Development of Modern Large Wind Turbine Design

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Outline

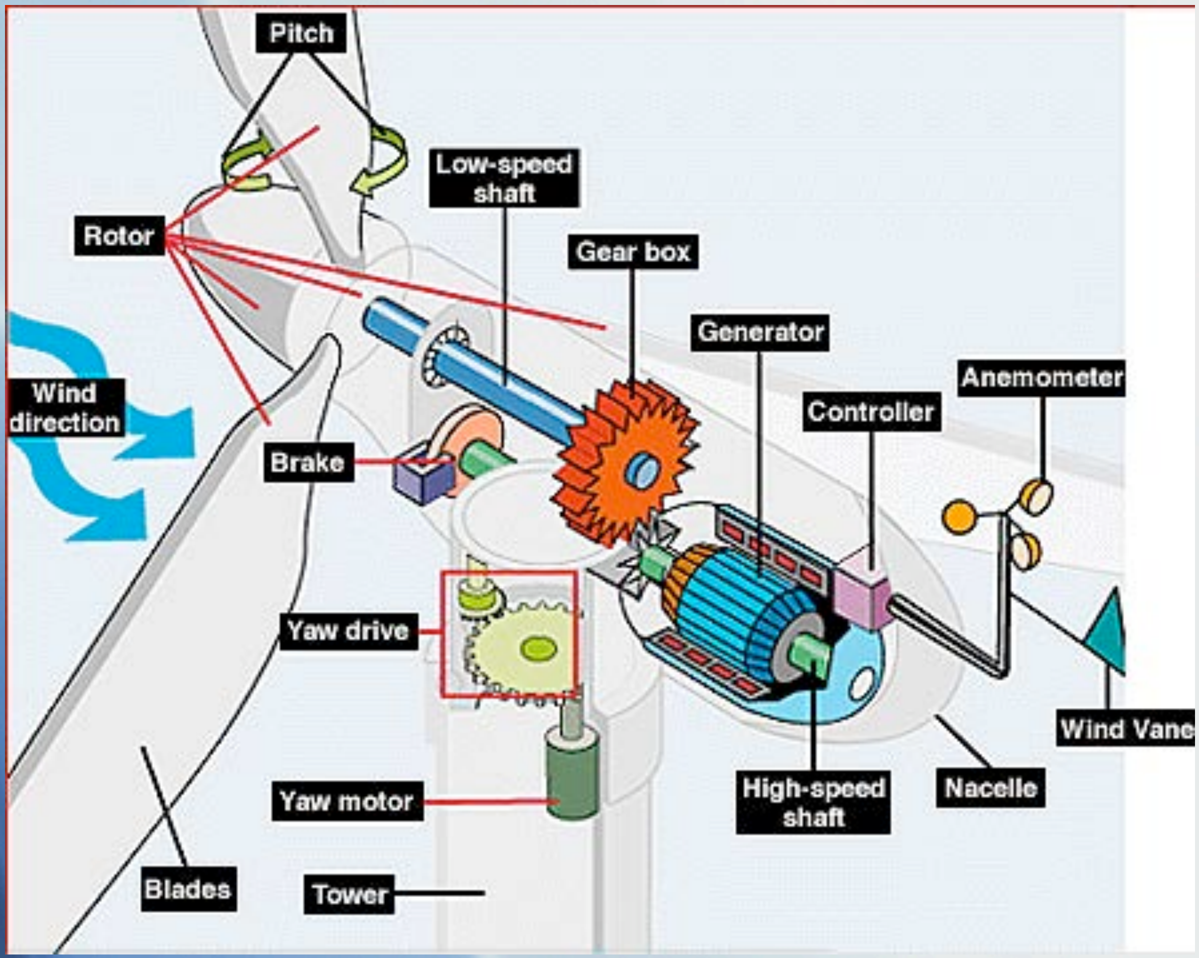
- Common wind turbines today
- Wind turbine history
- Major turbine design decisions

Standard Large Wind Turbine In Use Today

- Lift Device
- Horizontal axis
- Three blades
- Upwind
- 1.5 - 3 MW
- 85 - 105 m hub heights

How did we get here?

The Inside of a Wind Turbine



Common Turbines in Use

- GE 1.5 sle
  - 1.5 MW doubly fed induction generator
  - 77m rotor diameter
  - 11 to 20.4 rpm
  - Most common turbine installed in U.S.

Common Turbines in Use

- Vestas V90-3.0
  - 3.0 MW doubly fed induction generator
  - 90m rotor diameter
  - 8.6-18.4 rpm
  - On-board service hoist
  - Step-up transformer in nacelle
  - Fiberglass reinforced epoxy and carbon fiber blades

Common Turbines in Use

- Clipper Liberty C96
  - 2.5 MW
    - Has 4 synchronous permanent magnet generators
    - Full AC-DC-AC conversion before 4 sources paralleled
  - 96m rotor diameter
  - 9.6-15.5 rpm
  - On-board 2 ton service hoist

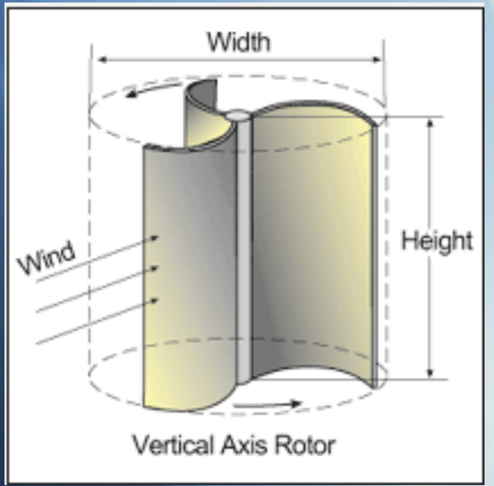
Mechanical Wind Mills

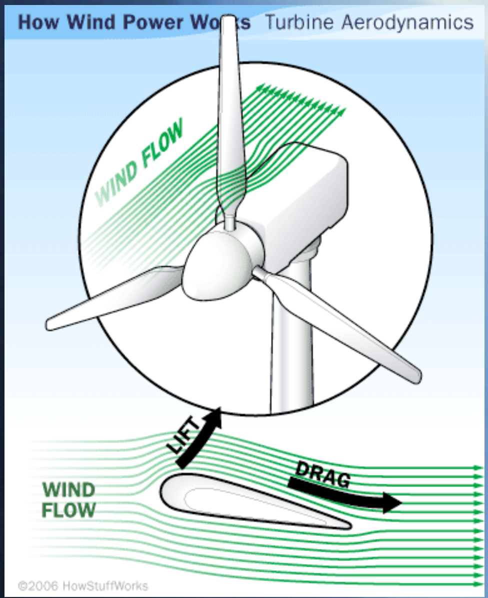
- First recorded use in Afghan highlands in 7th century BC
- Mainly used for grinding grain and pumping water

