Introduction to Wind Power

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With contributions from:
Katherine Dykes and Kathy Araujo
MIT Wind Energy Projects in Action (WEPA)

Overview

- US Wind Energy Market Update
- Brief History of Wind Power
- Wind Physics Basics
- Wind Power Fundamentals
- Technology Overview
2014 U.S. Wind Energy Market Update

- U.S. Annual and Cumulative Wind Power Capacity

- 65,879 MW total wind capacity, over 48,000 utility-scale wind turbines
- 18% of global wind energy capacity


World Wind Power Installations

Source: GWEC - Global Wind Energy Council
2014 Global Cumulative Capacity

**TOP 10 CUMULATIVE CAPACITY DEC 2014**

<table>
<thead>
<tr>
<th>Country</th>
<th>MW</th>
<th>% SHARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR China</td>
<td>114,609</td>
<td>31.0</td>
</tr>
<tr>
<td>USA</td>
<td>65,879</td>
<td>17.8</td>
</tr>
<tr>
<td>Germany</td>
<td>39,165</td>
<td>10.6</td>
</tr>
<tr>
<td>Spain</td>
<td>22,987</td>
<td>6.2</td>
</tr>
<tr>
<td>India</td>
<td>22,465</td>
<td>6.1</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>12,440</td>
<td>3.4</td>
</tr>
<tr>
<td>Canada</td>
<td>9,694</td>
<td>2.6</td>
</tr>
<tr>
<td>France</td>
<td>9,285</td>
<td>2.5</td>
</tr>
<tr>
<td>Italy</td>
<td>8,663</td>
<td>2.3</td>
</tr>
<tr>
<td>Brazil*</td>
<td>5,939</td>
<td>1.6</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>58,473</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>Total TOP 10</strong></td>
<td><strong>311,124</strong></td>
<td><strong>84.2</strong></td>
</tr>
<tr>
<td><strong>World Total</strong></td>
<td><strong>369,597</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

*Projects fully commissioned, grid connection pending in some cases  
Source: GWEC

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**U.S. Electricity Generation Mix**

- Wind energy provided 4.4% of the nation’s electricity during 2014
- One third of all renewable sources (13% of total)

Source: AWEA U.S. Wind Industry Annual Market Report 2013,  
DOE Wind Technologies Market Report 2014
Energy Cost by Generation Source

Wind Energy Growth and Cost Reduction

Source: AWEA, EIA, Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013

Source: US Department of Energy
Wind Power Price Trends

Source: Berkeley Lab, DOE Wind Technologies Market Report 2014

U.S. Wind Power Capacity Installations, by State

- Hoover Dam - 2,080 MW
- Pilgrim Nuclear Generating Station - 680 MW

U.S. Wind Energy Share of Electricity Generation, by State

- Iowa and South Dakota exceeded 25% generation from wind energy
- 9 states produced more than 10% of their generation from wind energy
- 6 states above 15%.

Market Share of U.S. Wind Power Capacity, by Owner

- 46,100 wind turbines, 61,110 MW capacity
- Average wind turbine installed during 2013:
  - rating of 1.87-MW
  - hub height 80 meters
  - rotor diameter 97 meters


Market Share for Wind Turbine Manufacturers of U.S. Wind Power Fleet

- The top three wind turbine manufacturers:
  - GE Energy - 40%
  - Vestas - 19%
  - Siemens - 14%

U.S. Manufacturing and Employment

- 560 manufacturing facilities
- 43 states
  - 12 utility-scale blade facilities
  - 14 tower facilities
  - 9 turbine nacelle assembly facilities
- Domestic manufacturing has grown from **25%** (2005) to **72%** (2012)
- **50,500** full-time equivalent jobs directly associated with wind energy project planning, siting, development, construction, manufacturing and supply chain, and operations


Wind Power in History …
**Brief History – Early Systems**

Harvesting wind power – centuries-long history

• 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


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**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 …**
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

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

Source for Graphic: NASA / GSFC
Wind Resource Variability and Uncertainty

Spatial variability

Diurnal and Seasonal Cycles

Temporal variability

Wind Profile Structure

Wind Veering

Turbulent profile

Land Roughness and Wind Shear
Climate and Weather Models

- Global Climate Model (GCM)
- Numerical Weather Prediction Models (NWP)
- Computational Fluid Dynamics (CFD)

CFD model of wind resource structure at MIT

- Wind speed
- Turbulence intensity
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 (mass, velocity):
  • KE = \( \frac{1}{2} \cdot m \cdot U^2 \)

