Wind Power Fundamentals

Presented by:
Alex Kalmikov and Katherine Dykes

With contributions from:
Kathy Araujo

PhD Candidates, MIT Mechanical Engineering, Engineering Systems and Urban Planning

MIT Wind Energy Group & Wind Energy Projects in Action
Overview

- Introduction
- History of Wind Power
- Wind Physics Basics
- Wind Power Fundamentals
- Technology Overview
- Beyond the Science and Technology
- What’s underway @ MIT
Global Cumulative Wind Power Capacity (MW)

Source: EWEA, 2009; Wind Power Monthly, 2010
Wind Potential Worldwide Estimate

40x the current power consumption or more than 5 times global use of all energy forms (Lu et al, 2009)

Wind Notables

- Cost competitive in areas with good wind resource (IEA, 2006)

- Most economically feasible and fastest growing ‘new’ renewable energy

- Wind 35-45% new generation recently added in US and Europe (GWEC, 2009)

- 5 countries account for roughly 75% of total world usage – US, Germany, China, Spain and India

- Share of wind as a % of total power in wind power leaders is on average 10-20% and continuing to increase
Wind Power Status -- 2009

Source: Wind Power Monthly, January 2010
Wind Power in History ...
Brief History – Early Systems

Harvesting wind power is not a new idea – sailing ships, wind-mills, wind-pumps

1st Wind Energy Systems
- Ancient Civilization in the Near East / Persia
- Vertical-Axis Wind-Mill: sails connected to a vertical shaft connected to a grinding stone for milling

Wind in the Middle Ages
- Post Mill Introduced in Northern Europe
- Horizontal-Axis Wind-Mill: sails connected to a horizontal shaft on a tower encasing gears and axles for translating horizontal into rotational motion

Wind in 19th century US
- Wind-rose horizontal-axis water-pumping wind-mills found throughout rural America


Photos by M. J. Roots and Ammodramus on Wikimedia Commons.
1888: Charles Brush builds first large-size wind electricity generation turbine (17 m diameter wind rose configuration, 12 kW generator)

1890s: Lewis Electric Company of New York sells generators to retro-fit onto existing windmills

1920s-1950s: Propeller-type 2 & 3-blade horizontal-axis wind electricity conversion systems (WECS)

1940s – 1960s: Rural Electrification in US and Europe leads to decline in WECS use

Brief History — Modern Era

Key attributes of this period:
• Scale increase
• Commercialization
• Competitiveness
• Grid integration

Catalyst for progress: OPEC Crisis (1970s)
• Economics
• Energy independence
• Environmental benefits

Turbine Standardization:
3-blade Upwind
Horizontal-Axis
on a monopole tower

Source for Graphic: Steve Connors, MIT Energy Initiative

Photo by Stig Nygaard on Flickr.

Courtesy of Stephen Connors. Used with permission.
Wind Physics Basics ...
**Origin of Wind**

**Wind** – Atmospheric air in motion

Energy source

**Solar radiation** differentially absorbed by earth surface converted through convective processes due to temperature differences to air motion

Spatial Scales

**Planetary scale**: global circulation

**Synoptic scale**: weather systems

**Meso scale**: local topographic or thermally induced circulations

**Micro scale**: urban topography

Photo by NASA Visible Earth, Goddard Space Flight Center.

Source for Graphic: NASA Goddard Space Flight Center.
Wind types

- Planetary circulations:
  - Jet stream
  - Trade winds
  - Polar jets
- Geostrophic winds
- Thermal winds
- Gradient winds
- Katabatic / Anabatic winds – topographic winds
- Bora / Foehn / Chinook – downslope wind storms
- Sea Breeze / Land Breeze
- Convective storms / Downdrafts
- Hurricanes / Typhoons
- Tornadoes
- Gusts / Dust devils / Microbursts
- Nocturnal Jets
- Atmospheric Waves
Wind maps from 3TIER and AWS removed due to copyright restrictions.

Source: Steve Connors, MIT Energy Initiative

Courtesy of Stephen Connors. Used with permission.

