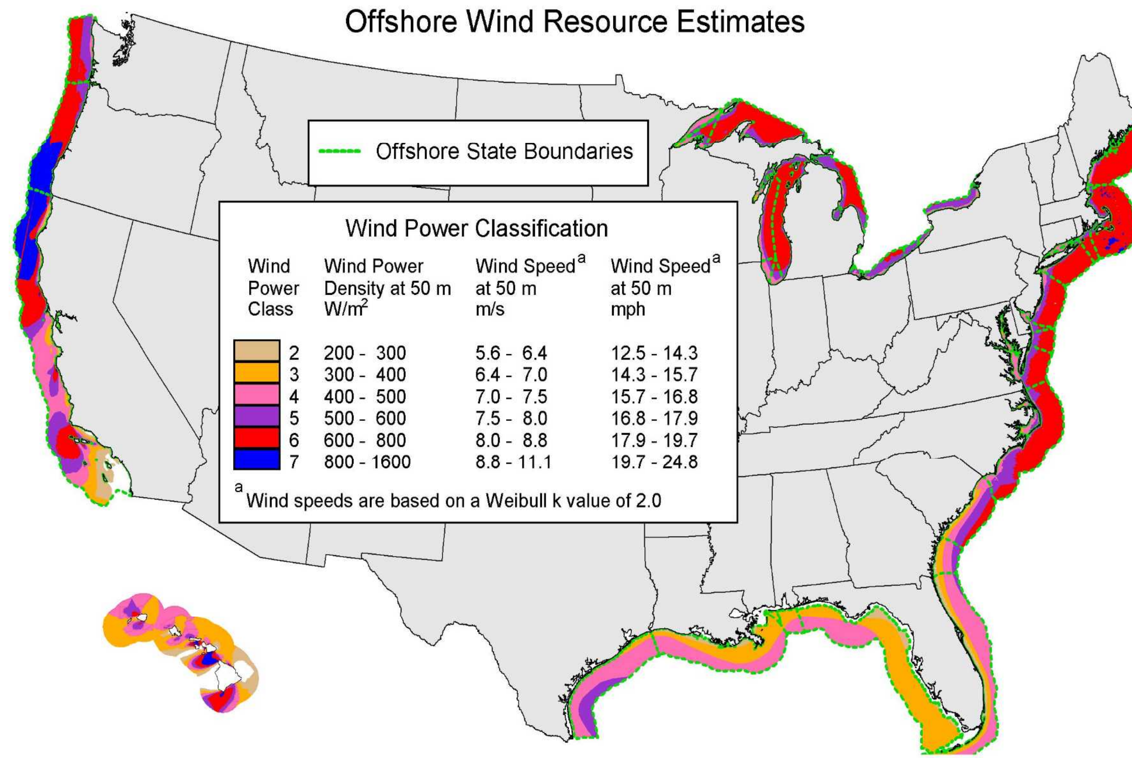
28 coastal states use 78% of the electricity in US