– Power is KE per unit time:
  • \( P = \frac{1}{2} \cdot \frac{dm}{dt} \cdot U^2 \)

– Thus:
  • \( P = \frac{1}{2} \cdot \rho \cdot A \cdot U^3 \)

• Power ~ cube of velocity
• Power ~ air density
• Power ~ rotor area ~ square of radius
\( A = \pi \cdot r^2 \)
Wind Power Density

Wind Power per unit Area:

\[ WPD \equiv \frac{P}{A} = \frac{1}{2} \rho U^3 \]

Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m</th>
<th>Wind Speed(^a) at 50 m</th>
<th>Wind Speed(^a) at 50 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>0 - 200</td>
<td>0.0 - 6.0</td>
<td>0.0 - 13.4</td>
<td></td>
</tr>
<tr>
<td>Marginal</td>
<td>200 - 300</td>
<td>6.0 - 6.8</td>
<td>13.4 - 15.2</td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td>300 - 400</td>
<td>6.8 - 7.5</td>
<td>15.2 - 16.8</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>400 - 500</td>
<td>7.5 - 8.1</td>
<td>16.8 - 18.1</td>
<td></td>
</tr>
<tr>
<td>Excellent</td>
<td>500 - 600</td>
<td>8.1 - 8.6</td>
<td>18.1 - 19.3</td>
<td></td>
</tr>
<tr>
<td>Outstanding</td>
<td>600 - 800</td>
<td>8.6 - 9.5</td>
<td>19.3 - 21.3</td>
<td></td>
</tr>
<tr>
<td>Superb</td>
<td>&gt; 800</td>
<td>&gt; 9.5</td>
<td>&gt; 21.3</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Wind speeds are based on a Weibull \(k\) of 2.4 at 500 m elevation.


Weibull Distribution of Wind Speed

Parameters:

- Scale factor: \(\lambda\)
- Shape factor: \(k\)

Probability distribution:

\[ pdf(U) = \frac{k}{\lambda} \left(\frac{U}{\lambda}\right)^{k-1} \exp\left[-\left(\frac{U}{\lambda}\right)^{k}\right] \]

- Exponential pdf \(k=1\)
- Rayleigh pdf \(k=2\)

Mean speed:

\[ \overline{U} = \lambda \Gamma\left(1 + \frac{1}{k}\right) \]

Standard deviation:

\[ \sigma_{STD} = \overline{U} \sqrt{\frac{\Gamma(1 + 2/k)}{\Gamma^2(1 + 1/k)}} - 1 \]

U.S. Department of Energy
National Renewable Energy Laboratory

United States - Wind Resource Map

Weibull Distribution of Wind Speed

\[ \lambda = 1, k = 0.5 \]
\[ \lambda = 1, k = 1 \]
\[ \lambda = 1, k = 1.5 \]
\[ \lambda = 1, k = 2 \]
Average Wind Power Density

\[ WPD = \frac{P}{A} = \frac{1}{2} \rho U^3 \]

Average Power Density

\[ WPD = \frac{1}{2} \rho U^3 K_E \]

Energy Pattern Factor

\[ K_E \equiv \frac{WPD}{\frac{1}{2} \rho U^3} = \frac{U^3}{U^3} = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)} \quad \text{for Weibull pdf} \]

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 power contained in the wind resource \( C_p = \frac{P_T}{P_{\text{Wind}}} \)
- Turbine power capture

\[ P_T = \frac{1}{2} \rho \cdot A \cdot U^3 \cdot C_p \]

- The Betz Limit is the maximal possible \( C_p = 16/27 \)
- 59% efficiency is the BEST a conventional wind turbine can do in extracting power from the wind
**Power Production and Wind Variability**

**Capacity Factor (CF):**
- The fraction of the year the turbine generator is operating at rated power (nominal capacity)

\[
\text{Annual Energy Generation} = \text{Rated Power} \cdot \text{Year} \cdot \text{CF}
\]

or equivalently

\[
\text{CF} = \frac{\text{Average Power}}{\text{Rated Power}} = 30\%
\]

- CF is based on both the characteristics of the turbine and the site – integrating the power curve with the wind resource variability

\[
\text{CF} = \frac{E_{\text{actual}}}{E_{\text{ideal}}} = \frac{\text{time} \cdot \overline{P}}{\text{time} \cdot P_N} = \frac{\overline{P}}{P_N} = \frac{E_{\text{actual}} / P_N}{\text{time}} = \frac{\text{time}}{\text{effective time}}
\]

![Power Curve of 2 MW Turbine](image1)

