Wind Power Fundamentals

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Overview

- History of Wind Power
- Wind Physics Basics
- Wind Power Fundamentals
- Technology Overview
- Beyond the Science and Technology
- What’s underway @ MIT
Harvesting wind power isn’t exactly 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

Brief History - Rise of Wind Powered Electricity

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 wind mills

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
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

Source for Graphic: NASA / GSFC
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 Resource Availability and Variability

Source: Steve Connors, MIT Energy Initiative

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):
  - \( \frac{d m}{d t} = \rho \times A \times v \)

- 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
**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)
Lift and Drag Forces
Wind Power Technology …
Wind Turbine

- Almost all electrical power on Earth is produced with a turbine of some type.
- Turbine – converting rectilinear flow motion to shaft rotation through rotating airfoils.

<table>
<thead>
<tr>
<th>Type of Generation</th>
<th>Combustion Type</th>
<th>Turbine Type</th>
<th>Primary Power</th>
<th>Electrical Conversion</th>
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<td>3 Traditional Boiler</td>
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*Source: Steve Connors, MIT Energy Initiative*
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
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

- Many different configurations proposed for offshore

Images from National Renewable Energy Laboratory
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

Wind Turbine Blades

- Blade tip speed:
- 2-Blade Systems and Teetered Hubs:
- Pitch control:

Electrical Generator

• Generator:
  – Rotating magnetic field induces current

• 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 Systems & Electronics

- 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
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

FloDesign WindTurbine

Sky Windpower
Going Beyond the Science & Technology of Wind...

Source: EWEA, 2009
Wind Energy Costs

Source: EWEA, 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
Policy Support Historically

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?

Δ Generation Capacity [MW]

-100 0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400

1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005

PTC Expirations

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;

The view from the southwest shows (left to right) the vertical-axis Mariah Windspire, Southwest Skystream, Swift, five AeroVironment AVX1000s, and Proven 6.

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

Graphic Source: Elsam Engineering and Enegi and Danish Energy Agency
What’s underway at MIT...

• Research project using Computational Fluid Dynamics techniques for urban wind applications

• Published paper at AWEA WindPower 2010 conference in Texas

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<th>Met station 1</th>
<th>MCP</th>
<th>CFD</th>
<th>MCP</th>
<th>CFD</th>
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<td>45%</td>
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<td>28%</td>
<td>n/a</td>
<td>30%</td>
<td>51%</td>
<td>33%</td>
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</table>
Spatial Analysis of Wind Resource at MIT
3D model of MIT campus
3D simulations of wind resource structure at MIT

(a) Wind speed
(b) Wind speed
(c) Turbulence intensity
(d) Turbulence intensity
Wind Power Density at MIT

Wind Power Density (W/m²)
Q & A

THANK YOU