Fundamentals of Wind Energy (Wind-Diesel 101)

E. Ian Baring-Gould,

National Wind Technology Center & Deployment & Industrial Partnerships Centers

May 31st 2009

TOPICS

- Introduction
- Energy and Power
- Wind Characteristics
- Wind Power Potential
- Basic Wind Turbine Theory
- Types of Wind Turbines
- Review of Small and Large Turbines
- Review of the Current Wind Market
- Further Information

What is Wind Power

1400-1800 years go, in the Middle East

800-900 years ago, in Europe

140 years ago, water-pumping wind mills

70 years ago, electric power

The ability to harness the power available in the wind and put it to useful work.

ENERGY AND POWER

ENERGY: The Ability to do work

Electrical energy is reported in kWh and may be used to describe a potential, such as in stored energy or the amount of energy used over a time period, like 1000 kWh per day

POWER: Force at any instant

The amount of energy needed at any instant in time. Represents current generation and constraints such as Generator Size or an instantaneous load which is measured in kW

Power in the Wind

$$P = 0.5\ \rho\ v^3$$

P: power, Watt

ρ: density of air, kg/m³

V: wind speed, m/s

We call this the Wind Power Density (W/m²) which is a measure of the power available in the wind at a specific point or as an average over a longer period of time

Power from the Wind

$$P = 0.5\ \rho\ v^3\ Cp\ A_S$$

Cp = Coefficient of Performance (an efficiency term)

A_S = The swept area of the wind turbine blades

Multiplied by time give you

Energy…

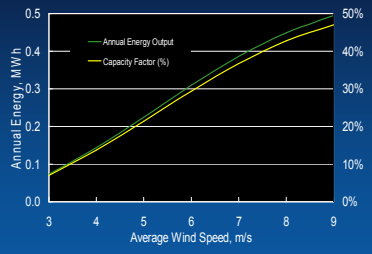
Critical Aspects of Wind Energy

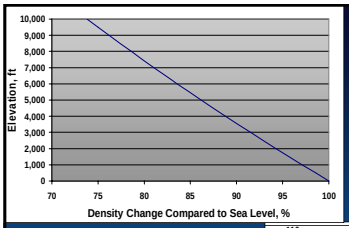
$$P = 0.5\ \rho\ Cp\ v^3\ A_s$$

- V^3: Doubling of the wind speed results in an 8 fold increase in power
- ρ: High density air results in more power (altitude and temperature)
- A_s: A slight increase in blade length, increases the area greatly
- Cp: Different types of wind turbines have different maximum theoretical efficiencies (Betz limit ≈0.593) but usually between .4 and .5

Velocity – The Impact on Increasing Wind Speed

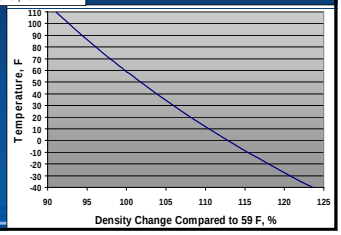
A small increase in wind speed can increase the power greatly



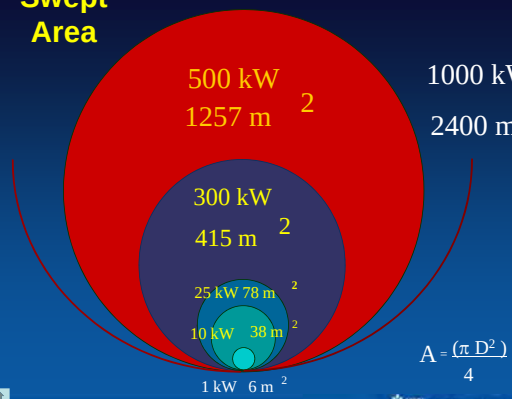


Air Density - Changes with Elevation

Changes with Temperature



Swept Area

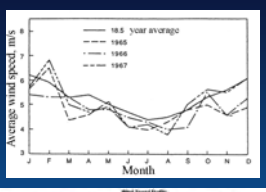


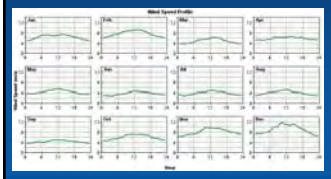
Wind Characteristics and Resources

Understanding the wind resource at your location is critical to understanding the potential for using wind energy