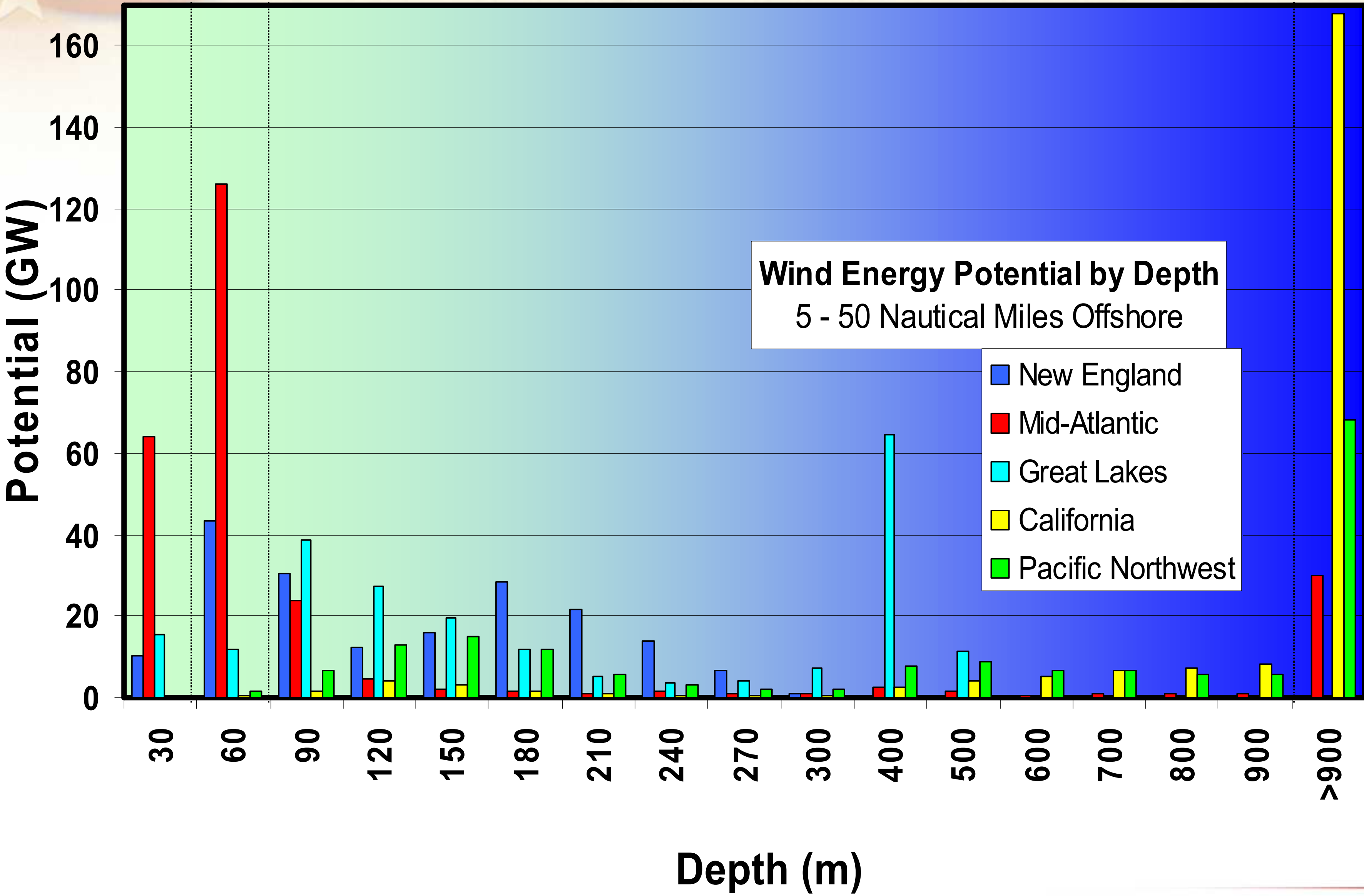
US Population Concentration



Graphic Credit: Bruce Bailey AWS Truewind

U.S. Wind Resource





Wind Energy Potential by Depth
5 - 50 Nautical Miles Offshore
New England
Mid-Atlantic
Great Lakes
California
Pacific Northwest
Potential (GW)
0
20
40
60
80
100
120
140
160
30
60
90
120
150
180
210
240
270
300
400
500
600
700
800
900
>900
Depth (m)

Carpe Ventem

Questions?

