



Wind Power Fundamentals

Presented by:

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With contributions from:

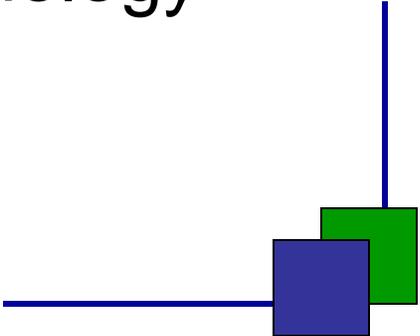
Kathy Araujo

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Engineering, Engineering Systems and
Urban Planning***

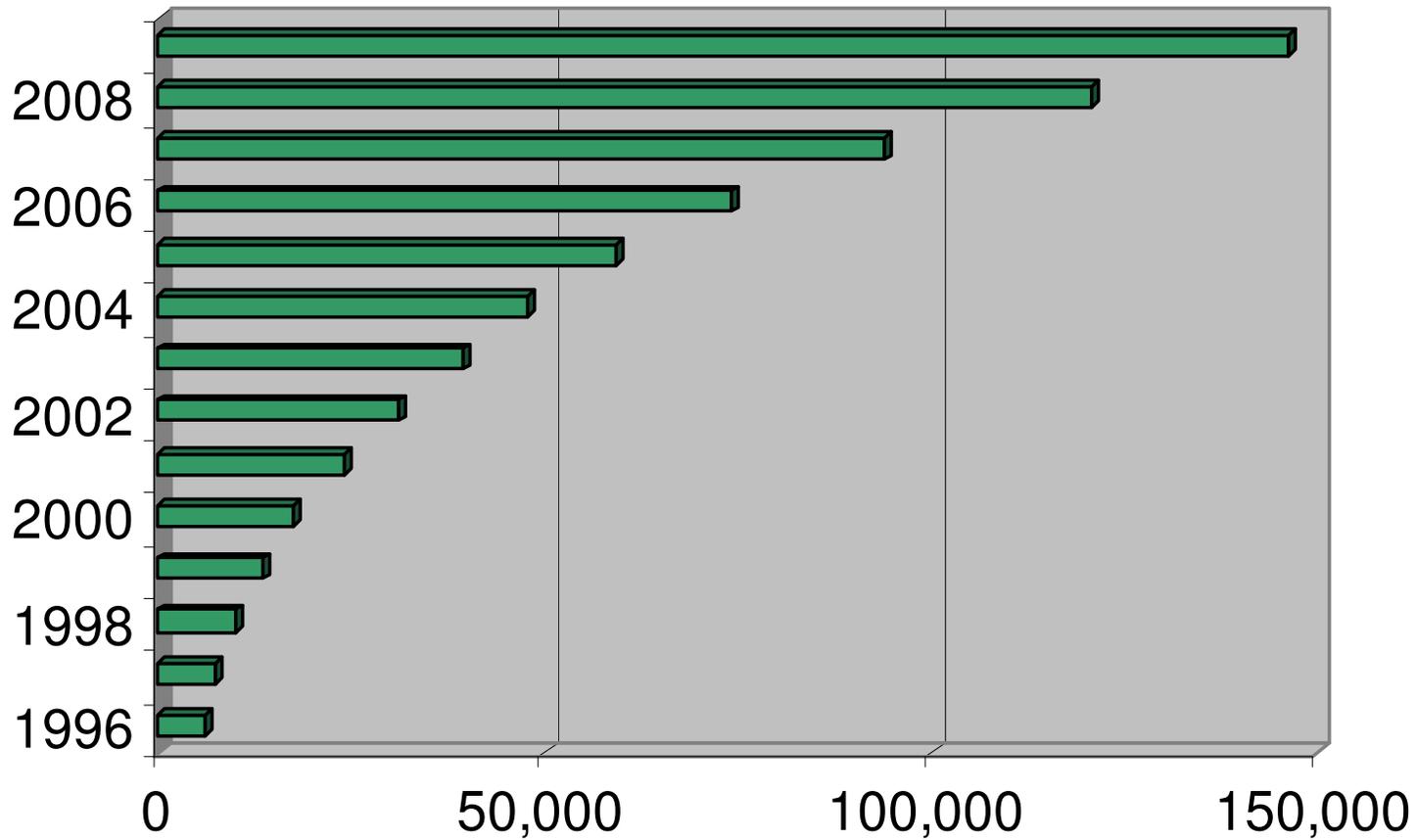
*MIT Wind Energy Group &
Wind Energy Projects in Action*



Overview

- Introduction
 - History of Wind Power
 - Wind Physics Basics
 - Wind Power Fundamentals
 - Technology Overview
 - Beyond the Science and Technology
 - What's underway @ MIT
- 

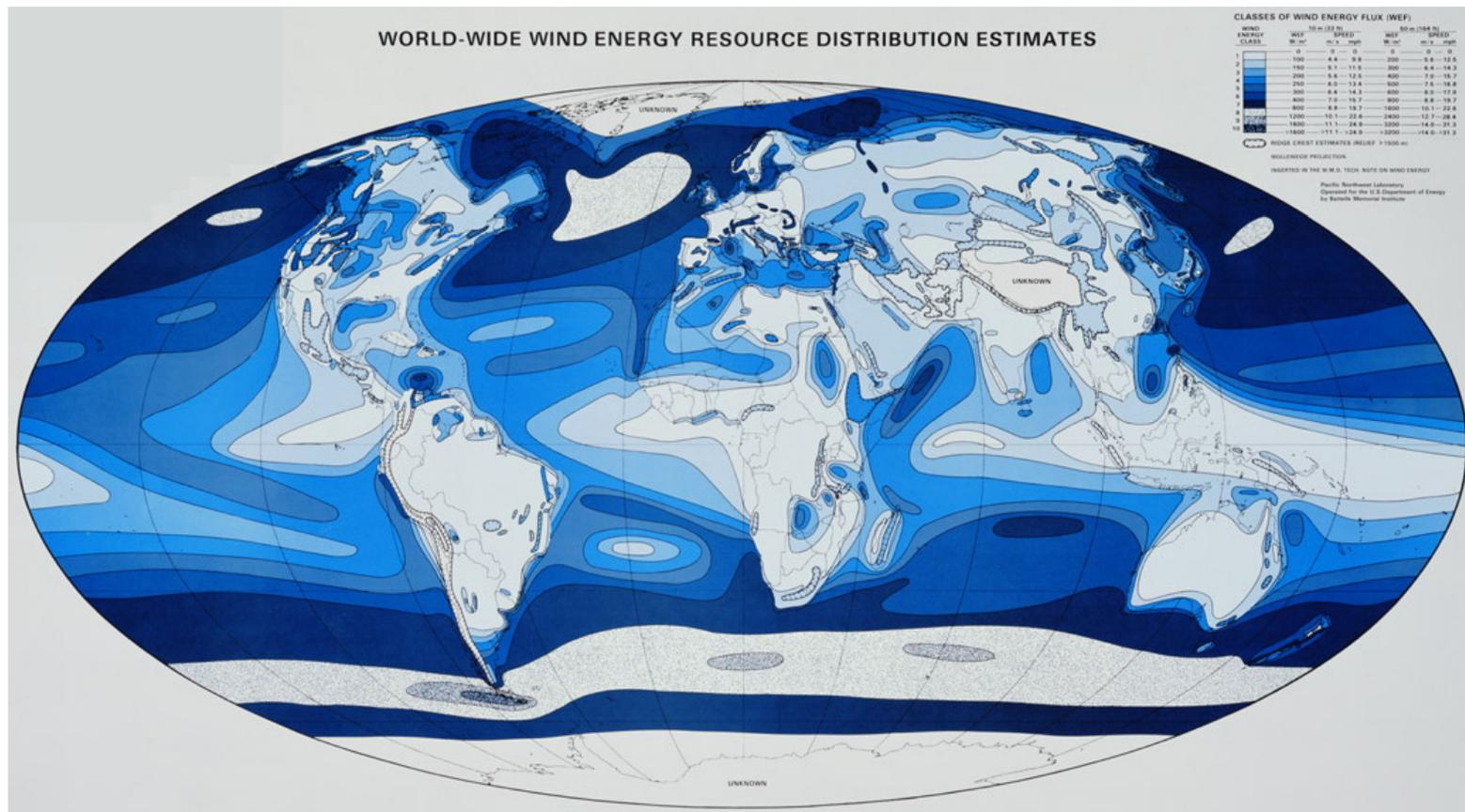
Global Cumulative Wind Power Capacity (MW)