- Wind Speed
  - Wind Profile
  - Wind classes
  - Collection and reporting
- Wind Direction
- Wind speed change with height

Wind Speed





- Measured in m/s or mph
- Varies by the second, hourly, daily, seasonally and year to year
- Usually has patterns
  - Diurnal - it always blows in the morning
  - Seasonal – The winter winds are stronger
  - Characteristics – Winds from the sea are always stronger and are storm driven.

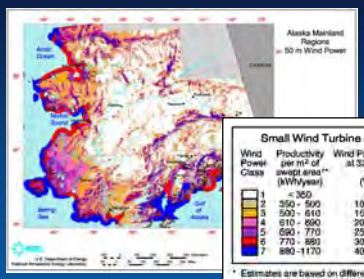
So, which is better…

1. A location where the wind that blows only 50% of the time at 10 m/s but is calm the rest of the time
2. A location where the wind that blows all of the time at 5 m/s

$$P = 0.5\ \rho\ C_p\ v^3\ A_S$$

Both have exactly the same annual average wind speed…

Wind Maps and Class



Careful:
Wind class is defined at a specific height

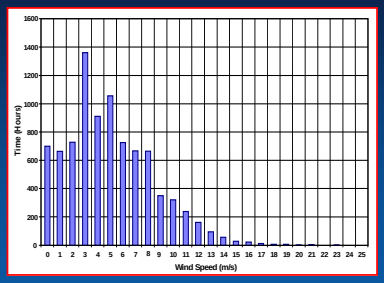
Small Wind Turbine Productivity Estimates*

Wind Power Class	Productivity per m² of swept area** (kWh/year)	Wind Power Density at 33 ft (10 m) (W/m²)	Wind Speed at 33 ft (10 m) (mph)	Wind Speed at 33 ft (10 m) (m/s)
1	< 350	<100	< 9.8	< 4.4
2	350 - 500	100 - 150	9.8 - 11.5	4.4 - 5.1
3	500 - 610	150 - 200	11.5 - 12.5	5.1 - 5.6
4	610 - 690	200 - 250	12.5 - 13.4	5.6 - 6.0
5	690 - 770	250 - 300	13.4 - 14.3	6.0 - 6.4
6	770 - 880	300 - 400	14.3 - 15.7	6.4 - 7.0
7	880 -1170	400 -1000	15.7 - 21.1	7.0 - 9.4

* Estimates are based on different models and sizes of wind turbines assuming a tower height of 80 ft (24 m).

** For systems of different sizes, multiply the estimated productivity by the total swept area of the turbine.

Wind Speed Data Collection and Reporting

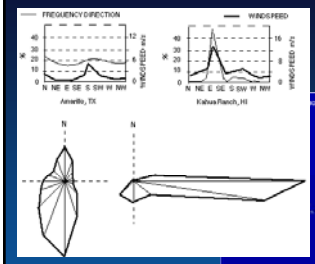


Collection
- **Measured every 1 or 2 seconds**
- **Averaged every 10 or 15 minutes**
- **Reported as hour averages**

Turbulence Intensity

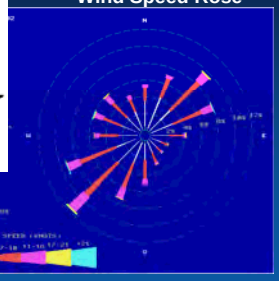
Wind Speed
Frequency of Occurrence Histogram based on hour average data for a year

Wind Direction



Wind Rose

Wind Speed Rose



CONTINENTAL **TRADE WINDS**

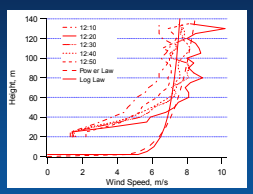
Can also have a wind direction change intensity – similar to turbulence