Electrical Wind Turbines

- First built in 1891 by Dane Poul LaCour
- Small battery-charging turbines common in rural America pre-rural electrification
- Little R&D after WWII outside of small battery charging turbines
- 1970's oil crisis sparked renewed efforts that have led to today's technology

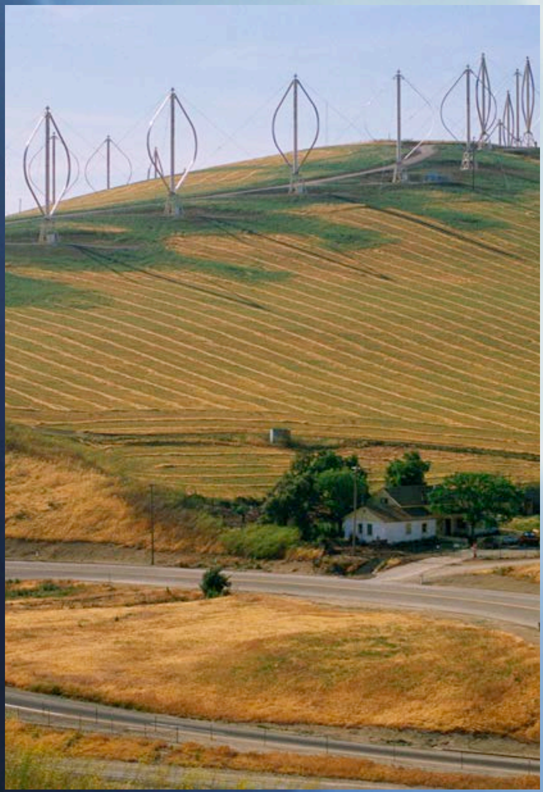
Lift v. Drag





- Power output from a wind turbine is
$$P = \frac{1}{2}\rho A V^3 C_p$$
- Betz limit is 0.593 (maximum theoretical C_p)
- Drag devices have max power coefficient of around 0.16
- Modern lift-based turbines typically have power coefficients from 0.25 to 0.45

Horizontal v. Vertical Axis



- Vertical Axis
  - Independent of wind direction so gearbox and generator can be at ground level.
  - High torque fluctuations, no self-starting capability, limited speed regulation options
- Horizontal Axis has dominated since 1990

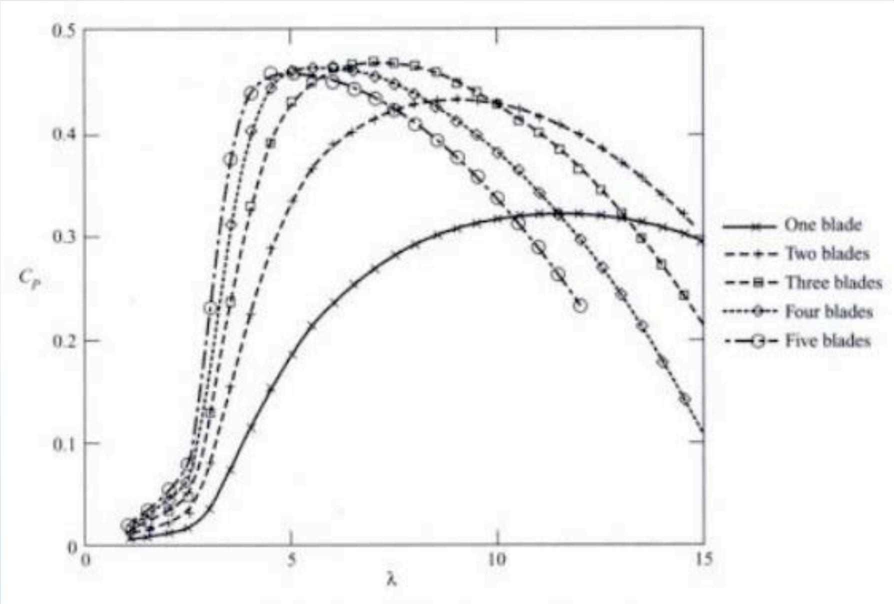
Tip Speed Ratio

- The ratio of the blade tip speed to the wind speed

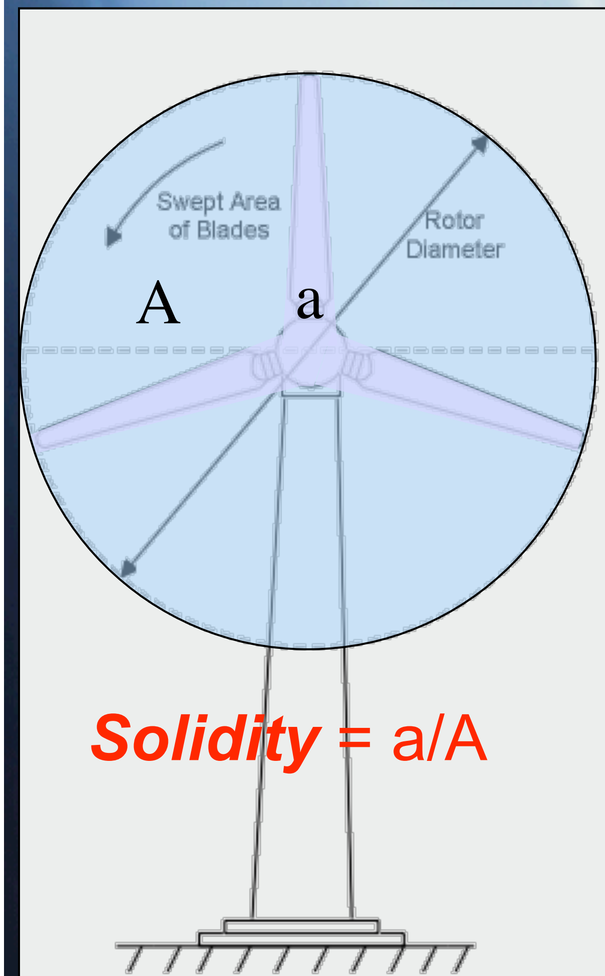
$$\lambda = \frac{\omega R}{V}$$

λ = tip speed ratio, ω = angular frequency, R = rotor radius, V = wind speed

Tip speed ratio key factor in turbine performance



Rotor Solidity



- Solidity is the total blade area divided by the swept area
- Higher solidity
  - Higher torque (higher gearbox costs)
  - Higher thrust (higher tower costs)
  - Higher rotor material costs