![Wind Frequency Distribution](image2)
Turbine

- *Turbine* from Latin *turbo*: whirl, vortex
- Turbine: rotary engine – converting rectilinear flow motion to shaft rotation through rotating airfoils

Lift and Drag Forces

- Aerodynamic forces
- Airfoil – “wing”

Changing Angle of attack ↔ Pitch angle
Turbines in Power Generation

- Almost all electrical power on Earth is produced with a turbine of some type

<table>
<thead>
<tr>
<th>Type of Generation</th>
<th>Combustion Type</th>
<th>Turbine Type</th>
<th>Primay Power</th>
<th>Electrical Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>³ Traditional Boiler</td>
<td>External</td>
<td>Gas</td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Fluidized Bed Combustion</td>
<td>External</td>
<td>Steam</td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Integrated Gasification Combined-Cycle</td>
<td>Both</td>
<td>Water</td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Combustion Turbine Combined Cycle</td>
<td>Internal Both</td>
<td>Aero</td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Nuclear</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Diesel Genset</td>
<td>Internal</td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Micro-Turbines</td>
<td>Internal</td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Fuel Cells</td>
<td></td>
<td></td>
<td></td>
<td>Direct Inverter</td>
</tr>
<tr>
<td>Hydropower</td>
<td>External</td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Biomass &amp; WTE</td>
<td>External</td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Windpower</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Photovoltaics</td>
<td></td>
<td></td>
<td></td>
<td>Direct Inverter</td>
</tr>
<tr>
<td>³ Solar Thermal</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Geothermal</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Wave Power</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>Tidal Power</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
<tr>
<td>³ Ocean Thermal</td>
<td></td>
<td></td>
<td>Shaft Generator</td>
<td></td>
</tr>
</tbody>
</table>

Source: Steve Connors, MIT Energy Initiative

Wind Turbine Types

- Horizontal-Axis – HAWT vs.
- Vertical-Axis – VAWT

- Upwind facing vs.
- Downwind facing

- Lift force driven vs.
- Drag force driven

Photos courtesy of Steve Connors, MITEI
Wind Turbine Types

Vertical-Axis – VAWT
- Darrieus / Egg-Beater (lift force)
- Giromills
- Gorlov helical turbine
- Savonius (drag force)
- Lift / Drag force combinations

Horizontal-Axis – HAWT
- One bladed
- Two bladed
- Three bladed
- ... Multi bladed

Rotor Solidity

*Blade planform* is the shape of the flatwise blade surface

*Solidity* is the ratio of total rotor planform area to total swept area

Low solidity (0.10) = high speed, low torque

High solidity (>0.80) = low speed, high torque

Solidity = $3a/A$
Tip-Speed Ratio

Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the free stream wind.

\[
\lambda = \frac{\Omega R}{V}
\]

Where,
\[\Omega = \text{rotational speed in radians/sec}\]
\[R = \text{Rotor Radius}\]
\[V = \text{Free Stream Velocity}\]

- Normalized turbine rate of rotation
- Scaled by rotor size and wind speed

Rotor Design

Power Coefficient, \(C_p\)

Torque Coefficient
Wind Turbine Subsystems

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


Control Methods

- Drivetrain Speed
  - **Fixed** (direct grid connection)
  - **Variable** (power electronics for indirect grid connection)

- Blade Regulation
  - **Stall** – blade pitch angle fixed, angle of attack increases with wind speed until stall occurs behind blade
  - **Pitch** – blade pitch angle adjusted with wind speed to actively control shaft rotation speed for a clean power curve
Future Technology Development

- Novel designs:
  - Shrouded turbines
  - Floating turbines
  - Flying turbines:
    • Lighter-than-air (LTA)
    • Heavier-than-air (HTA)

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, advanced materials

- Improving Reliability and Availability:
  - Forecasting tools (technology and models)
  - Dealing with system loads,
    • preemptive diagnostics and maintenance
  - Direct drive – complete removal of gearbox
Wind Turbine Generator (WTG) Classes

IEC 61400-1 International Standard for WTG Design

<table>
<thead>
<tr>
<th>WTG Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average wind speed [m/s]</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>6</td>
<td>Special</td>
</tr>
<tr>
<td>50 year extreme wind speed [m/s]</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td>30</td>
<td>Special</td>
</tr>
<tr>
<td>50 year extreme gust speed [m/s]</td>
<td>70</td>
<td>59.5</td>
<td>52.5</td>
<td>42</td>
<td>Special</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbulence Class</th>
<th>I$_{15}$ turbulence intensity at 15 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>18%</td>
</tr>
<tr>
<td>Class B</td>
<td>16%</td>
</tr>
</tbody>
</table>