Impacts on Wind Speed

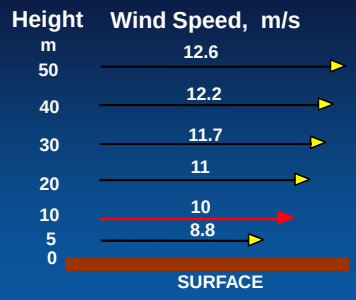
Many things impact the speed and direction of the wind at any specific location, making local measurements important

Wind Speed Increases with Height

- Because of friction with the earth, air closer to the surface moves more slowly
- The farther we get away from the earth (increase in altitude) the higher the wind speed gets until it is no longer effected by the earths surface



Wind Shear



- The type of surface (grass, trees) impacts the wind shear
- Real vs. apparent height

Factoring in Measurement Height The Power Law

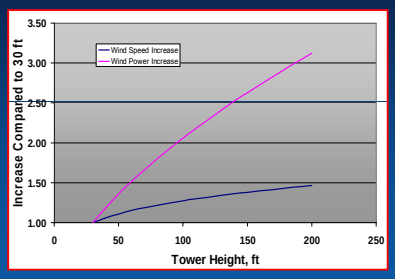
$$V_N = V_O\left[\frac{h_N}{h_O}\right]^N$$

V_N: Wind speed at new height,
V_O: Wind speed at original height,
h_N: New height,
h_O: Original height,
N: Power law exponent.

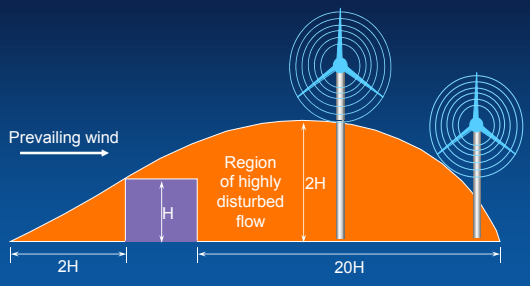
Terrain	Power Law Exponent
Water or ice	0.1
Low grass or steppe	0.14
Rural with obstacles	0.2
Suburb and woodlands	0.25

Source: Paul Gipe, Wind Energy Comes of Age, John Wiley and Sons Inc, 1995, pp 536.

Height Impacts on Power



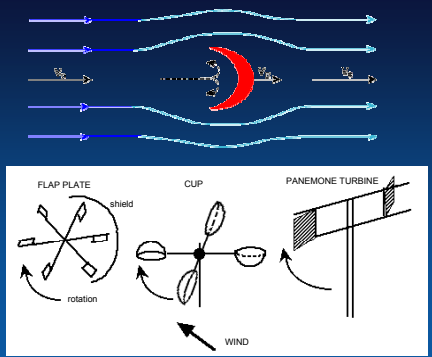
Micro-Siting Example:
Obstruction of the Wind by a Small Building



Basic Wind Turbine Theory

Lift and Drag – The different types of wind turbines
Aerodynamics – How turbines work
Power Curves – The performance of wind turbines
Power Availability - Power your can get from the wind
Different types of lift turbines