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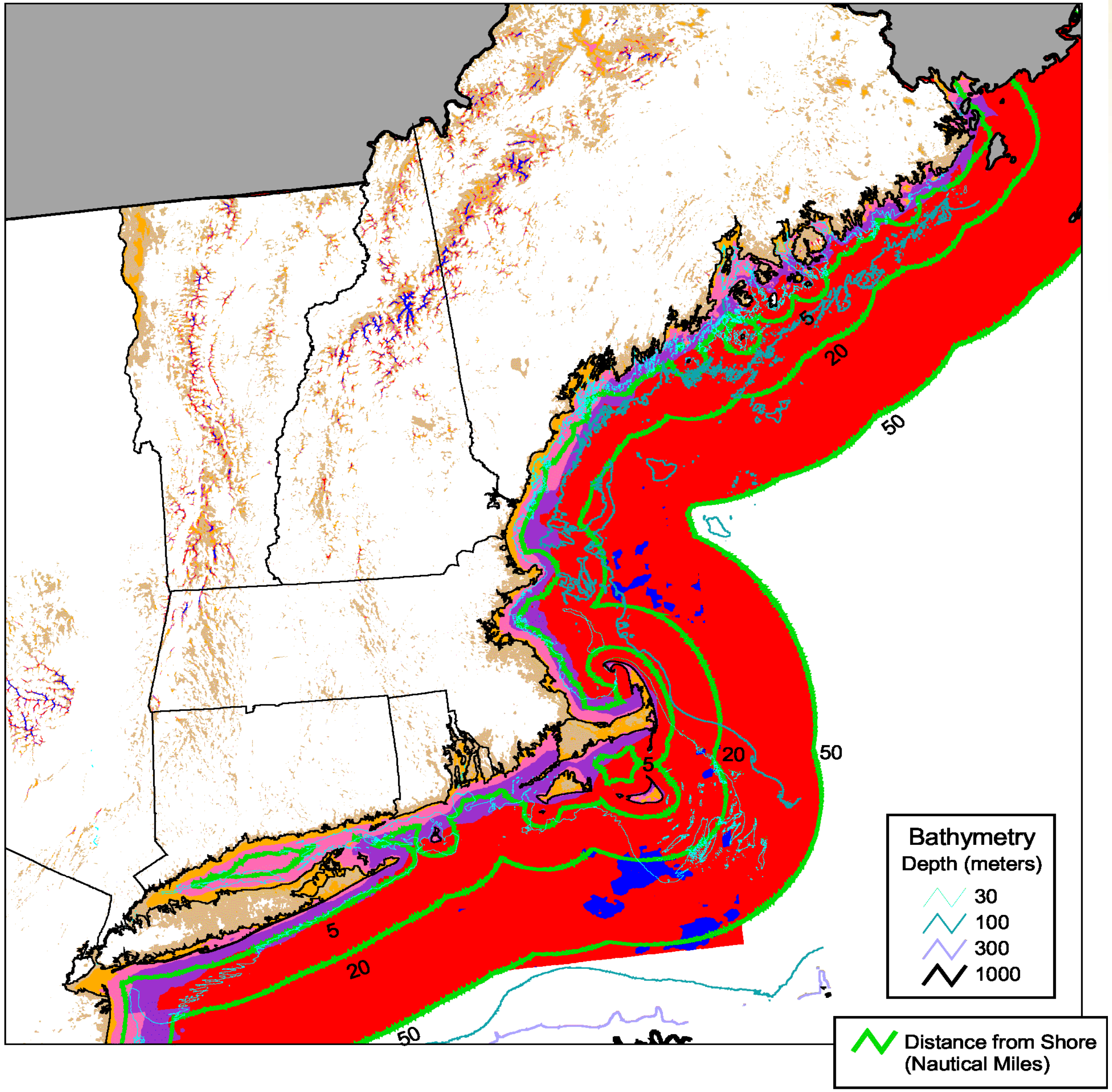
EXTRAS

New England Offshore Resource



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
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	> 8.8	> 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory

