Development of Modern Large Wind Turbine Design

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Outline

- NH Development
- Common wind turbines today
- Wind turbine history
- Major turbine design decisions
New Hampshire Wind

Lempster Wind
24MW – 12 G87 machines
Built in 2008

Granite Reliable Power
99MW – 33 V90 machines
Proposed construction 2009-2010

Proposed 50MW in Grafton County

Proposed 180MW and 34MW in Coos County

Lempster Wind
24MW – 12 G87 machines
Built in 2008

AWS Mean Wind Speed at 100m
Pink to red is viable for development
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
  \[ P = \frac{1}{2} \rho AV^3 C_p \]
- 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
  \[ \lambda = \frac{\omega R}{V} \]

\( \lambda \) = tip speed ratio, \( \omega \) = 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

Solidity = \( \frac{a}{A} \)
One Bladed Machines

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

- Slightly higher tip speed ratio than 3 bladed machines
  - Slightly noisier
  - Slightly higher drag losses
- Less sensitive to changes in $\lambda$
- 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 $\lambda$
- 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?

Percentage of turbines installed in the U.S. in various size classes from '98 to '06

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
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

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

\( V = \text{wind speed}, \ H = \text{height}, \ \alpha = \text{wind shear exponent} \)
Tower Height

- 80m hub heights standard in New England
Questions?

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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

- 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

**Annual Installed U.S. Wind Power Capacity**

- **Continuity in the availability of the federal production tax credit ensures steady growth (2005, 2006, 2007)**

*Source: AWEA*
Wind Power Cost Reductions

Installed U.S. Wind Project Costs Over Time

Source: Berkeley Lab database (some data points suppressed to protect confidentiality).

Source: Berkeley Lab database.
Beyond the PTC

- RPS’s drive development
- Voluntary green pricing programs
- Carbon legislation
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\textsubscript{2} to 10% below 1990 levels in 2020 (ME commitment)
Avian Impact

<table>
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<tr>
<th>Wind Project and Location</th>
<th>Total Fatalities</th>
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<tr>
<td>Stateline, OR/WA</td>
<td>2.92</td>
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<tr>
<td>Vansycle, OR</td>
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<tr>
<td>Combine Hills, OR</td>
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<tr>
<td>Klondike, OR</td>
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<td>Nine Canyon, WA</td>
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<td>Foote Creek Rim, WY (Phase 2)</td>
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<td>Wisconsin</td>
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<td>Buffalo Ridge, MN (Phase 1)</td>
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<td>Buffalo Mountain, TN</td>
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<td>Mountaineer, WV</td>
<td>2.69</td>
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</table>

Source: Data adapted from Strickland and Johnson (2006)

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

Wind Turbines: Compatible with Birds

Causes of Bird Fatalities, Number per 10,000 fatalities

Habitat Disturbance & Land Use
A Comparison

- U.S. Coal mining disturbs 400k ha/yr
- 20% wind would disturb up to 250k ha
Difficulty Siting Wind Projects in the Northeast
Difficulty Siting Wind Projects in the Northeast
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.”

The Alternatives

Changes in Greenhouse Gases from Ice-Core and Modern Data

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