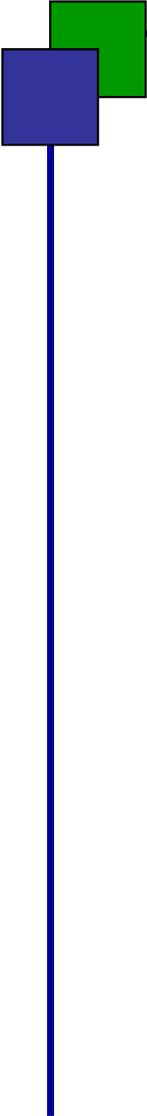
Source: EWEA, 2009; Wind Power Monthly, 2010

Wind Potential Worldwide Estimate

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



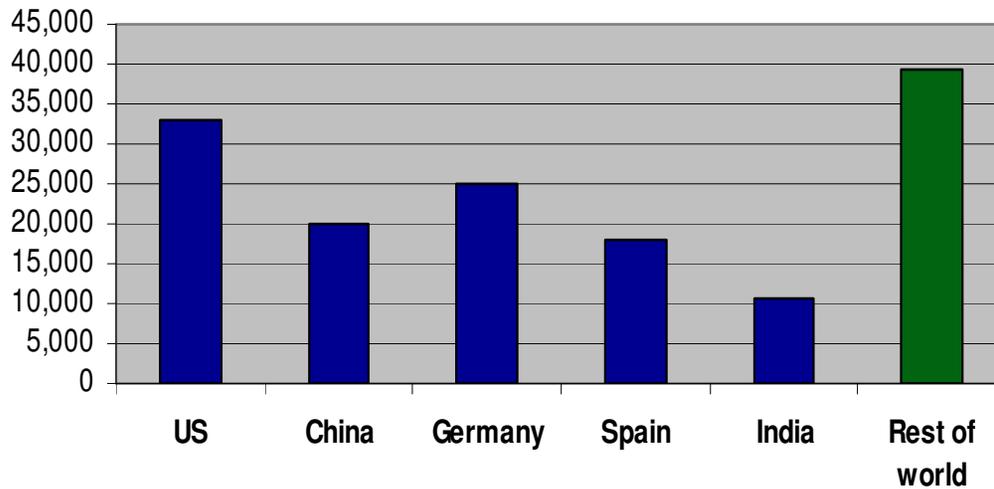
U.S. Department of Energy, National Renewable Energy Lab, 1985.



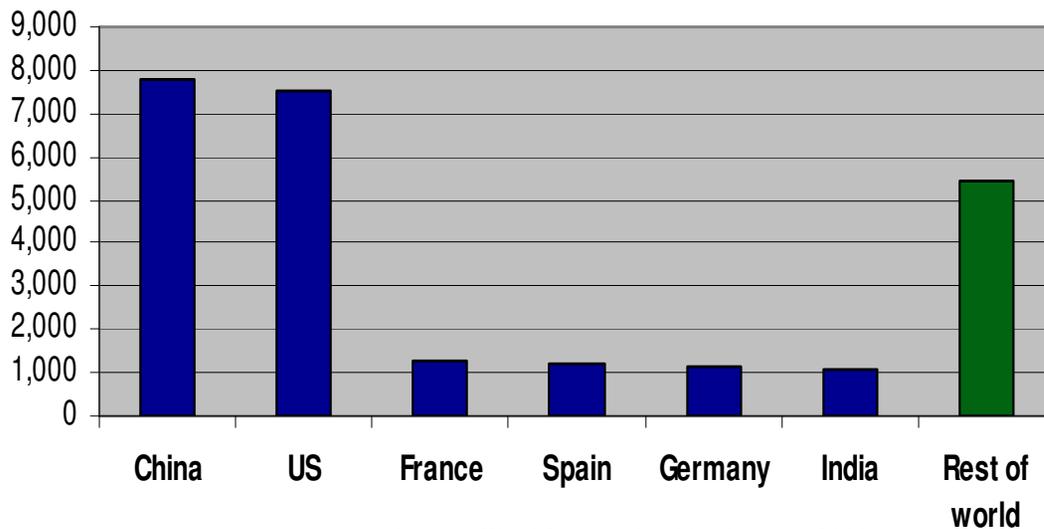
Wind Notables

- 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



Total Cumulative Capacity



New Capacity Adds

Source: Wind Power Monthly, January 2010



Wind Power in History ...

Photo of windmills in *Campo de Criptana, Spain* removed due to copyright restrictions.

Brief History – Early Systems

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

1st Wind Energy Systems

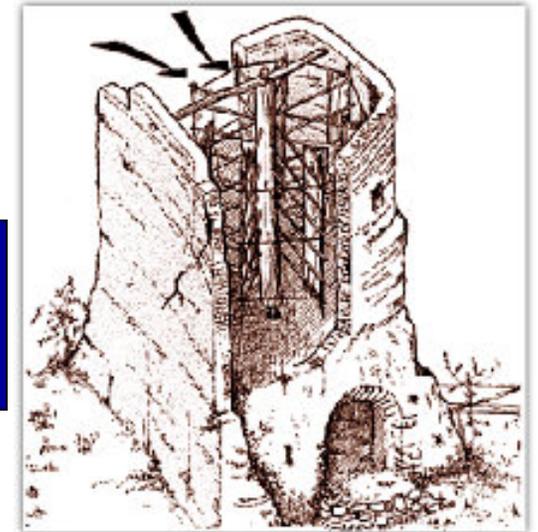
- Ancient Civilization in the Near East / Persia
- Vertical-Axis Wind-Mill: sails connected to a vertical shaft connected to a grinding stone for milling

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

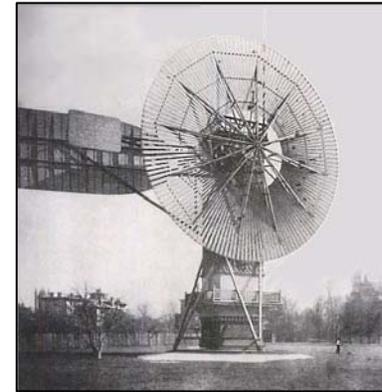
Wind in 19th century US

- Wind-rose horizontal-axis water-pumping wind-mills found throughout rural America



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)



Please see Heimpel, L. G. "How To Convert an Old Auto Generator into a Wind-Driven Battery Charger." *Popular Science* 123 (August 1933): 68, 76. (View on [Google Books](#).)