One Bladed Machines

- Need to operate at a higher tip speed ratio to capture maximum power
  - Noisier
  - High drag losses (drag proportional to λ^3)
- Counterweight negates much of the material savings

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Two Bladed Machines

- Slightly higher tip speed ratio than 3 bladed machines
  - Slightly noisier
  - Slightly higher drag losses
- Less sensitive to changes in λ
- Lighter structure

Three Bladed Machines

- Balance between high C_p and sensitivity to tip speed ratio
- Visually appealing

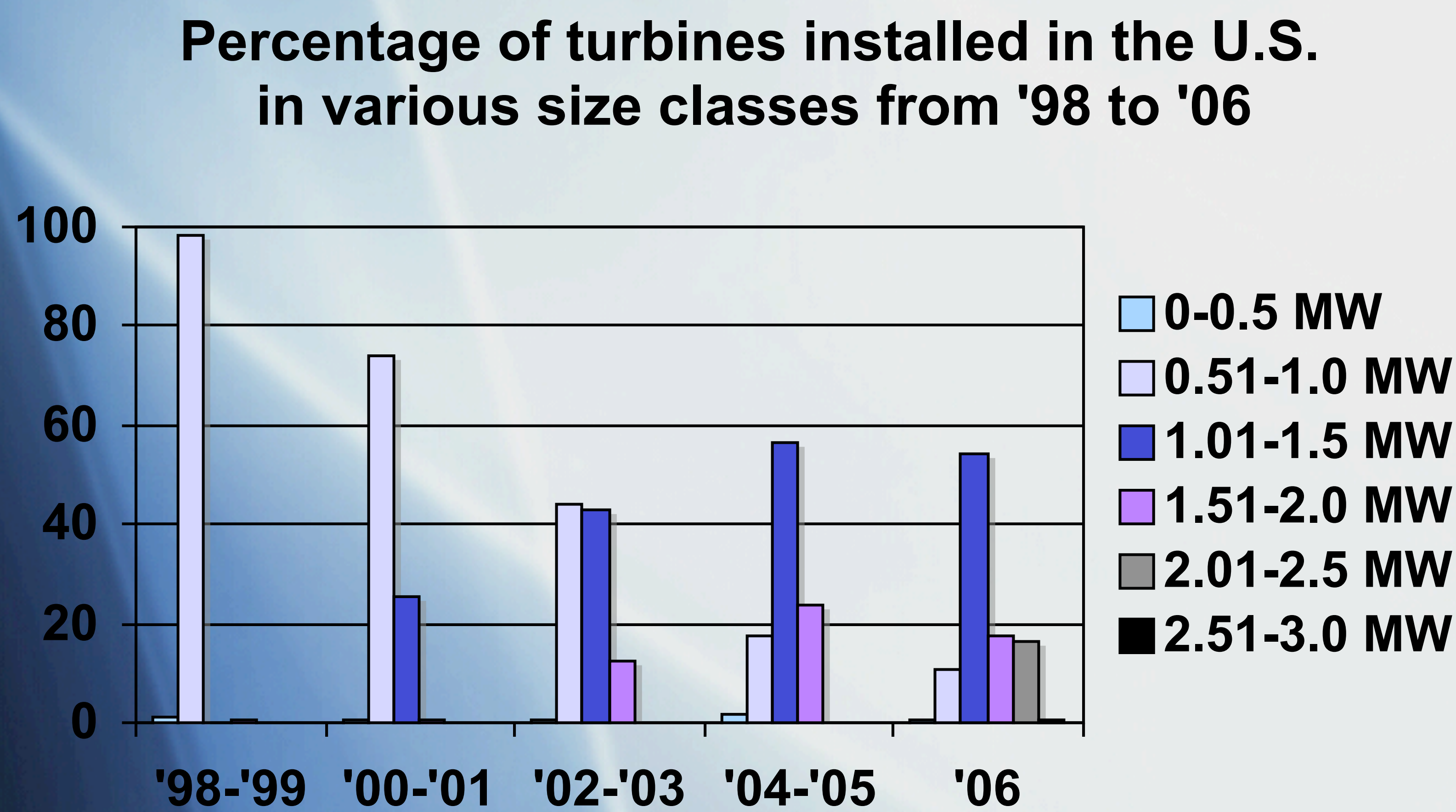
Four^{+} Bladed Machines

- Higher rotor material costs with no additional power potential
- Very sensitive to λ
- Increased torque and thrust cause higher gearbox and tower costs

Upwind v. Downwind

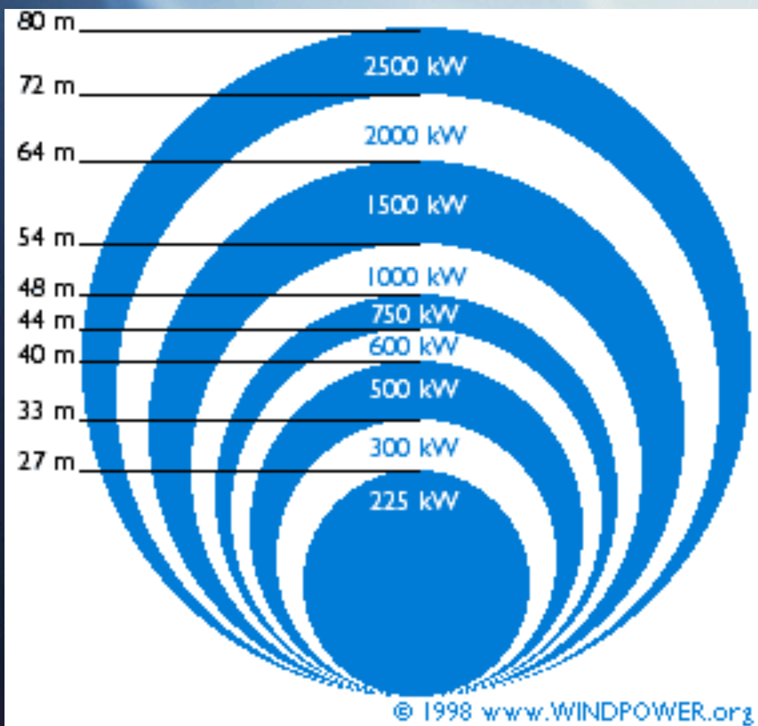
- Downwind
  - Lighter, more flexible blades
  - Noisier (thumping infrasound)
  - Can extend blades further from tower
- Upwind
  - Stiffer blades
    - rotor tilted and blades coned away from tower
  - Reduced dynamic loading
  - Yaw drive keeps blades facing into wind

Bigger is Better?