Source for Wind Map Graphics: AWS Truewind and 3Tier
Wind Power Fundamentals ...
Fundamental Equation of Wind Power

- Wind Power depends on:
  - amount of air (volume)
  - speed of air (velocity)
  - mass of air (density)
  - flowing through the area of interest (flux)

- **Kinetic Energy** definition:
  - KE = \( \frac{1}{2} \times m \times v^2 \)

- Power is KE per unit time:
  - \( P = \frac{1}{2} \times \dot{m} \times v^2 \)

- Fluid mechanics gives **mass flow rate** (density * volume flux):
  - \( \dot{m} = \frac{dm}{dt} = \rho \times A \times v \)

- Thus:
  - \( P = \frac{1}{2} \times \rho \times A \times v^3 \)

- Power ~ cube of velocity
- Power ~ air density
- Power ~ rotor swept area \( A = \pi r^2 \)
Efficiency in Extracting Wind Power

Betz Limit & Power Coefficient:

• Power Coefficient, $C_p$, is the ratio of power extracted by the turbine to the total contained in the wind resource $C_p = \frac{P_T}{P_W}$

• Turbine power output

$$P_T = \frac{1}{2} \rho A v^3 C_p$$

• The **Betz Limit** is the maximal possible $C_p = \frac{16}{27}$

• **59% efficiency** is the **BEST** a conventional wind turbine can do in extracting power from the wind

Please see Betz' Law, Danish Wind Industry Association.
Power Curve of Wind Turbine

Capacity Factor (CF):

- The fraction of the year the turbine generator is operating at rated (peak) power
  \[
  \text{Capacity Factor} = \frac{\text{Average Output}}{\text{Peak Output}} \approx 30\%
  \]

- CF is based on both the characteristics of the turbine and the site characteristics (typically 0.3 or above for a good site)

Power Curve of 1500 kW Turbine

Wind Frequency Distribution
Wind Power Technology ...
Wind Turbine Types

Horizontal-Axis – HAWT
- Single to many blades - 2, 3 most efficient
- Upwind, downwind facing
- Solidity / Aspect Ratio – speed and torque
- Shrouded / Ducted – Diffuser Augmented Wind Turbine (DAWT)

Vertical-Axis – VAWT
- Darrieus / Egg-Beater (lift force driven)
- Savonius (drag force driven)

Photos courtesy of Steve Connors, MITEI

Photos by Louise Docker on Flickr and aarchiba on Wikimedia Commons.
Photo of Windpods, Skystream, and Aerovironment Architectural Wind removed due to copyright restrictions.
Lift and Drag Forces

Images of wind turbine aerodynamics and airfoil forces removed due to copyright restrictions.
Wind Turbine Subsystems

- Foundation
- Tower
- Nacelle
- Hub & Rotor
- Drivetrain
  - Gearbox
  - Generator
- Electronics & Controls
  - Yaw
  - Pitch
  - Braking
  - Power Electronics
  - Cooling
  - Diagnostics

Foundations and Tower

• Evolution from truss (early 1970s) to monopole towers

Photo by Rocco Lucia on Flickr and Leaflet on Wikimedia Commons.

• Many different configurations proposed for offshore

Images from National Renewable Energy Laboratory
Nacelle, Rotor & Hub

- Main Rotor Design Method (ideal case):
  1. Determine basic configuration: orientation and blade number
  2. Take site wind speed and desired power output
  3. Calculate rotor diameter (accounting for efficiency losses)
  4. Select tip-speed ratio (higher → more complex airfoils, noise) and blade number (higher efficiency with more blades)
  5. Design blade including angle of attack, lift and drag characteristics
  6. Combine with theory or empirical methods to determine optimum blade shape


Image removed due to copyright restrictions. Please see Fig. 121 in Fraenkel, P. L. Water Lifting Devices. FAO Irrigation and Drainage Paper 43. Rome, Italy: Food and Agriculture Organization, 1986. ISBN: 9789251025154.
Wind Turbine Blades

- Blade tip speed:

- 2-Blade Systems and Teetered Hubs:

- Pitch control:

Please see Rotor aerodynamics, No. of rotor blades, and Power control of wind turbines, Danish Wind Industry Association.
Electrical Generator

• Generator:
  – Rotating magnetic field induces current

Please see [Synchronous machines and No. of poles, Danish Wind Industry Association](http://wiki.windpower.org/index.php/No._of_poles).