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

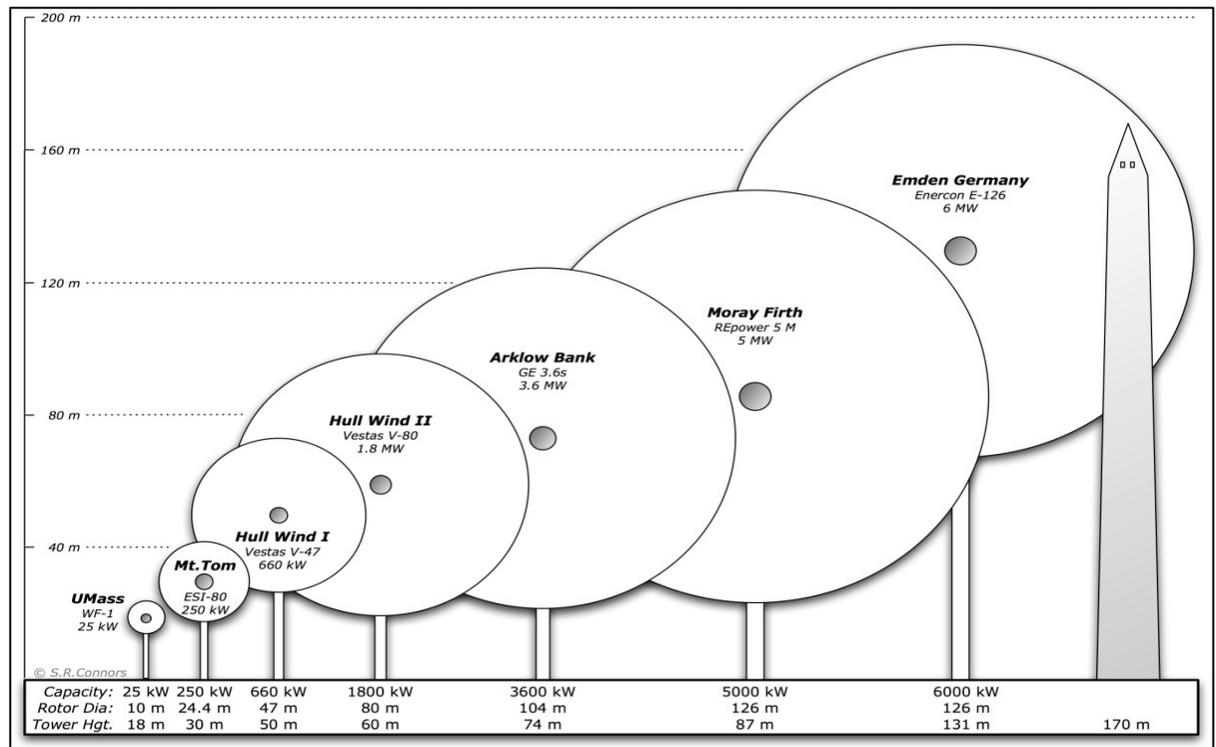


Photo by [Stig Nygaard](#) on Flickr.

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

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

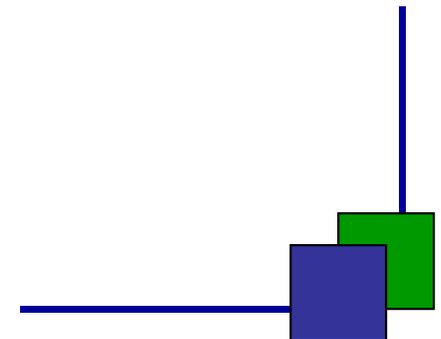


Photo by [NASA Visible Earth, Goddard Space Flight Center](#).



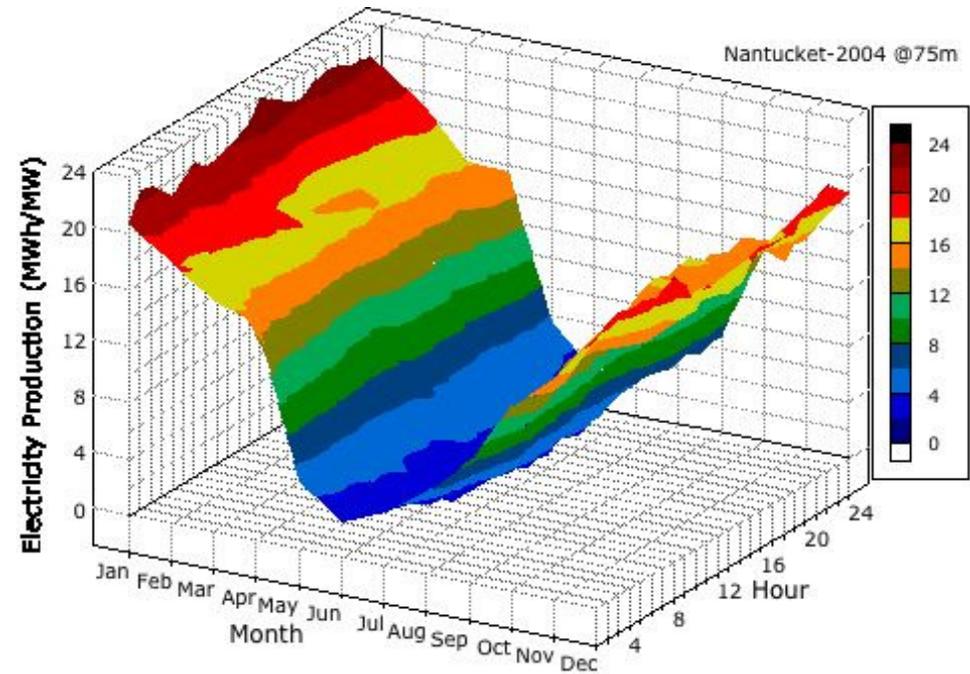
Wind types

- 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

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:

- $KE = \frac{1}{2} * m * v^2$

- Power is KE per unit time:

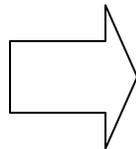
- $P = \frac{1}{2} * \dot{m} * v^2$

- Fluid mechanics gives **mass flow rate** (density * volume flux):

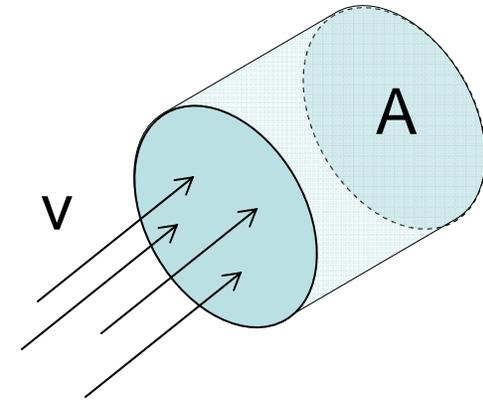
- $\dot{m} = \frac{dm}{dt} = \rho * A * v$

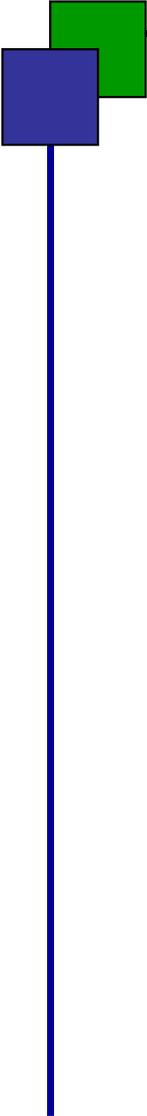
- Thus:

- $P = \frac{1}{2} * \rho * A * v^3$



- Power ~ cube of velocity
- Power ~ air density
- Power ~ rotor swept area $A = \pi r^2$





Efficiency in Extracting Wind Power

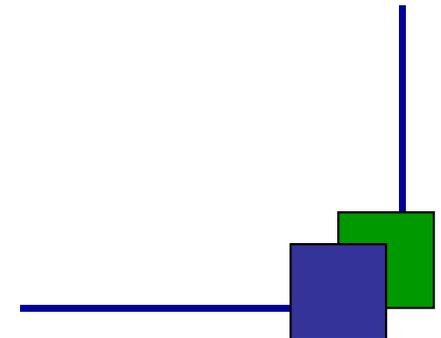
Betz Limit & Power Coefficient:

- Power Coefficient, C_p , is the ratio of power extracted by the turbine to the total contained in the wind resource $C_p = P_T/P_W$
- Turbine power output

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

- The **Betz Limit** is the maximal possible $C_p = 16/27$
- **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

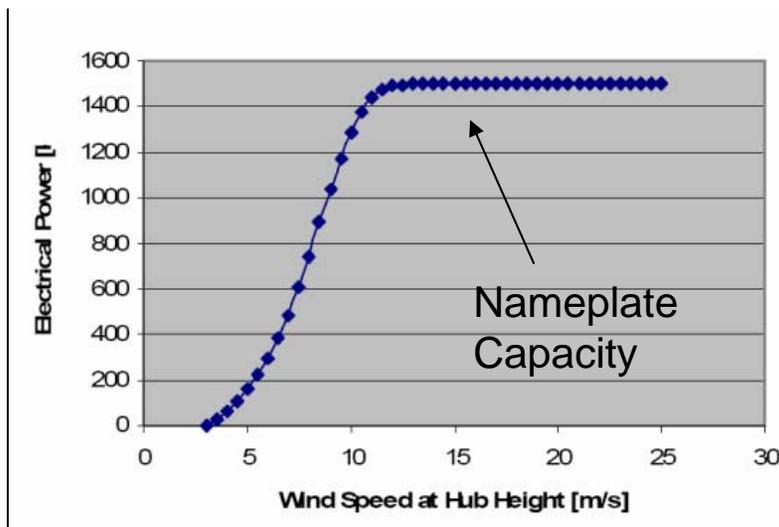
Capacity Factor (CF):

- The fraction of the year the turbine generator is operating at rated (peak) power

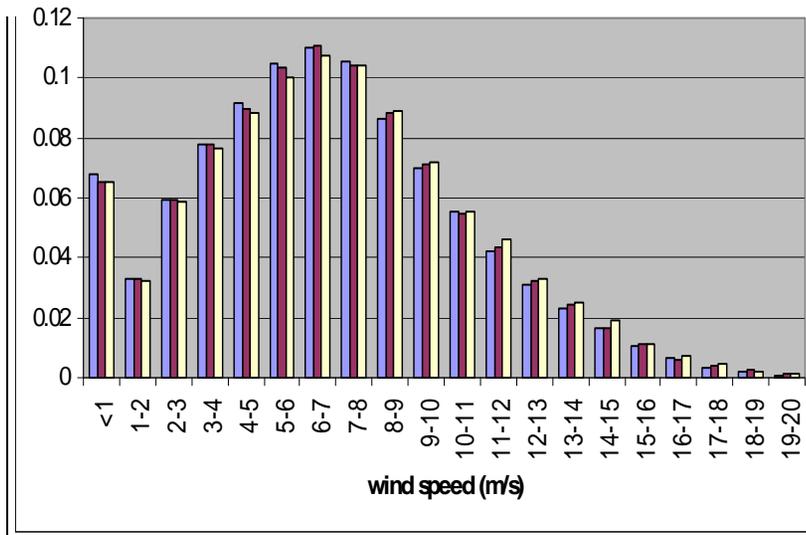
$$\text{Capacity Factor} = \text{Average Output} / \text{Peak Output} \approx 30\%$$

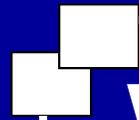
- CF is based on both the characteristics of the turbine and the site characteristics (typically 0.3 or above for a good site)

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)

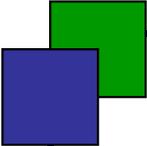
Vertical-Axis – VAWT

- Darrieus / Egg-Beater (lift force driven)
- Savonius (drag force driven)



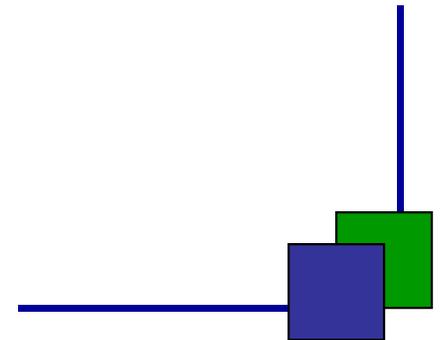
Photos by [Louise Docker](#) on Flickr and [aarchiba](#) on Wikimedia Commons.
Photo of [Windpods](#), [Skystream](#), and [Aerovironment Architectural Wind](#) removed due to copyright restrictions.