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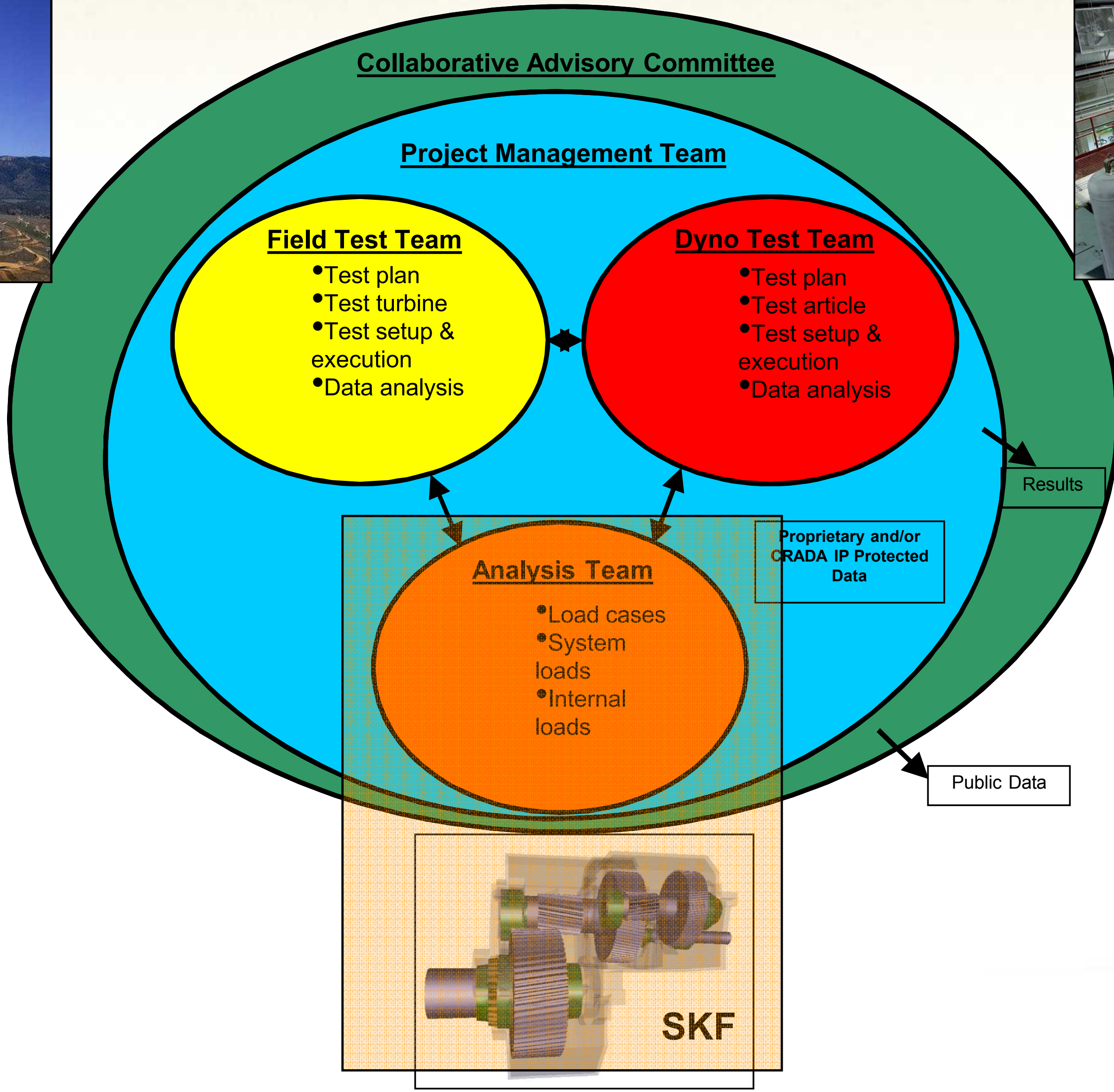
Different rotor designs

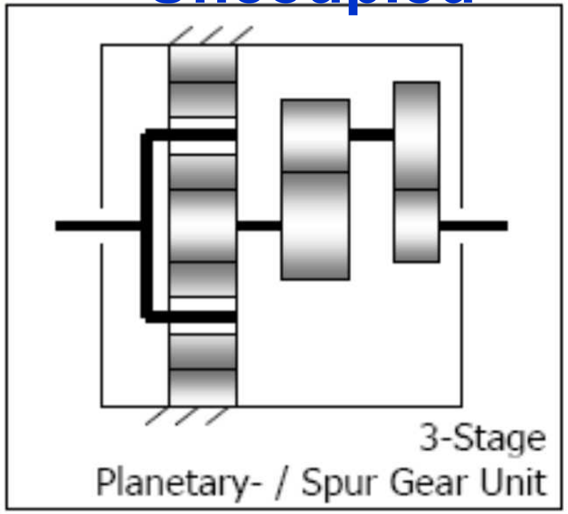
- Vertical axis
- Upwind
- Downwind
- Light weight / flexible
- High solidity / low solidity
- High tip speeds / low tip speeds

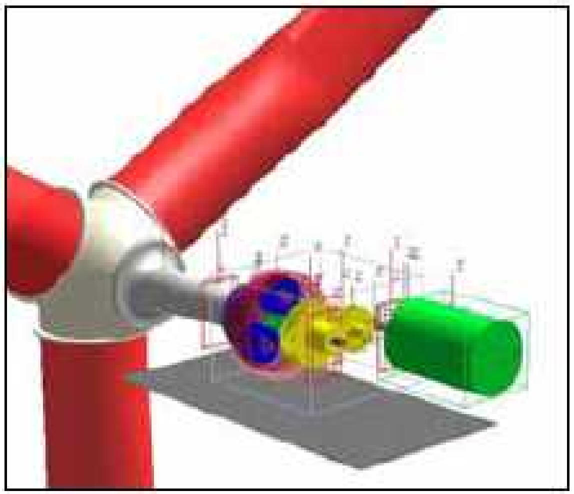
NREL Wind Turbine Gearbox Reliability Collaborative