Reliability and Safety guidelines for turbine selection

- High wind site: IA
- Low wind site: IIIB

Wind Turbine Selection

Technical Data

<table>
<thead>
<tr>
<th>Data</th>
<th>1.5s</th>
<th>1.5se</th>
<th>1.5sl (50Hz only)</th>
<th>1.5sle</th>
<th>1.5xle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Rated capacity:</td>
<td>1,500 kW</td>
<td>1,500 kW</td>
<td>1,500 kW</td>
<td>1,500 kW</td>
<td>1,500 kW</td>
</tr>
<tr>
<td>• Cut-in wind speed:</td>
<td>4 m/s</td>
<td>4 m/s</td>
<td>4 m/s</td>
<td>4 m/s</td>
<td>4 m/s</td>
</tr>
<tr>
<td>• Cut-out wind speed (10 min. avg):</td>
<td>25 m/s</td>
<td>25 m/s</td>
<td>20 m/s</td>
<td>20 m/s</td>
<td>20 m/s</td>
</tr>
<tr>
<td>• Rated wind speed:</td>
<td>13 m/s</td>
<td>13 m/s</td>
<td>14 m/s</td>
<td>14 m/s</td>
<td>12.5 m/s</td>
</tr>
<tr>
<td>• Wind Class - IEC:</td>
<td>IIA</td>
<td>III</td>
<td>II</td>
<td>II</td>
<td>II</td>
</tr>
<tr>
<td>• Wind Class - DIBT WZ:</td>
<td>II/III</td>
<td>-</td>
<td>II</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rotor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Number of rotor blades:</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>• Rotor diameter:</td>
<td>70.5 m</td>
<td>70.5 m</td>
<td>77 m</td>
<td>77 m</td>
<td>82.5 m</td>
</tr>
<tr>
<td>• Swept area:</td>
<td>3964 m$^2$</td>
<td>3964 m$^2$</td>
<td>4657 m$^2$</td>
<td>4657 m$^2$</td>
<td>5346 m$^2$</td>
</tr>
<tr>
<td>• Rotor speed (variable):</td>
<td>12.0 - 22.2 rpm</td>
<td>12.0 - 22.2 rpm</td>
<td>11.0 - 20.4 rpm</td>
<td>11.0 - 20.4 rpm</td>
<td>10.1 - 18.7 rpm</td>
</tr>
<tr>
<td>Tower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Hub heights - IEC:</td>
<td>64.7 m</td>
<td>54.7/64.7 m</td>
<td>-</td>
<td>61.4/64.7/80 m</td>
<td>58.7/80/100 m</td>
</tr>
<tr>
<td>• Hub heights - DIBT</td>
<td>64.7 m</td>
<td>-</td>
<td>61.4 to 100 m</td>
<td>61.4/64.7/80/85/100 m</td>
<td>58.7/80/100 m</td>
</tr>
</tbody>
</table>


Source: GE Energy 1.5MW Series Wind Turbine.
www.geenergy.com
Trivia

• What is the largest wind turbine in the world? *(Largest Capacity)*

**Enercon E-126**

• Rotor Diameter: 127 m (413 ft)
• Hub height: 135 m (443 ft)
• Total height: 198 m (650 ft)
• Rated Power (Capacity): 7.5 MW
• Measured Power: up to 7.7 MW
• IEC Wind Class: IA
• Cut-out wind speed: 28 - 34 m/s
• Gearless direct-drive generator
• Variable speed
• Single blade pitch control
• State of the art power electronics

Q & A

THANK YOU
The annual wind power estimates for this map were produced by TrueWind Solutions using their Mesomap system and historical weather data. This work was commissioned by the Massachusetts Technology Collaborative, in conjunction with the Connecticut Clean Energy Fund and Northeast Utilities, and the results have been validated by NREL.

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<th>Wind Speed at 50 m m/s</th>
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<td>Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.8 - 17.9</td>
</tr>
<tr>
<td>Outstanding</td>
<td>600 - 600</td>
<td>8.5 - 8.8</td>
<td>17.6 - 19.7</td>
</tr>
<tr>
<td>Superb</td>
<td>&gt; 600</td>
<td>&gt; 8.8</td>
<td>&gt; 19.7</td>
</tr>
</tbody>
</table>

* Wind speeds are based on a Weibull k value of 2.0

Wind Power Density at MIT
NIMBY – "Not In My Back Yard"