Photos courtesy of Steve Connors, MITEI



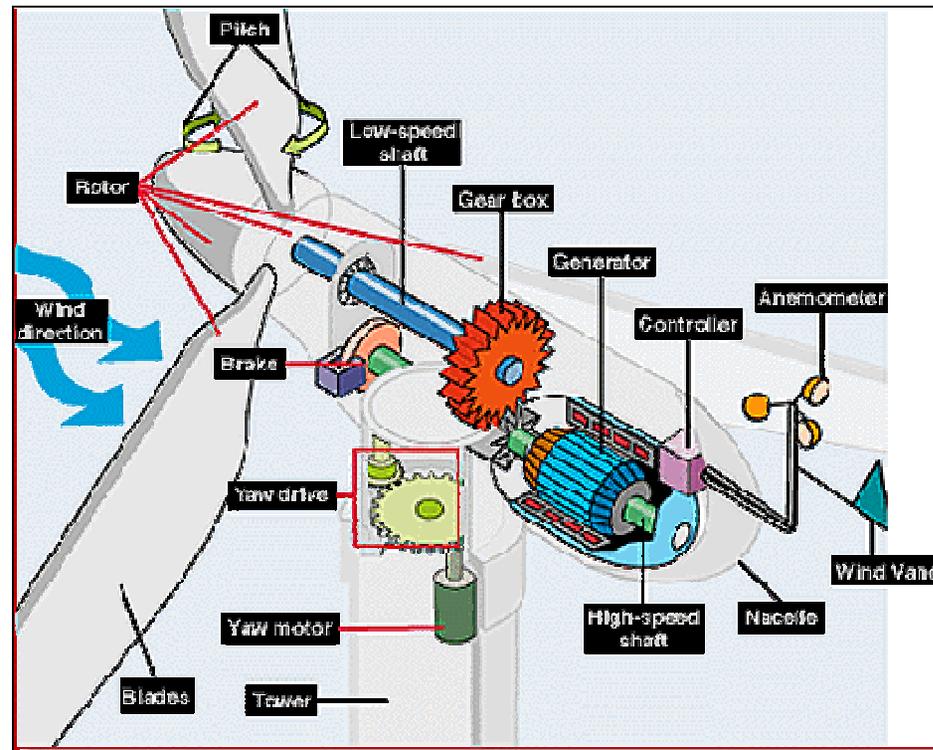
Lift and Drag Forces

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



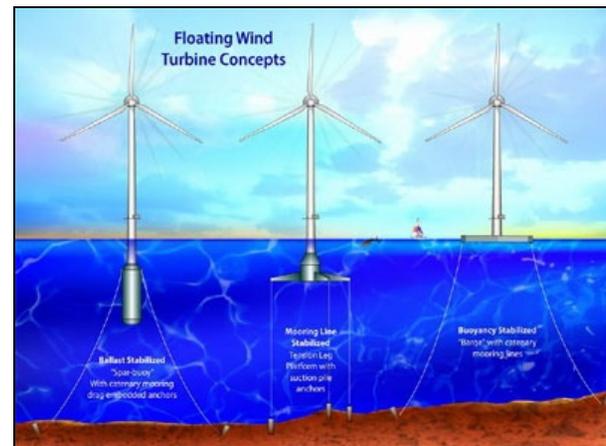
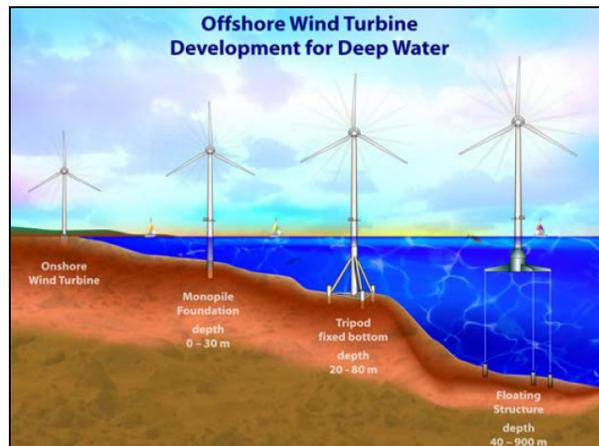
Foundations and Tower

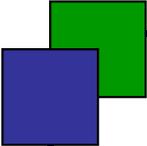
- Evolution from truss (early 1970s) to monopole towers



Photo by [Rocco Lucia](#) on Flickr and [Leaflet](#) on Wikimedia Commons.

- Many different configurations proposed for offshore





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

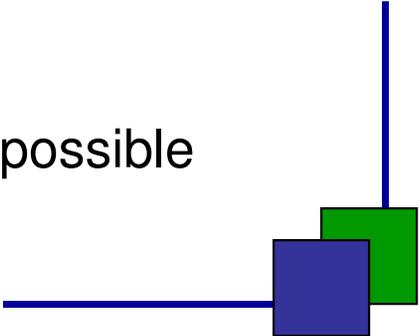
- Generator:
 - Rotating magnetic field induces current

Please see [Synchronous machines](#) and [No. of poles](#), Danish Wind Industry Association.

- 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

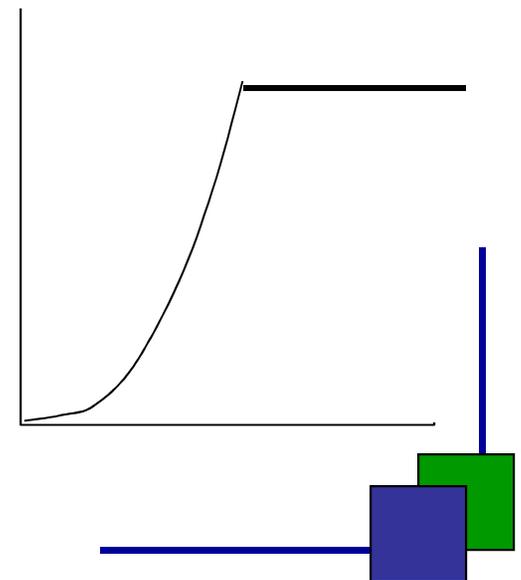
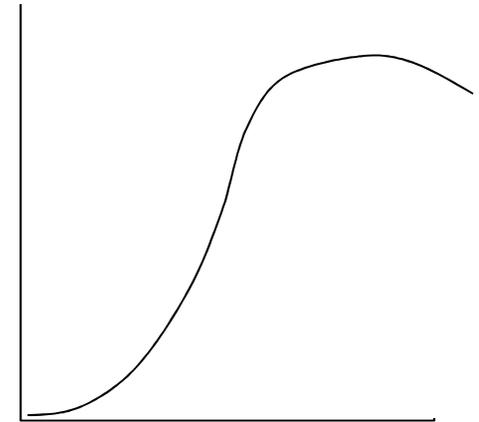
Masters, Gilbert, *Renewable and Efficient Electric Power Systems*, Wiley-IEEE Press, 2003

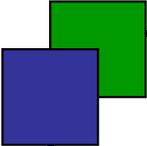
http://wiki.windpower.org/index.php/No._of_poles .



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)

Slide 8 in Dumas, John. "[Impact of Wind Generation on ERCOT Operations.](#)" *Gulf Coast Power Association*, September 29, 2008.
Slide 14 in Atienza, Luis. "[Wind Energy Development in Spain.](#)" *Red Electrica de Espana*, April 3, 2009.

Left graphic courtesy of ERCOT

Right graphic courtesy of RED Electrica de Espana

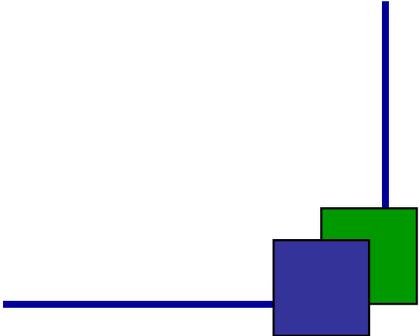


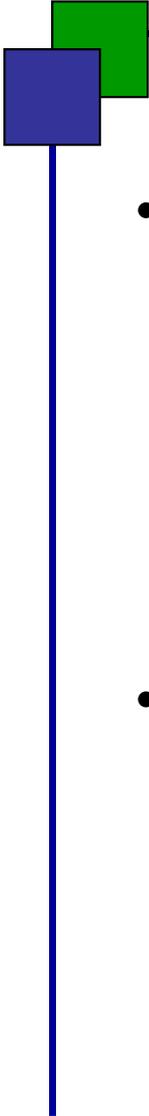


Future Technology Development

- 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](#).