Source: AWEA

Rotor Size



- How big should the rotor be for a 1.5 MW turbine with a 0.35 C_p and rated wind speed of 13 m/s?

$$P = \frac{1}{2} C_p \rho A V^3$$

$$1{,}500{,}000 = \frac{1}{2} \times 0.35 \times 1.225 \times \Pi r^2 \times 13^3$$

$$diameter = 64m$$

- GE 1.5 sle has a 77m rotor diameter

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Increasing Rotor Sizes

- Low-wind speed R&D one of drivers towards larger rotors
- 45m blades (shown in photo) largest installed in US to date
- European test facilities planning for 100m blades

Tower Type

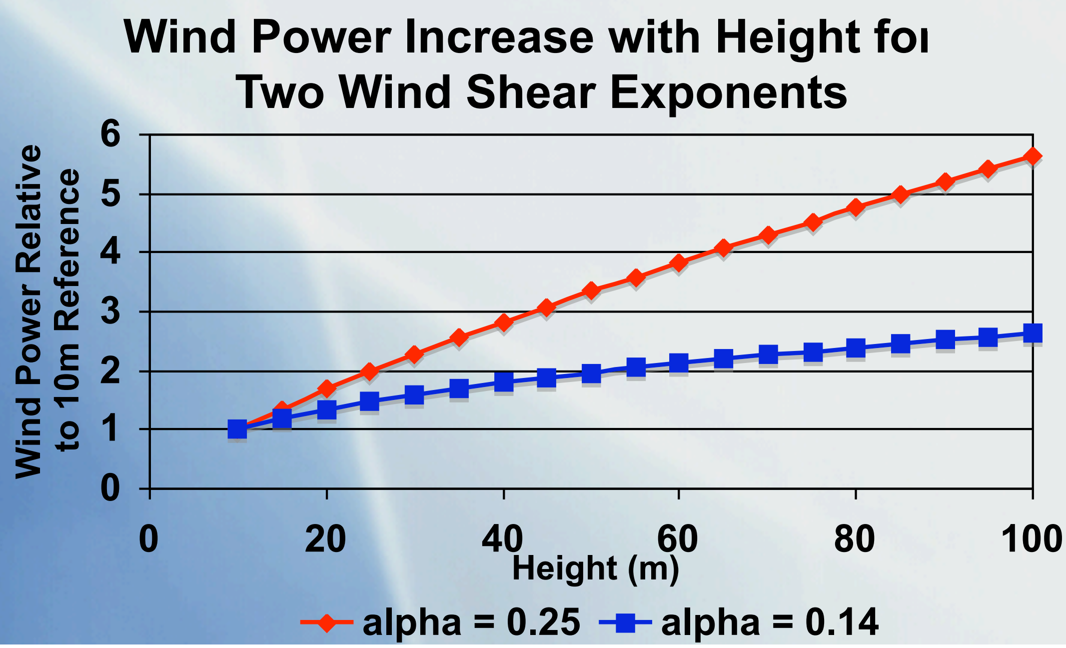
- Lattice towers have given way to tubular steel towers
- Base section limited by transportation
  - 14.5’ diameter, 100,000 lbs

Tower Height

- Wind speed (and tower cost) increases with height

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\alpha}$$

V = wind speed, H = height, α = wind shear exponent



Tower Height

- 80m hub heights standard in New England

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Questions?

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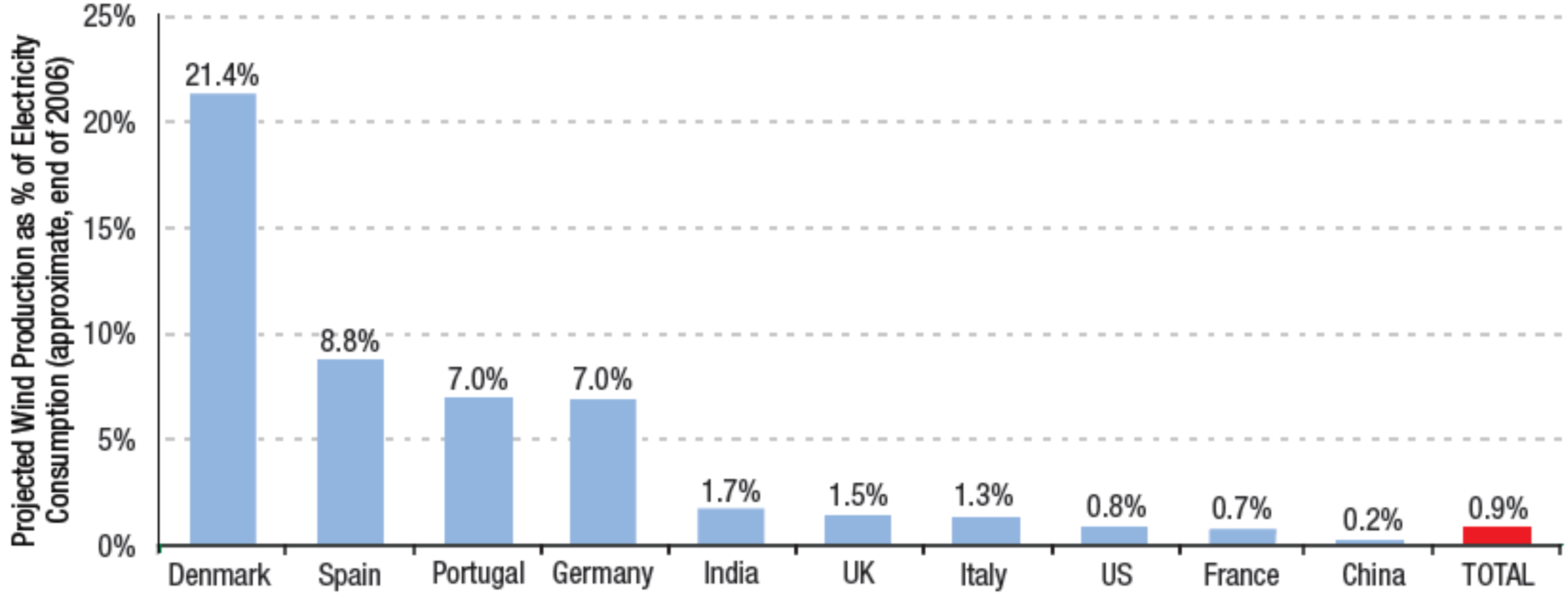
Wind's Potential



Source: Berkeley Lab estimates based on data from BTM and elsewhere.