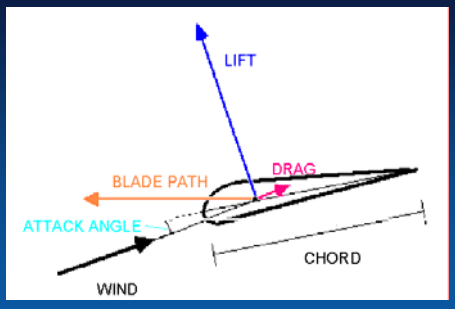
Aerodynamic Drag



Classic Drag Devices

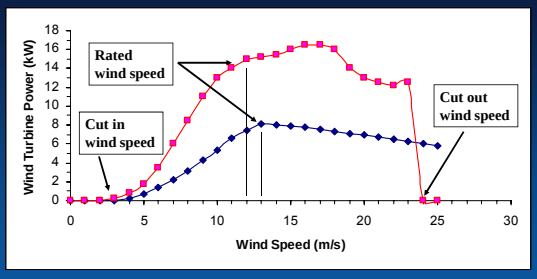
Some Modified Drag Devices

Aerodynamic Lift



Lift Wind Turbines

WTG Power Curve

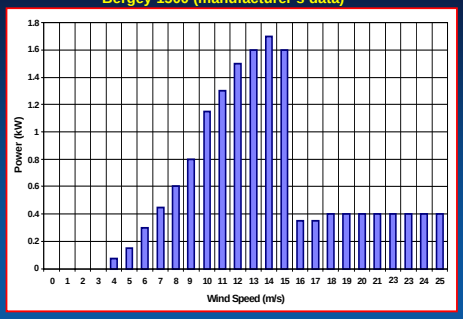


Important Terms

- Cut in wind speed: The wind speed that the turbine starts producing power (may be different than the speed at which the turbine starts spinning)
- Rated Wind Speed: The wind speed at which the turbine is producing "rated power" – though "rated power" is defined by the manufacture
- Cut out wind speed: The wind speed at which the turbine stops producing power
- Shut down wind speed: The wind speed at which the turbine stops to prevent damage
- Survival wind speed: Wind speed that the turbine is designed to withstand without falling over

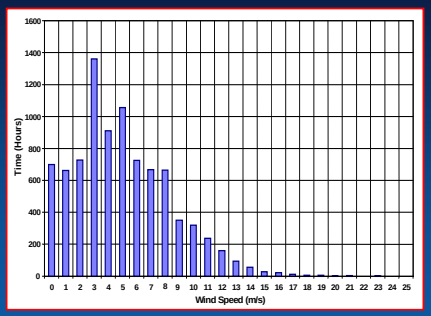
Wind Turbine Power Curve

Bergey 1500 (manufacturer's data)



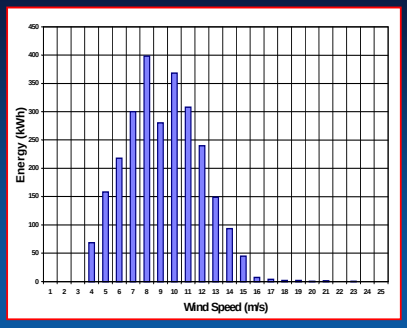
Wind Speed Frequency of Occurrence

Average Wind Speed: 5 m/s (11 mph)



Annual Energy Production: 2643 kWh/year

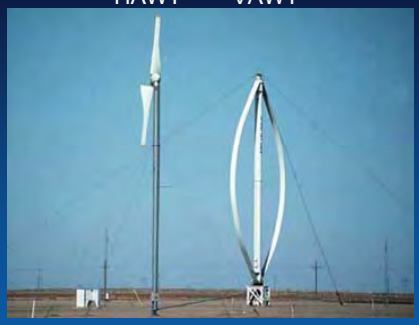
Bergey 1500 @ 5 m/s (11 mph) average wind speed



All available energy may not be captured

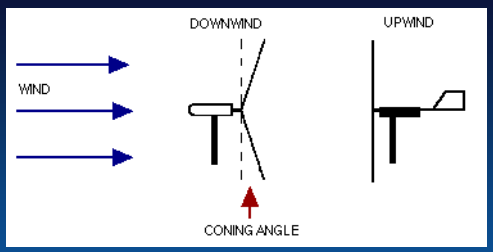
Types of Lift Turbines

HAWT VAWT

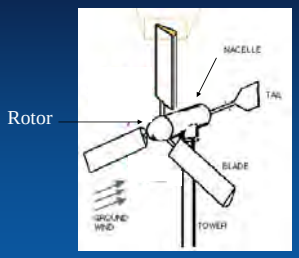


Basic Properties of HAWT

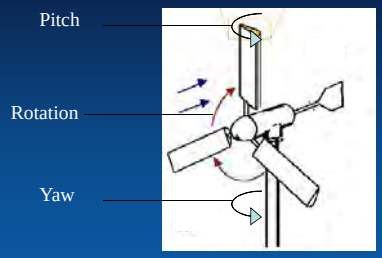
- Basics of a horizontal axis wind turbine
- Types of turbines
- Small distributed turbines
- Large grid connected turbines