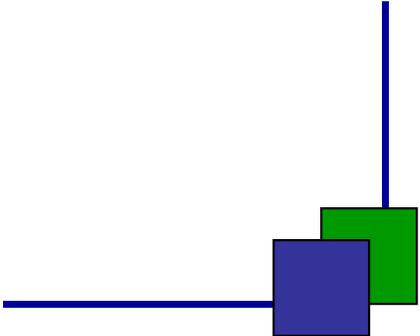




Future Technology Development

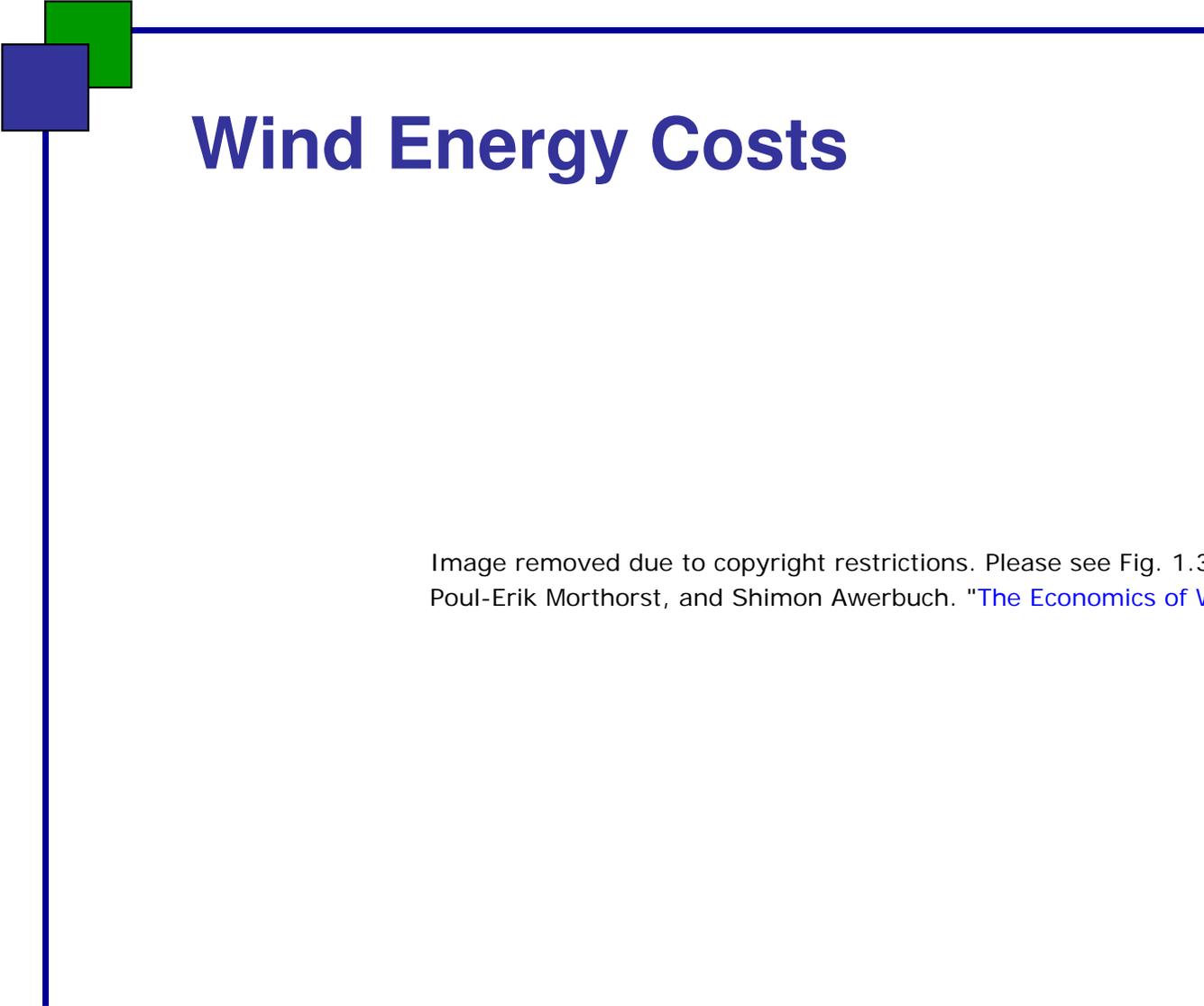
- Improving Reliability and Availability:
 - Forecasting tools (technology and models)
 - Dealing with system loads
 - Advanced control methods, materials, preemptive diagnostics and maintenance
 - Direct drive – complete removal of gearbox
- Novel designs:
 - Shrouded, floating, direct drive, and high-altitude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

Please see [FloDesign Wind Turbine](#) and [Sky Windpower](#).





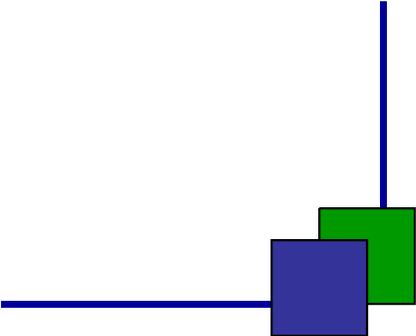
Going Beyond the Science & Technology of Wind...



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.

Source: EWEA, 2009

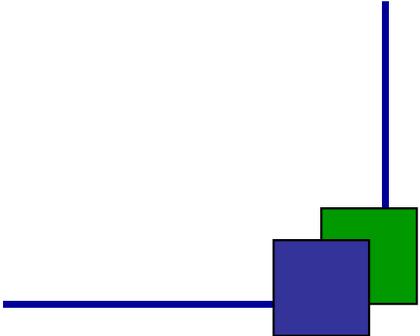




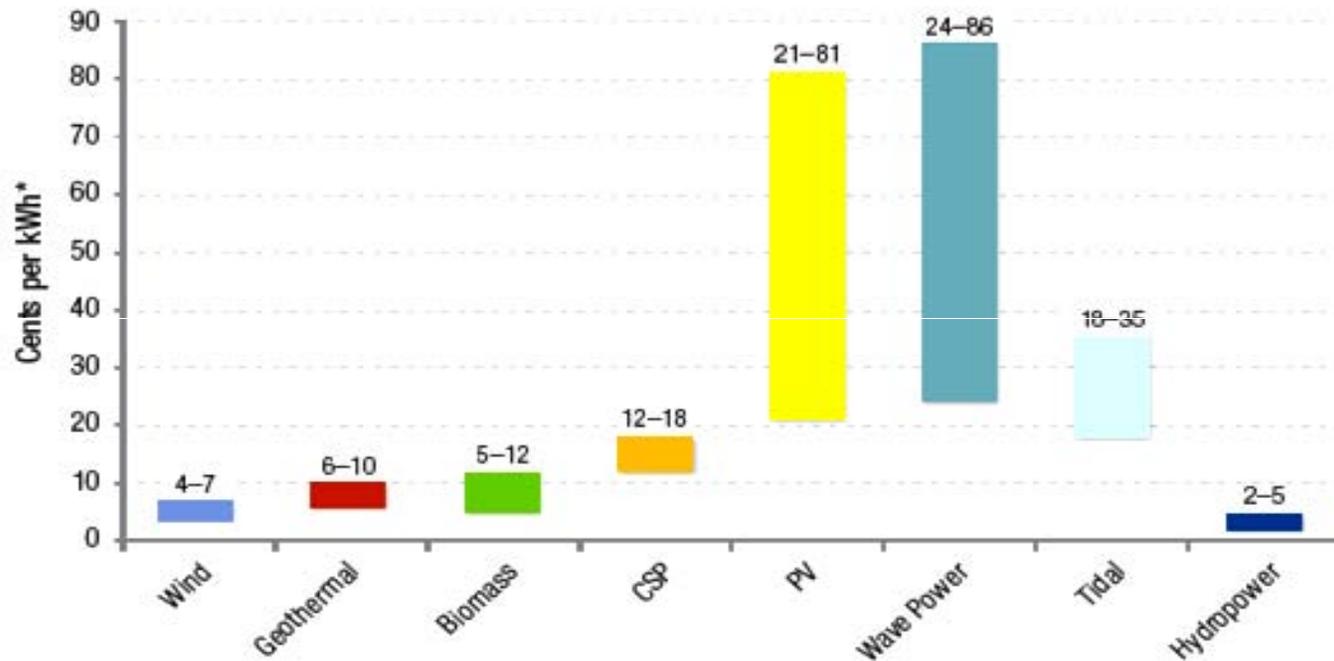
% Cost Share of 5 MW Turbine Components

Image removed due to copyright restrictions. Please see Fig. 1.11 in Krohn, Soren, Poul-Erik Morthorst, and Shimon Awerbuch. "[The Economics of Wind Energy](#)." EWEA, March 2009.