- A 2005 GE study found NY could accommodate 10% wind energy penetration (3,300MW) with only minor adjustments to its existing planning, operation, and reliability practices.

1970's Oil Shock

- Germany, USA, and Sweden put significant resources towards developing large-scale turbines with little commercial success
- 1978 Public Utility Regulatory Policies Act (PURPA) and tax incentives led to first U.S. wind boom
  - huge wind farms installed in CA
  - 50kW to 200kW machines
  - most machines imported from Denmark
  - 1.2GW installed by '86 accounting for 90% of global installations

Increased European Development

- In the 1990's support for wind faded in the U.S. but picked up in Europe
- Fixed feed-in tariffs were the main mechanism in Europe
  - 2004 German Renewable Energy Sources Act set purchase price as 8.8 Eurocents/kWh for first 5 years and 5.9 Eurocents after that
- 12,000 MW installed in Europe by 2000 compared with 2,500 in U.S.

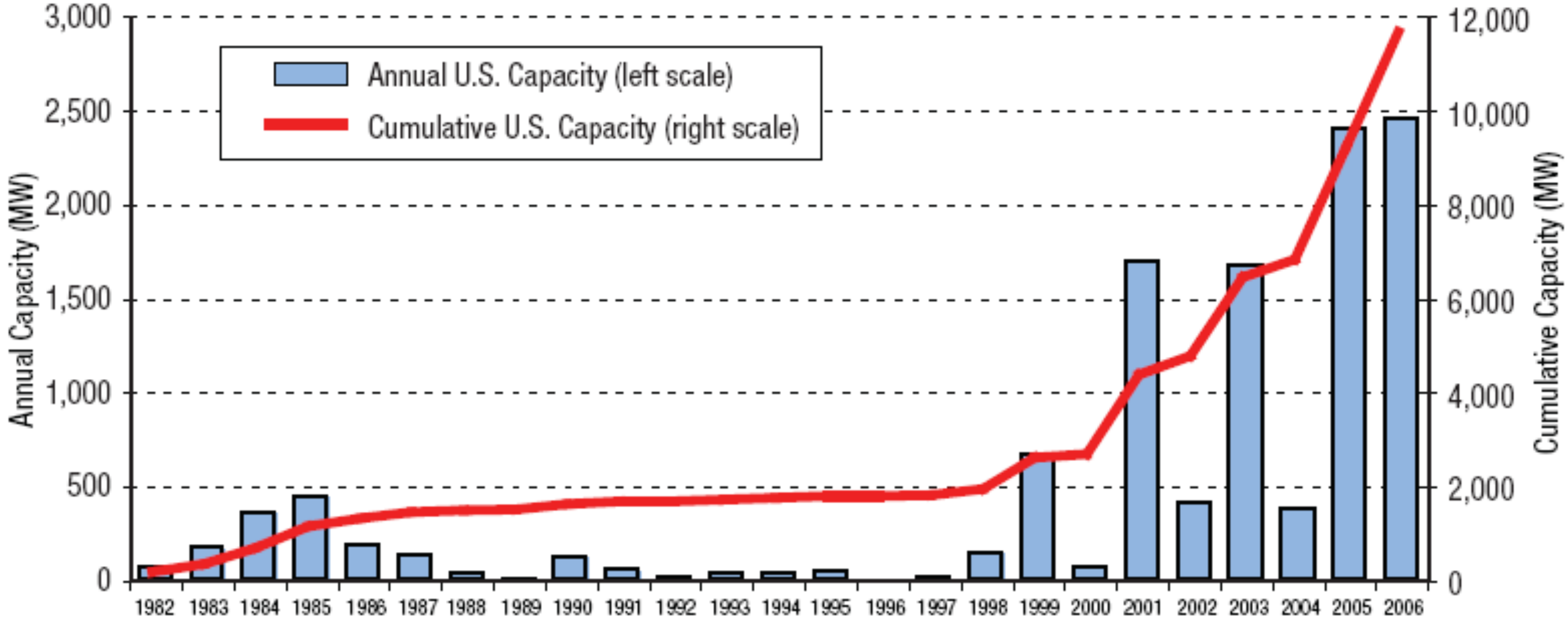
The Indian Boom

- In 1992 government started offering
  - a minimum purchase rate
  - a 100% tax depreciation in the first year of operation
- 'Power Banking' system also introduced in which electricity producers could bank their power and avoid being cut off during load shedding events

Second US Wind Boom

- In 1992 the Production Tax Credit (PTC) was introduced and set to expire in 1999
- PTC added $0.015/kWh for first 10 years of a wind project