Parts of a Wind Turbine

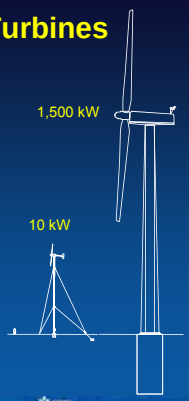


Basic Motion of a Wind Turbine

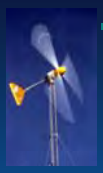


Different Types of Wind Turbines

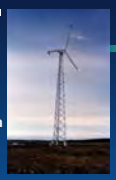
- Utility-Scale Wind Power
  600 - 5,000 kW wind turbines
  - Installed on wind farms, 10 – 300 MW
  - Professional maintenance crews
  - Classes 5 and 6 (> 6 m/s average)
- Distributed Wind Power
  300 W - 600 kW wind turbines
  - Installed at individual homes, farms, businesses, schools, etc.
  - On the "customer side" of the meter
  - High reliability, low maintenance
  - Classes 2 and 3 (5 m/s average)



Sizes and Applications

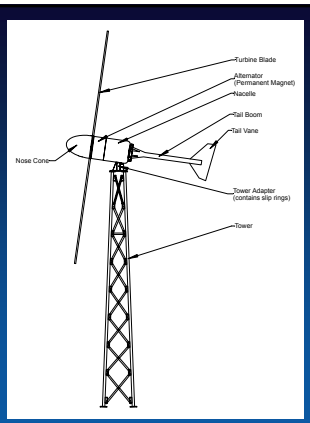


Small (≤10 kW)
Homes
Farms
Remote Applications (e.g. water pumping, telecom sites, icemaking)



Intermediate (10-250 kW)
Village Power
Hybrid Systems
Distributed Power

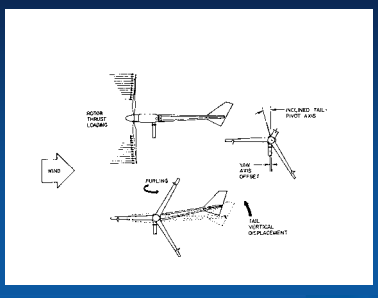
Large (250 kW – 2+ MW)
Central Station Wind Farms
Distributed Power



Small wind turbines

- Typically use a permanent magnet alternator
- Generates wild AC (variable voltage and frequency) power that must be treated.
- Can provide AC or DC power
- Passively controlled

Overspeed Protection of Small WTG During High Winds

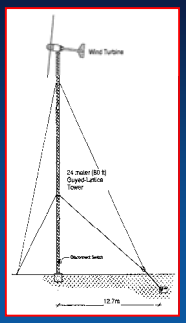


Furling: The rotor turns out of the wind during high winds to reduce power

- Used to control rotor speed and power output
- Dynamic activity
- Can cause noise issues (flutter)
- Not all small wind turbines do this

Small Wind Turbine Towers

- Guyed lattice and tube towers are the least expensive and most commonly used towers for small wind turbines
- Adequate space is needed for the guy wires and their anchors
- Free-standing towers are used where space is limited

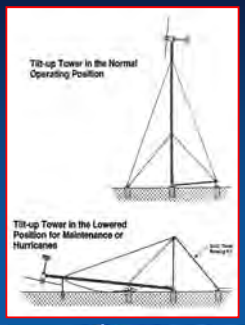


Tilt-Up Towers

Turbine installation in remote areas can be a problem.