Source: EWEA, 2009, citing Wind Direction, Jan/Feb, 2007



Costs -- Levelized Comparison



* Average cost will vary according to financing used and the quality of the renewable energy resource available.

Sources: Idaho National Laboratory, Carbon Trust, Simmons Energy Monthly, U.S. DOE-EERE, IEA, Solarbuzz LLC, REN21, LBNL

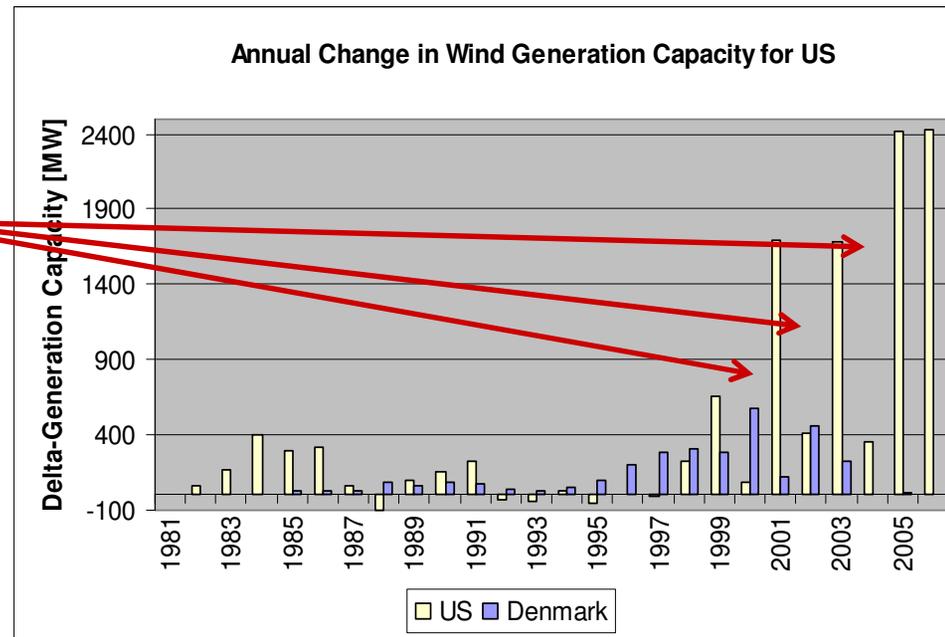
Reported in US DOE. 2008 Renewable Energy Data Book

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?

PTC Expirations



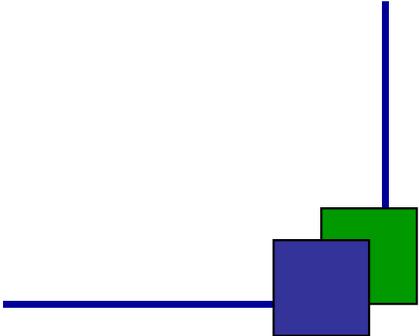
¹Wiser, R and Bolinger, M. (2008). Annual Report on US Wind Power: Installation, Cost, and Performance Trends. US Department of Energy – Energy Efficiency and Renewable Energy [USDOE – EERE].



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.



The Environment

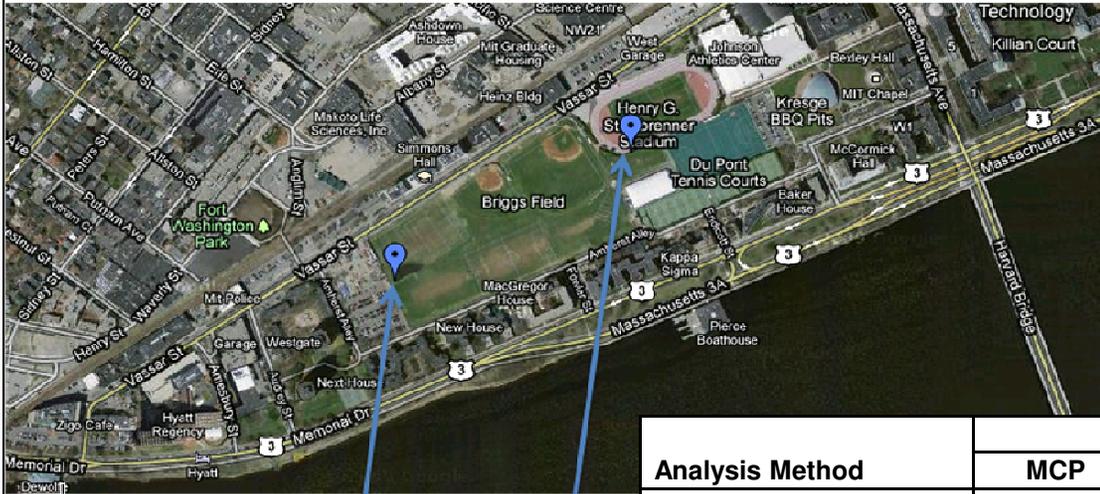
- Cleaner air -- reduced GHGs, particulates/pollutants, waste; minimized opportunity for oil spills, natural gas/nuclear plant leakage; more sustainable effects
 - Planning related to wildlife migration and habitats
 - Life cycle impacts of wind power relative to other energy sources
 - Some of the most 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