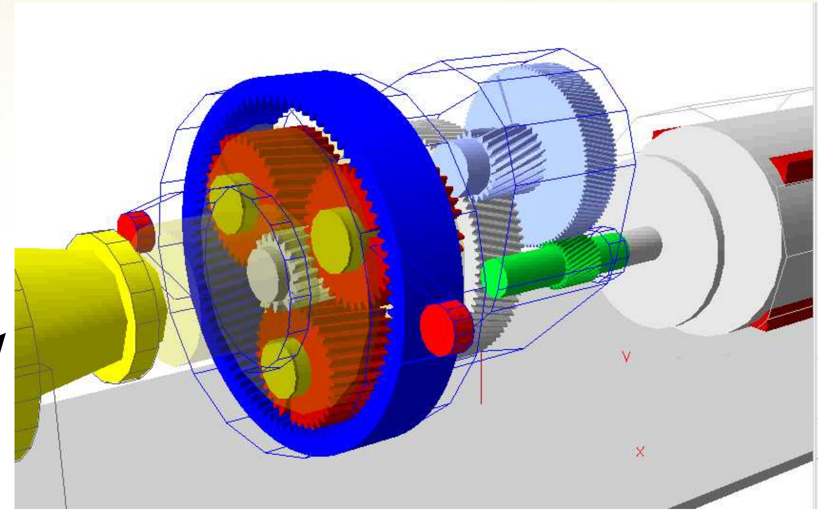
Comprehensive Multibody Dynamics Modeling

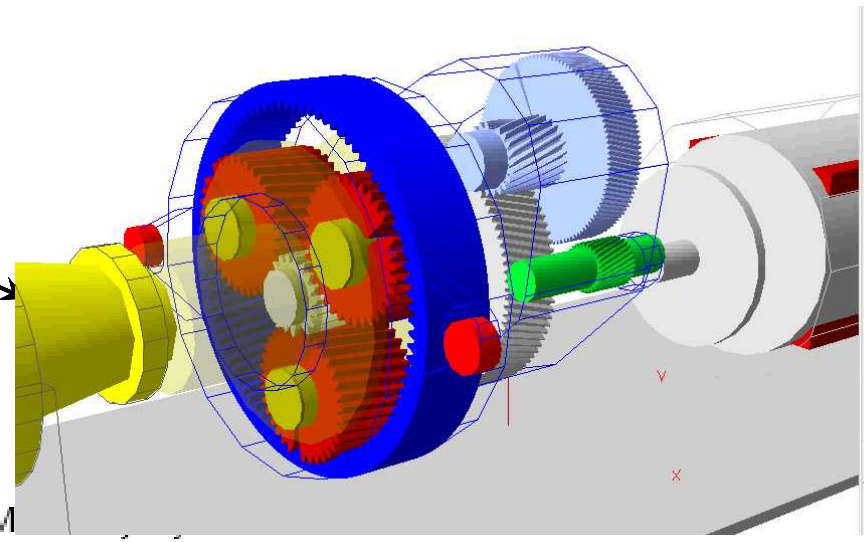
Uncoupled





System Coupling





Technische Universität Dresden
Institut für Maschinenelemente
und Maschinenkonstruktion
Prof. Dr.-Ing. Berthold Schlecht

M
SIMPACK User Meeting 2004 – Wartburg / Eisenach
Dipl.-Ing. Tobias Schulze, 09./10. November 2004