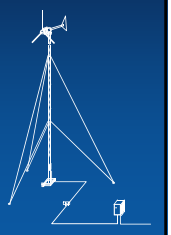
To solve this problem:

- Tilt-up versions of guyed towers are available for easier installation and maintenance.
- Self erecting technology also used wisely



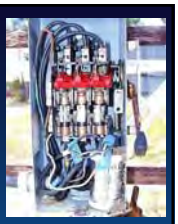
The Wind Turbine Controller

- Battery-Charging
  - Converts AC power to DC for battery-charging
  - Regulates the battery voltage to prevent over-charging
  - When the battery is fully charged:
    - Power is diverted to another load, or …
    - The rotor is unloaded and allowed to "freewheel"
- Grid Interconnection
  - "Inverter," converts the power to constant frequency 60 Hz AC
- Water Pumping
  - Direct connection to the pump



Small Wind Turbine Maintenance and Lifetime

- **"Low maintenance" not "no maintenance"**
  - Inspection and maintenance every year: tightening bolts and electrical connections, inspecting slip ring brushes, checking for corrosion, etc.
  - Between 2 and 4 years: blade leading edge tape may need replacement
  - Beyond 5-10 years: blade or bearing replacement may be needed
- **Lifetimes of 10 to 20 years are possible**
  - Some Jacobs wind turbines have been operating for more than 60 years with periodic maintenance!



"Hot Tips" on Small Wind Energy

- "Buy Reliability"
  "Based on experience, I side with the 'school of heavy metal,' those who believe that beefiness of components is directly related to the longevity of the equipment." M. Sagrillo, small wind turbine expert
- "Taller is Better"
  Taller towers give better performance due to smoother wind and higher wind speeds
- "Micro-Siting"
  For best performance, locate wind turbines above and away from obstructions to the wind

0277034
6

Small turbines – the Wild West of Wind

- Small Wind Turbine industry is unorganized & lacks working standards
  - Currently, Third party certification is typically limited to the inverter (UL 1740)
  - Limited 3rd party testing & certification
- Current IEC small turbine testing standard generally not used due to the expense
- Small wind turbine testing & certification schemes for North America are under development (Small Wind Certification Council [SWCC, AWEA Small Wind Test Standard (in draft stage)]

Questions to Ask about SWT

- What level of certification does the turbine have?
- Is a power curve available? If so, how was it developed?
- Has the turbine been previously installed? (In the U.S., near the proposed site)
- How many units have been deployed?
- Is there any sort of dealer infrastructure?
- How long has the manufacturer been in business? (What is the experience of the company key personnel?)
- Is the inverter UL listed? (Grid tied systems)


Loopwing Tromc


Hush Turbine 3000


Vertikalrotor 500

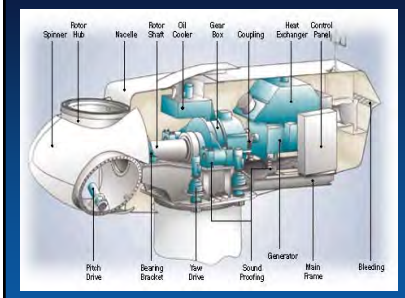

Skystream 2400


Windkraft 500


Windport 5000

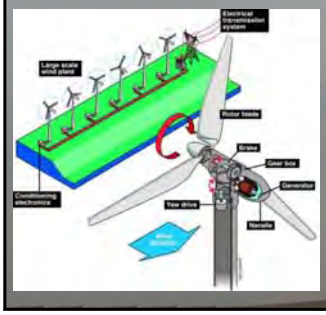
http://www.allsmallwindturbines.com/

Large Wind Turbines



- Typically induction or variable speed permanent magnet generators
- Create AC power supplied to the grid
- Actively controlled

Parts of a Wind Turbine Power Plant



Nacelle

Blades

Boeing 747-200

Tower

Characteristics of Large WTG

Power Types
- Induction (Constant speed)
- Permanent Magnet (Variable speed) using power electronics

Power System Efficiencies
- Aerodynamic
- Rotor
- Drive train / gear box
- Generator
- Power Conversion (if applicable)

Control of Large WTG

Fixed Pitch (Stall regulated): The shape of the blade varies over its length so that as wind speed increase parts of the blade stop producing lift and limit power.

Variable Pitch: The rotation (pitch) of each blade is individually controlled to control lift

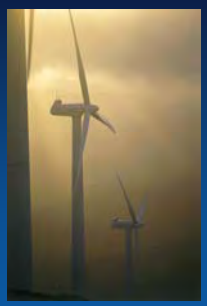
Yaw: Motors control yaw behavior based on a wind direction vain, used to shut down wind turbine in high winds but can also be a source of problems.