US Wind Capacity Takes Off

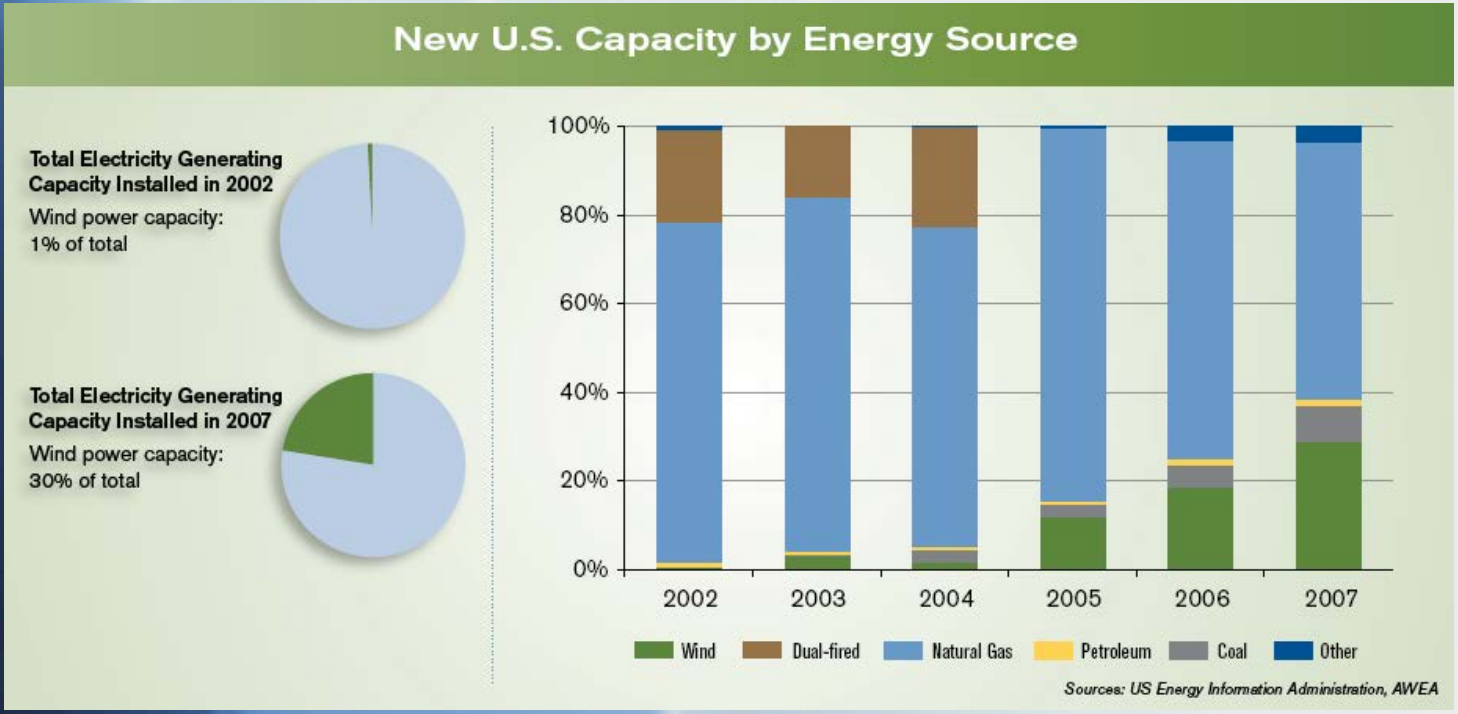


Source: AWEA/GEC database.

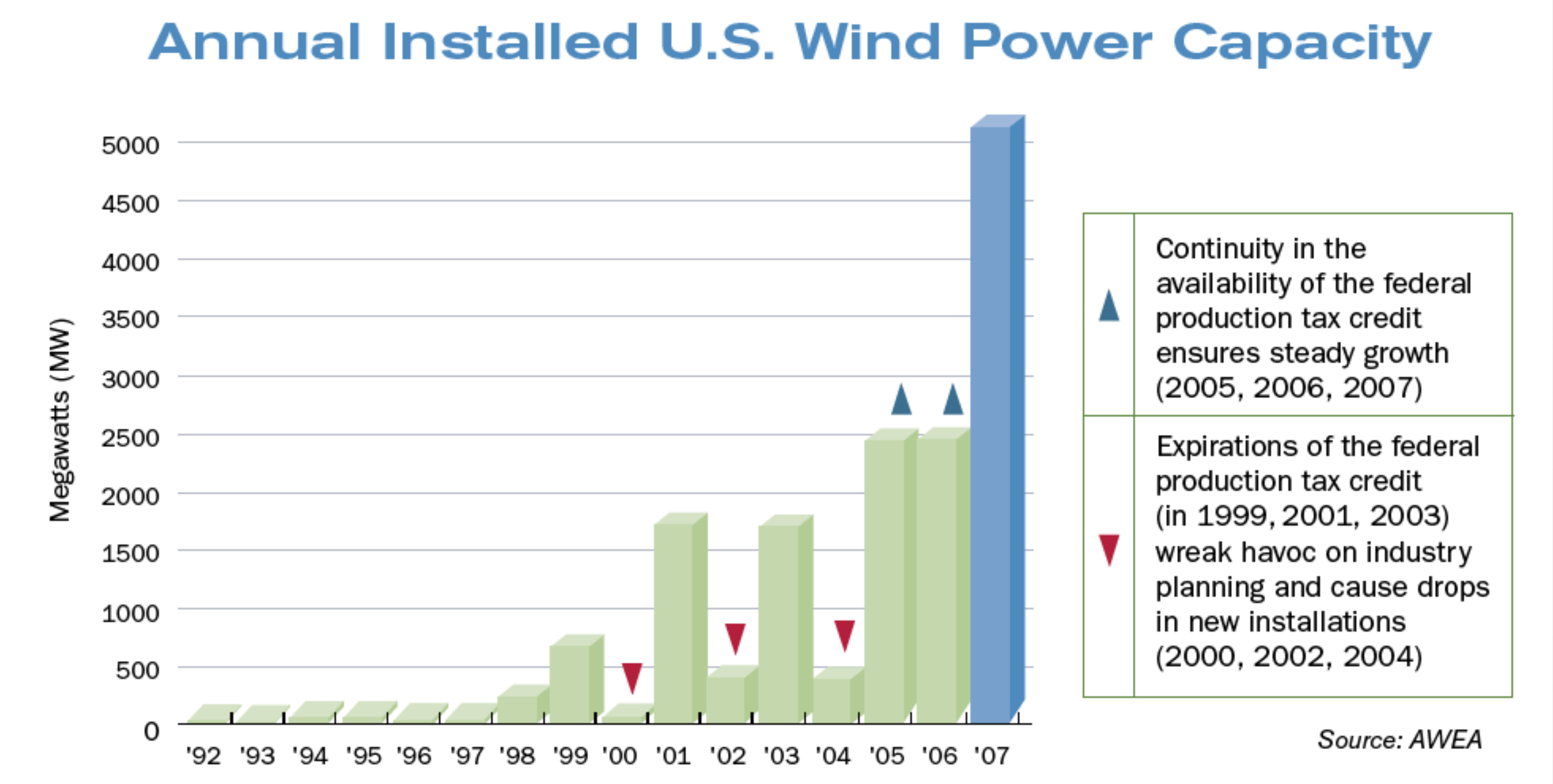
- Since 2005 U.S. has been the largest global wind market