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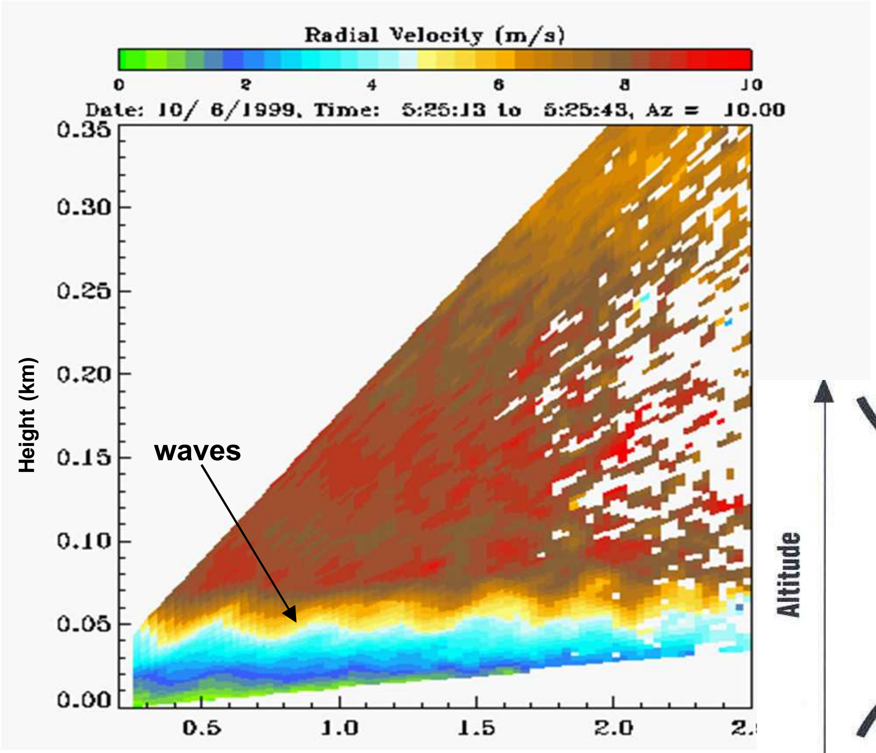
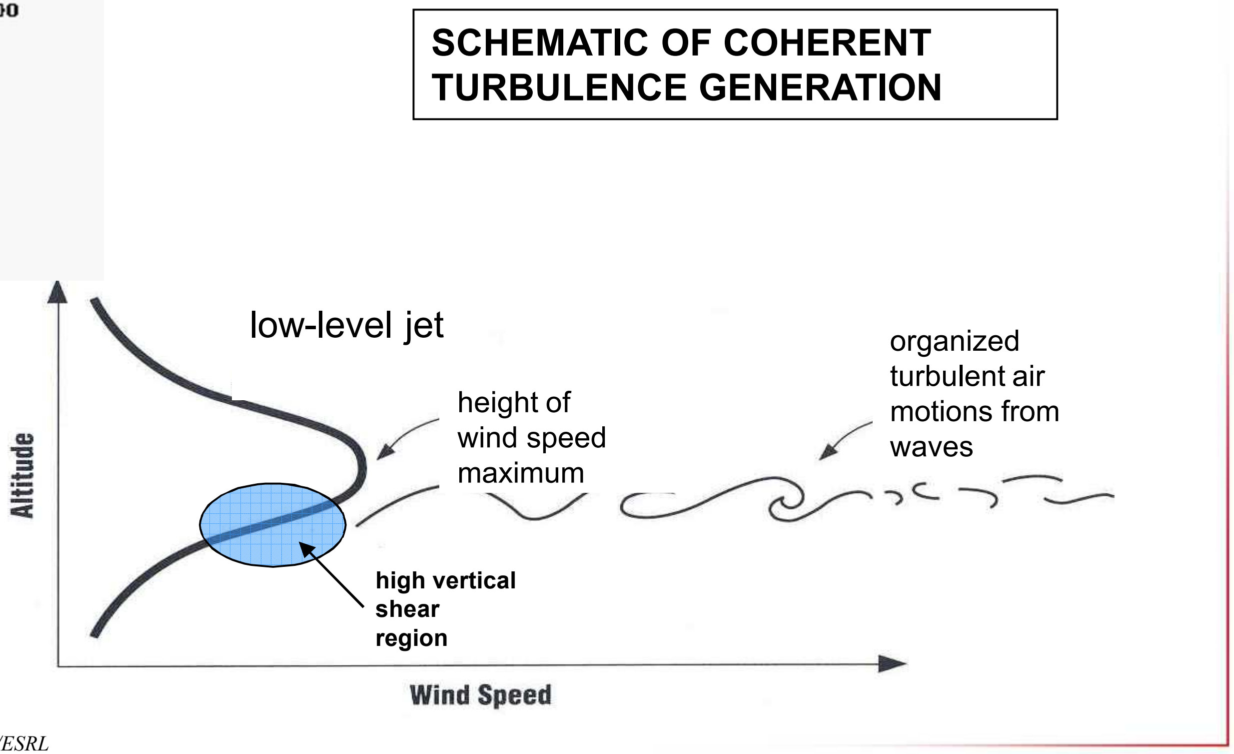
Measuring and Modeling the Low-Level Nocturnal Jet