Brake: All wind turbines are required to have two of them but there are several types:

Aerodynamic: Flaps on the blades that cause drag.
Mechanical: Disks or calipers, like your car.
Electrical: using the generator to cause electrical resistance.

Other Large (and Small) Turbines Considerations

- Policy
- Siting
- Transmission
- External Conditions
- Intermittency



Policy

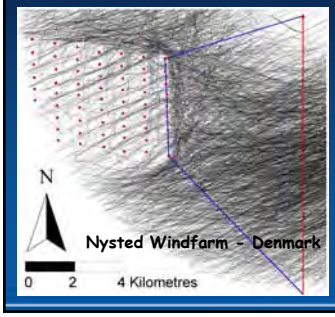
- Encourage economic development and use of local resources
- facilitate “green” markets
- Federal, state and local incentives such as the Production Tax Credit (PTC) and Renewable Portfolio Standards (RPS)

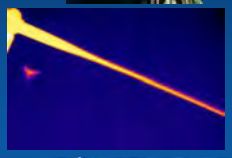
Siting

- Avian and other wildlife
- Noise
- Visual Impact
- Land Ownership

Avian (Bird) Research

- **Over 200 projects, two problem sites.**
- **Biggest problem was in the Altamont Pass.**
- **Managed by careful site selection.**

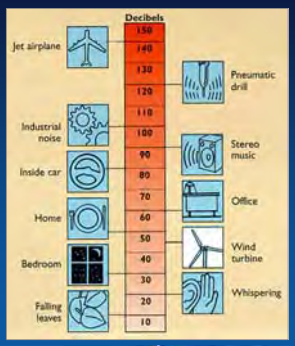




Are Wind Turbines Noisy?

What is the sound level of a utility-scale turbine?

45 decibels at 350 meters



Transmission

- Grid Access
- System studies
- Allocation of available capacity
- Scheduling and costs for usage (firm and non-firm)

Intermittency

- Operational Impacts (ancillary services)
  - voltage/VAR control, load following, etc.
- 10-20% of system capacity is reasonable

External Conditions

- Lightening
- Extreme Winds
- Corrosion
- Extreme temperatures

Remote Systems

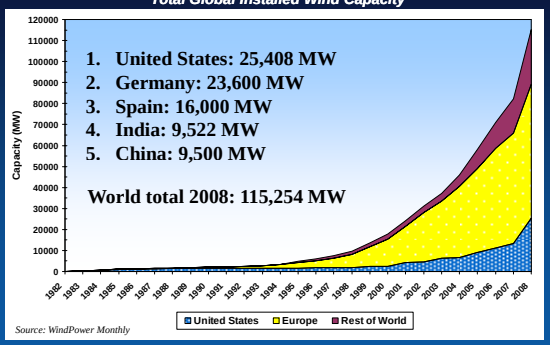
- Amount of energy from wind
- Control of system voltage and frequency
- Use of excess wind energy

Other General Wind Terms

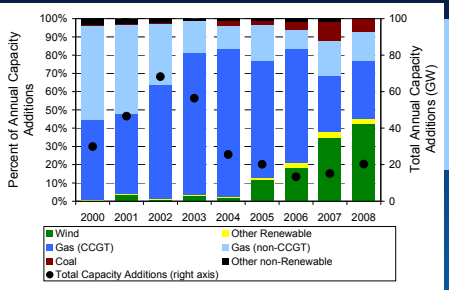
- Availability: The amount of time that the wind turbine is available to produce power (Maintenance parameter)
- Capacity Factor: The annual energy production of a wind turbine divided by the theoretical production if it ran at full rated power all of the time (Resource parameter)
  - The stronger the resource the higher the Capacity Factor
  - Usually reported monthly or yearly
  - 25-40% is typical, up to 60% has been reported
  - Reason for the “only works 1/3 of the time” quote.