U.S. Wind in Perspective: 2007

- 5,244 MW wind installed
- 17,500 MW total generation installed



PTC's Boom and Bust Cycle



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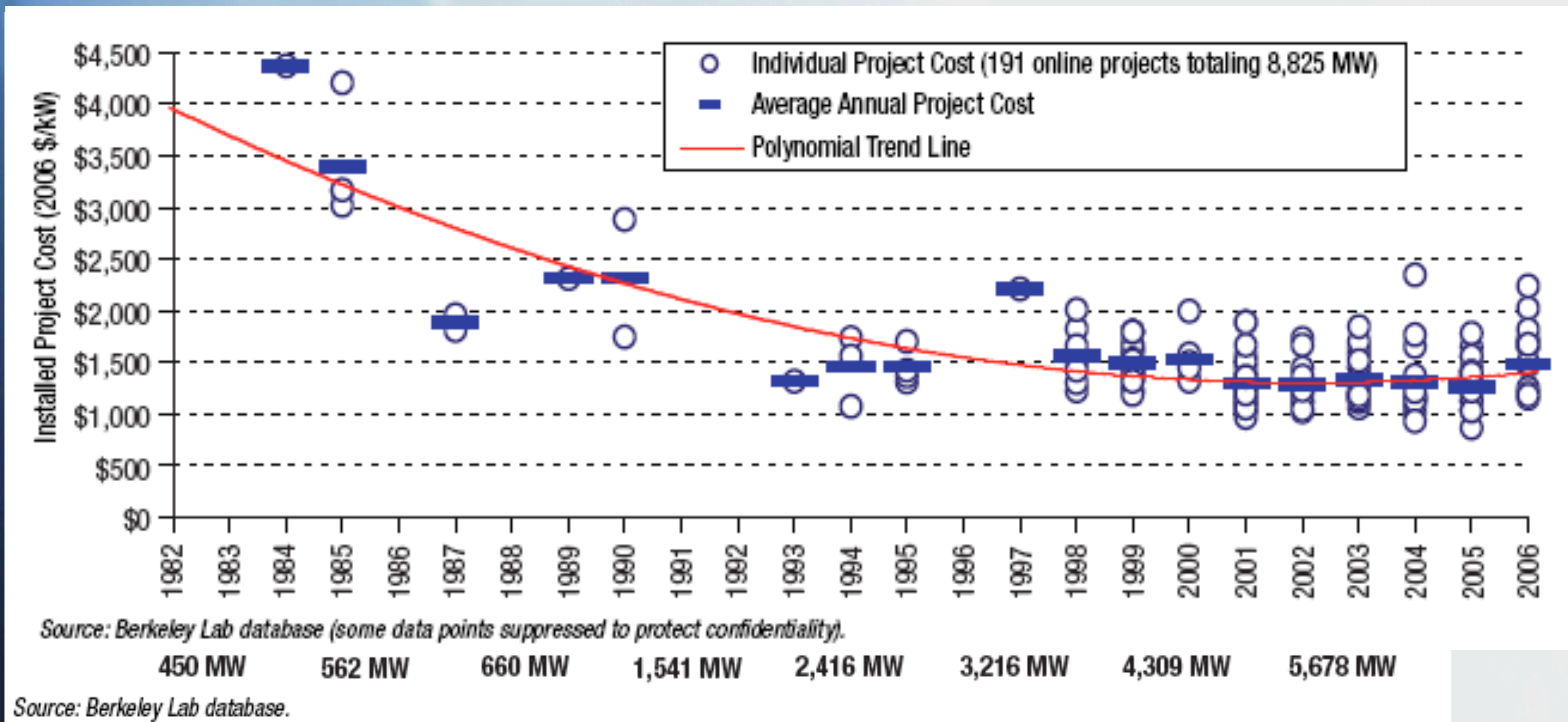
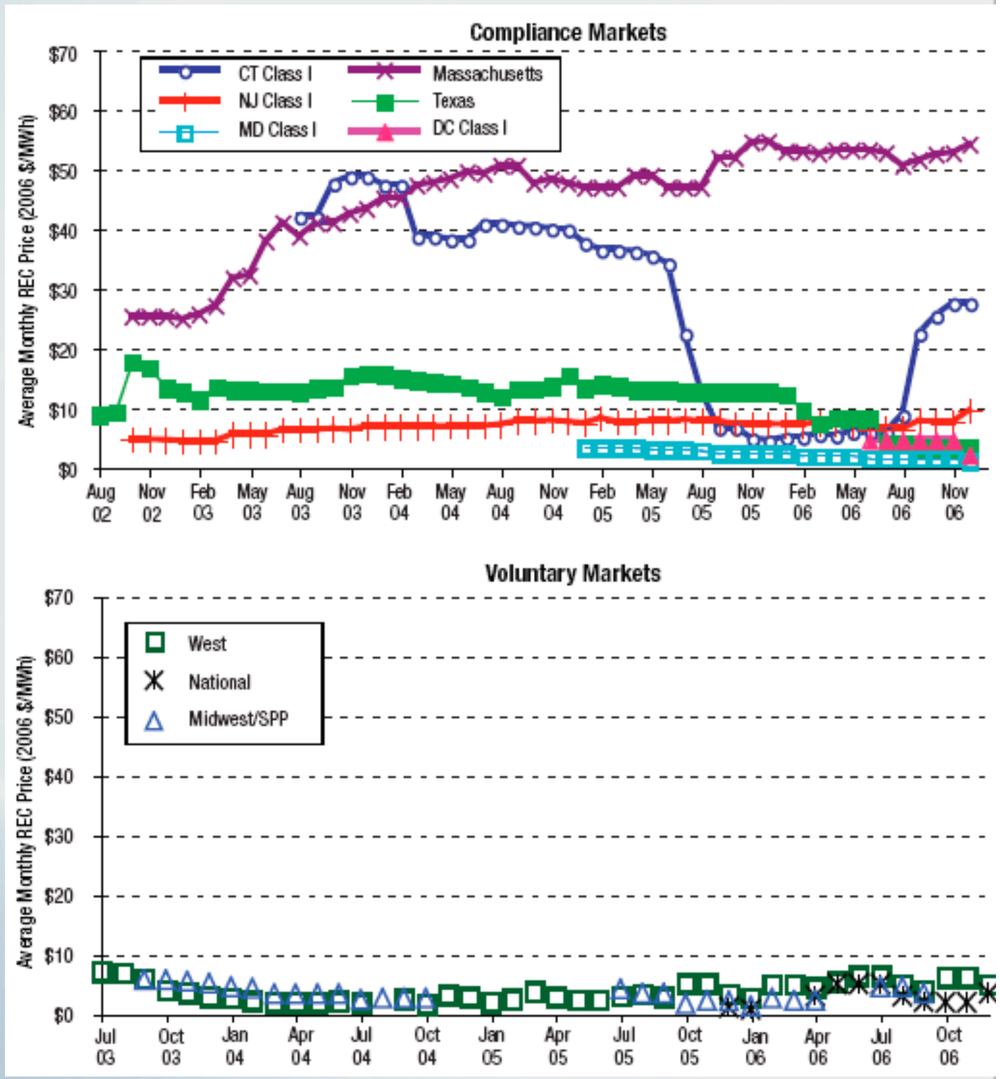
Wind Power Cost Reductions