LIDAR Observation of Wave Motions in Southern Kansas

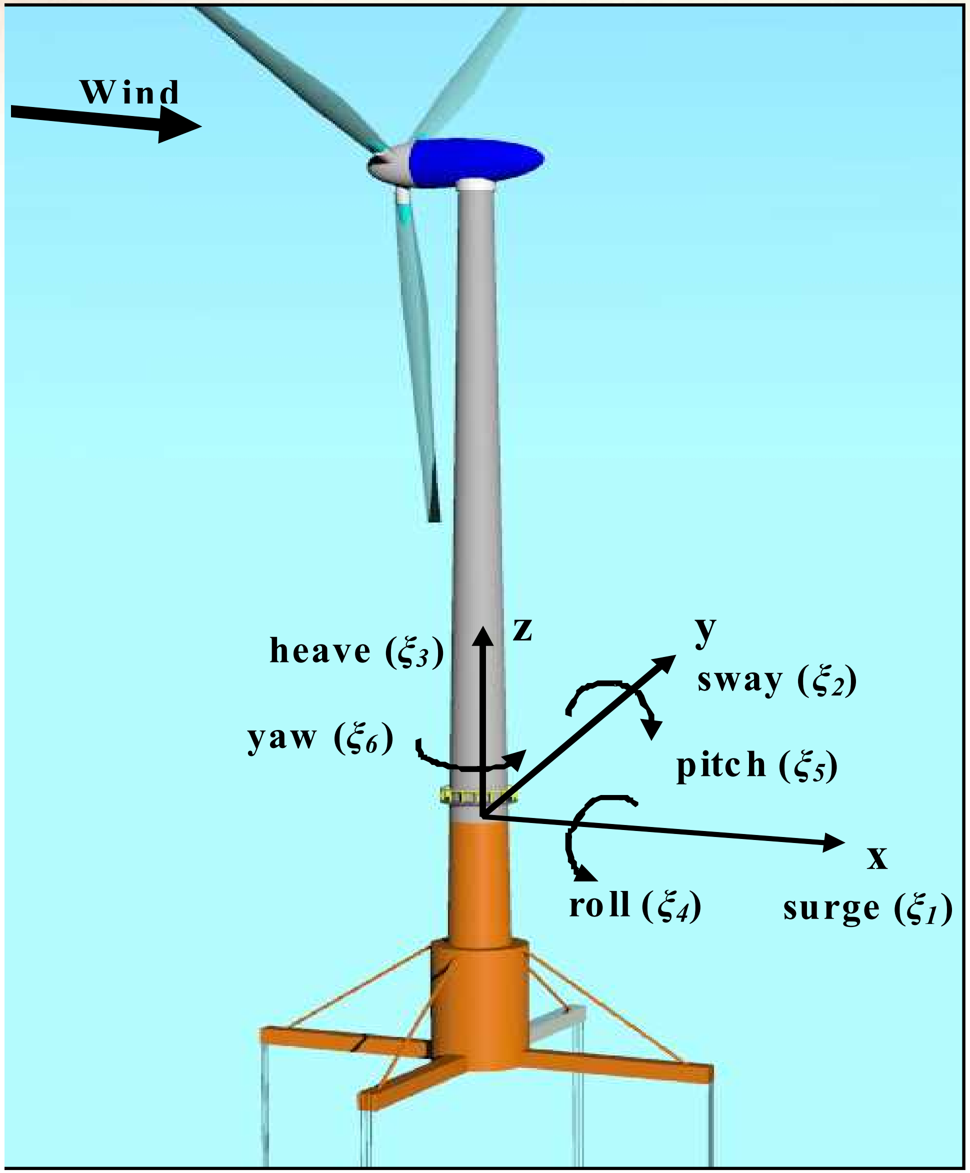


Horizontal distance (km)

Courtesy: R. Banta, NOAA/ESRL



Key Offshore Research



- **Reliable analytical design techniques**
- **Design basis**
  - External conditions
  - Installation
  - Access
  - Stability
- **Low cost deepwater support structures**
- **Offshore turbine designs**

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