Current Status of the Wind Industry

Total Global Installed Wind Capacity



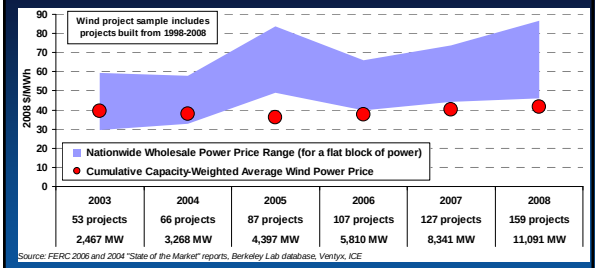
Major Source of New Generation Capacity Additions



- 2008: 42%
- 2007: 35%
- 2006: 18%
- 2005: 12%
- 2000-04: <5%

Source: EIA, Ventyx, AWEA, IREC, Berkeley Lab

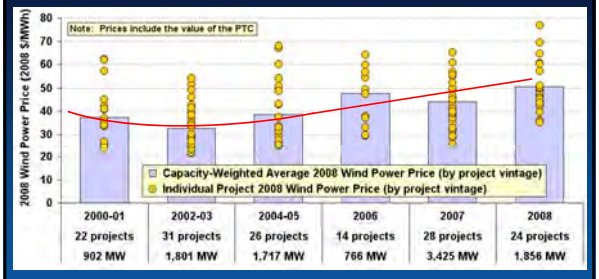
Wind Has Been Competitive with Wholesale Power Prices in Recent Years



Source: FERC 2006 and 2004 "State of the Market" reports, Berkeley Lab database, Ventyx, ICE

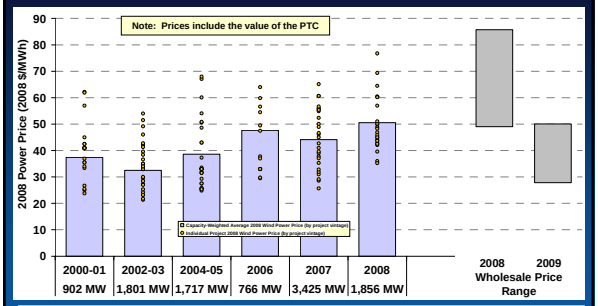
Note: Wholesale price range reflects flat block of power across 23 pricing locations; wind costs represent capacity-weighted average price for wind power for entire sample of projects built from 1998-2008

Wind Prices Have Been Rising Since 2002-03…



- Wind power prices bottomed out with projects built in 2002-03
- Projects built in 2008 are ~$15-20/MWh higher on average

The Near-Term Wind has Become Somewhat Less Attractive



- Wind prices are likely to increase further in 2009 as installed costs will remain high as developers work through turbines ordered at peak prices, and given higher equity yields.
- Wholesale price's are also likely to increase as the economic depression reverses course

Drivers for Wind Power

- Declining Wind Costs
- Fuel Price Uncertainty
- Federal and State Policies
- Economic Development
- Public Support
- Green Power
- Energy Security
- Carbon Risk

Further Information / References

Web Based:

- American Wind Energy Association http://www.awea.org/
- Wind Powering America http://www.eere.energy.gov/windpoweringamerica/
- Danish Wind Industry Association guided tour and information. http://www.windpower.org/en/tour/

Publications:

- Ackermann, T. (Ed's), *Wind Power in Power Systems*, John Wiley and Sons, west Sussex, England, (2005).
- Hunter, R., Elliot, G. (Ed's), *Wind-Diesel Systems*. Cambridge, UK: Cambridge University Press, 1994.
- Wind Energy Explained, J. F. Manwell, J. G. McGowan, A. L. Rogers John Wiley & Sons Ltd. 2002.
- Paul Gipe, Wind Energy Basics: A Guide to Small and Micro Wind Systems, Real Goods Solar Living Book.
- AWS Scientific Inc. "Wind Resource Assessment Handbook" produced by for the National Renewable Energy Laboratory, Subcontract number TAT-5-15283-01, 1997

Thanks to:

- Ken Starcher, Alternative Energy Institute, West Texas A&M University

Carpe Ventem

E. Ian Baring-Gould
National Wind Technology Center &
Deployment & Industrial Partnerships
Centers
303-384-7021
Ian.baring-gould@nrel.gov