• Synchronous / Permanent Magnet Generator
  – Potential use without gearbox
  – Historically higher cost (use of rare-earth metals)

• Asynchronous / Induction Generator
  – Slip (operation above/below synchronous speed) possible
  – Reduces gearbox wear

• Control methods
  – Drivetrain Speed
    • Fixed (direct grid connection) and Variable (power electronics for indirect grid connection)
  – Blade Regulation
    • Stall – blade position fixed, angle of attack increases with wind speed until stall occurs behind blade
    • Pitch – blade position changes with wind speed to actively control low-speed shaft for a more clean power curve
Wind Grid Integration

- Short-term fluctuations and forecast error
- Potential solutions undergoing research:
  - Grid Integration: Transmission Infrastructure, Demand-Side Management and Advanced Controls
  - Storage: flywheels, compressed air, batteries, pumped-hydro, hydrogen, vehicle-2-grid (V2G)


Left graphic courtesy of ERCOT
Right graphic courtesy of RED Electrica de Espana
Future Technology Development

• Improving Performance:
  – Capacity: higher heights, larger blades, superconducting magnets
  – Capacity Factor: higher heights, advanced control methods (individual pitch, smart-blades), site-specific designs

• Reducing Costs:
  – Weight reduction: 2-blade designs, advanced materials, direct drive systems
  – Offshore wind: foundations, construction and maintenance

Please see American Superconductor, Vergnet Groupe, and Northern Power Systems.
Future Technology Development

• Improving Reliability and Availability:
  – Forecasting tools (technology and models)
  – Dealing with system loads
    • Advanced control methods, materials, preemptive diagnostics and maintenance
      – Direct drive – complete removal of gearbox
  • Novel designs:
    – Shrouded, floating, direct drive, and high-altitude concepts

Please see FloDesign Wind Turbine and Sky Windpower.
Going Beyond the Science & Technology of Wind...
Wind Energy Costs

Image removed due to copyright restrictions. Please see Fig. 1.3 in Krohn, Soren, Poul-Erik Morthorst, and Shimon Awerbuch. "The Economics of Wind Energy." EWEA, March 2009.
% Cost Share of 5 MW Turbine Components

Source: EWEA, 2009, citing Wind Direction, Jan/Feb, 2007
Costs -- Levelized Comparison

Reported in US DOE. 2008 Renewable Energy Data Book
US federal policy for wind energy

- Periodic expiration of Production Tax Credit (PTC) in 1999, 2001, and 2003
- 2009 Stimulus package is supportive of wind power
- Energy and/or Climate Legislation?

Policy Options Available

- Feed-in Tariff
- Guaranteed Markets (Public land)
- National Grid Development
- Carbon Tax/Cap and Trade

Others:
- Quota/Renewable Portfolio Standard
- Renewable Energy Credits (RECs)/Green Certificates
- Production Tax Credit (PTC)
- Investment Tax Credit (ITC)
Communities

Question: At the urban level, do we apply the same level of scrutiny to flag and light poles, public art, signs and other power plants as we do wind turbines?

Considerations: Jobs and industry development; sound and flicker; Changing views (physical & conceptual); Integrated planning;

Cambridge, MA

Photos from Boston Museum of Science Wind Turbine Lab removed due to copyright restrictions.

Graphics Source: Museum of Science Wind Energy Lab, 2010
The Environment

• Cleaner air -- reduced GHGs, particulates/pollutants, waste; minimized opportunity for oil spills, natural gas/nuclear plant leakage; more sustainable effects

• Planning related to wildlife migration and habitats

• Life cycle impacts of wind power relative to other energy sources

• Some of the most extensive monitoring has been done in Denmark – finding post-installation benefits

• Groups like Mass Audubon, Natural Resources Defense Council, World Wildlife Fund support wind power projects like Cape Wind
What’s underway at MIT...
MIT Project Full Breeze

- 3 and 6+ months of data at two sites on MIT’s Briggs Field
- Complemented with statistical analysis using Measure-Correlate-Predict method

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<th>MCP</th>
<th>CFD</th>
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- Research project using Computational Fluid Dynamics techniques for urban wind applications
- Published paper at AWEA Windpower 2010 in Texas
Spatial Analysis of Wind Resource at MIT
3D simulations of wind resource structure at MIT

(a) Wind speed
(b) Turbulence intensity

(c) Turbulence intensity
(d) Wind speed
Wind Power Density at MIT
Q & A

THANK YOU