Installed U.S. Wind Project Costs Over Time

Beyond the PTC

- RPS's drive development
- Voluntary green pricing programs
- Carbon legislation



Jobs and Economic Impact

- 42 MW Mars Hill Project
  - $95M capital investment
  - $10M to town of Mars Hill over 20 years
  - 300 Maine employees during construction
  - 13 permanent Maine employees

Climate and Air Pollution

- Emission-free wind energy displaces other polluting energy sources
- Estimated that 11,000 MW of wind needed in New England to reduce CO_2 to 10% below 1990 levels in 2020 (ME commitment)

Avian Impact

Wind Project and Location	Total Fatalities
Stateline, OR/WA	2.92
Vansycle, OR	0.95
Combine Hills, OR	2.56
Klondike, OR	0.95
Nine Canyon, WA	2.76
Foote Creek Rim, WY (Phase 1)	2.50
Foote Creek Rim, WY (Phase 2)	1.99
Wisconsin	1.97
Buffalo Ridge, MN (Phase 1)	3.27
Buffalo Ridge, MN (Phase 2)	3.03
Buffalo Ridge, MN (Phase 3)	5.93
Top of Iowa	1.44
Buffalo Mountain, TN	11.67
Mountaineer, WV	2.69

Source: Data adapted from Strickland and Johnson (2006)

Total annual avian fatalities per MW from a sampling of operating wind projects

Habitat Disturbance & Land Use
A Comparison

- U.S. Coal mining disturbs 400k ha/yr
- 20% wind would disturb up to 250k ha

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Difficulty Siting Wind Projects in the Northeast

Maple Ridge Wind Farm windmills loom large over Rector Road in West Martinsburg.

NIKO J. KALLIANIOTIS ■ WATERTOWN DAILY

Difficulty Siting Wind Projects in the Northeast

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Tragedy of the Common

"[T]he environmental benefits of wind energy, mainly reductions in atmospheric pollutants, are enjoyed at wide spatial scales, while the environmental costs, mainly aesthetic impacts and ecological impacts such as increased mortality of birds and bats, occur at much smaller spatial scales" and that "[T]here are similar, if less dramatic, disparities in the scales of occurrence of economic and other societal benefits and costs."

- National Research Council of the National Academy of Sciences "Environmental Impacts of Wind-Energy Projects" 2007, p. 148

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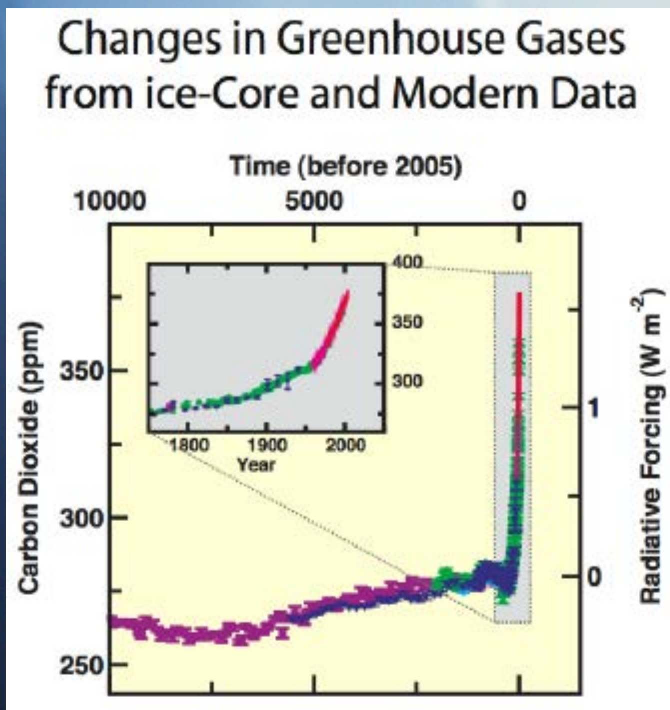
The Alternatives



Studies Find Northeast Mercury Hotspots

January 10, 2007 — By Philip Elliott, Associated Press

CONCORD, N.H. -- Mercury levels near some coal-burning power plants are five times higher than previous government estimates, calling into question how the Environmental Protection Agency

ME Wind Potential

- With current economics ME could site 5,320 MW of land-based wind power, excluding:
  - Very steep slopes
  - State parks, lakes, wildlife refuges
  - 2 mile buffer around AT
  - 85% of National Forest Land
  - 50% of forested lands
- 1,200 MW estimated off-shore potential

New ME Drivers for Wind

- 2007: ISO-NE Forward Capacity Market
- 2007: Renewable Portfolio Standard
  - 10% new renewables by ‘17 starting in ‘08 (310MW)
  - ME ACP starting at $57.12/MWh
- 2008: Wind Legislation
  - At least 2,000 MW of wind by 2015
  - At least 3,000 MW of wind by 2020

Surge in ME Wind Development

- 99 MW of wind power operating in ME
- 1,487 MW of wind power being actively developed in ME
  - average project size = 93 MW

5,320 MW potential (Onshore, current technology)

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Where is the Wind Potential?

- Site screening done for ME Governor’s Task Force on Wind Power Development
- Yellow is not currently economically viable