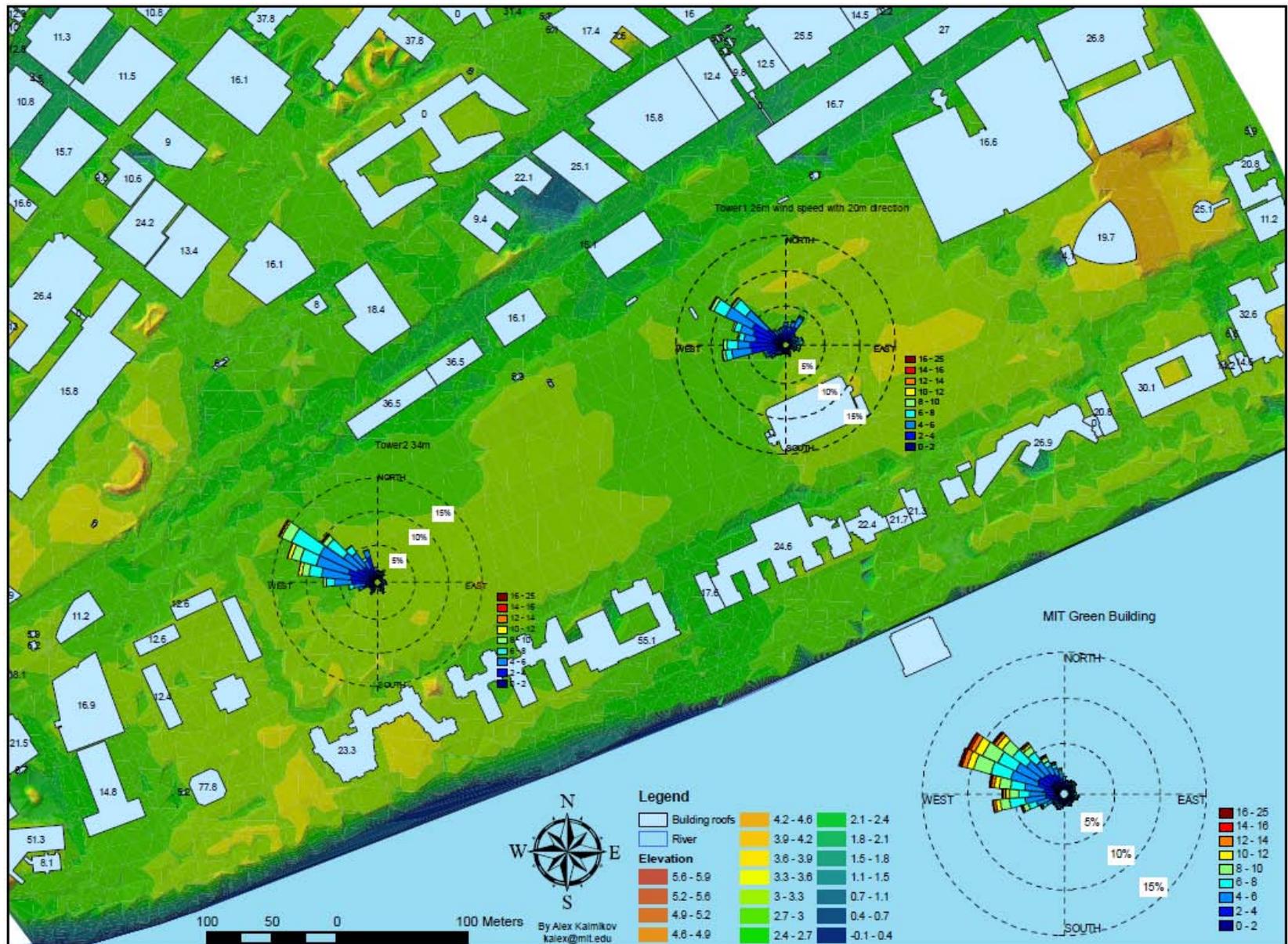


- 3 and 6+ months of data at two sites on MIT's Briggs Field
- Complemented with statistical analysis using Measure-Correlate-Predict method

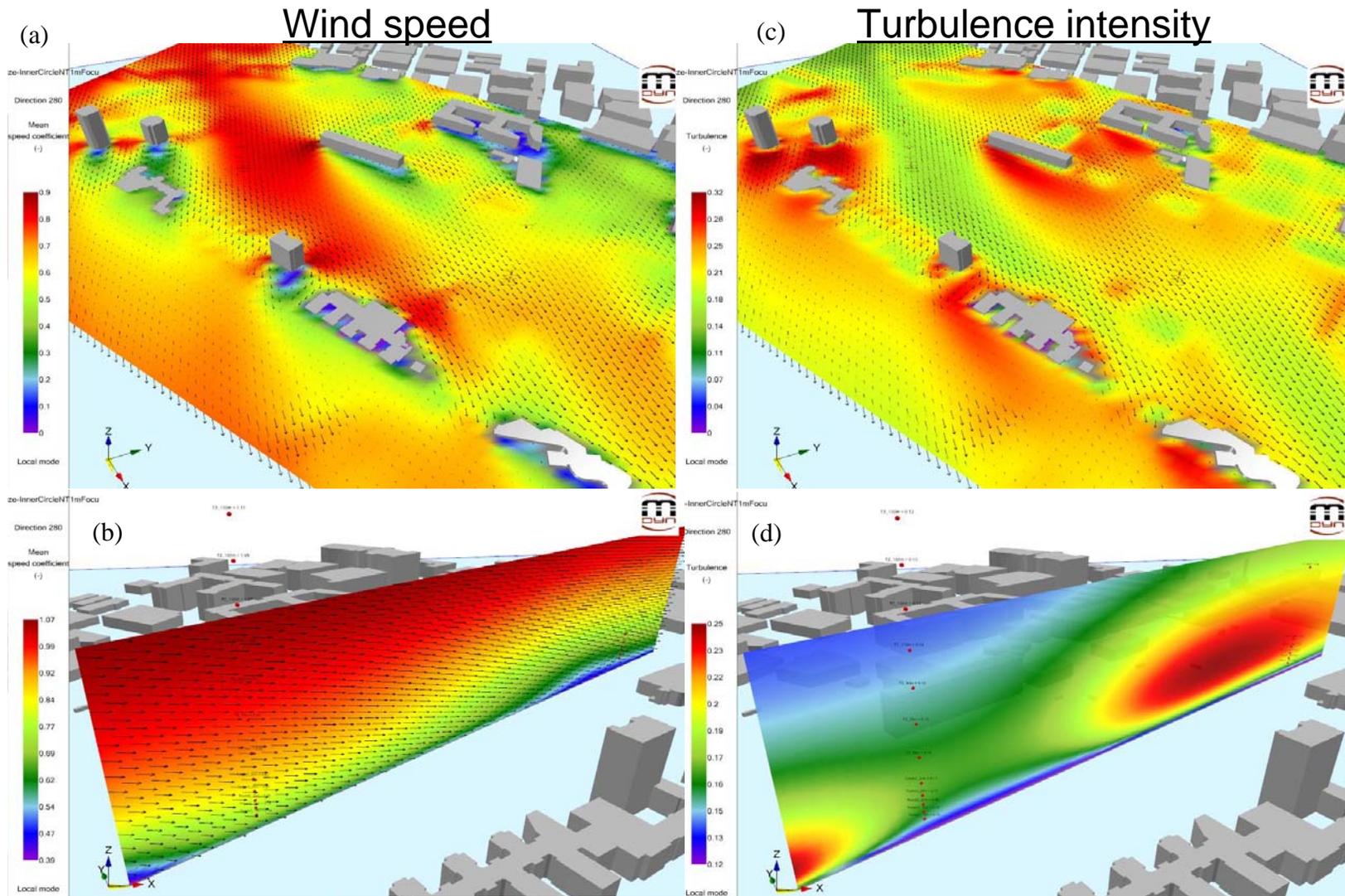
- Research project using Computational Fluid Dynamics techniques for urban wind applications
- Published paper at AWEA Windpower 2010 in Texas

Analysis Method	Met station 2					
	MCP	CFD	MCP	CFD	MCP	CFD
Height [m]	20	20	26	26	34	34
Mean Wind Speed [m/s]	3.4	2.9	n/a	3.0	4.0	3.2
Power Density [W/m ²]	46.5	51.7	n/a	60.4	74.6	70.9
Annual Energy Output [kW-hr]	1,017	1,185	n/a	1,384	1,791	1,609
Annual Production CFD [kW-hr]	n/a	1,136	n/a	1,328	n/a	1,558
Capacity Factor	5%	6%	n/a	7%	9%	8%
Operational Time	38%	28%	n/a	30%	51%	33%
Analysis Method	Met station 1					
	MCP	CFD	MCP	CFD	MCP	CFD
Height [m]	20	20	26	26	34	34
Mean Wind Speed [m/s]	3.3	2.7	3.7	2.9	n/a	3.1
Power Density [W/m ²]	39.4	41.9	55.6	50.2	n/a	60.5
Annual Energy Output [kW-hr]	817	974	1,259	1,193	n/a	1,430
Annual Production CFD [kW-hr]	n/a	931	n/a	1,135	n/a	1,377
Capacity Factor	4%	5%	6%	6%	n/a	7%
Operational Time	35%	26%	45%	29%	n/a	32%

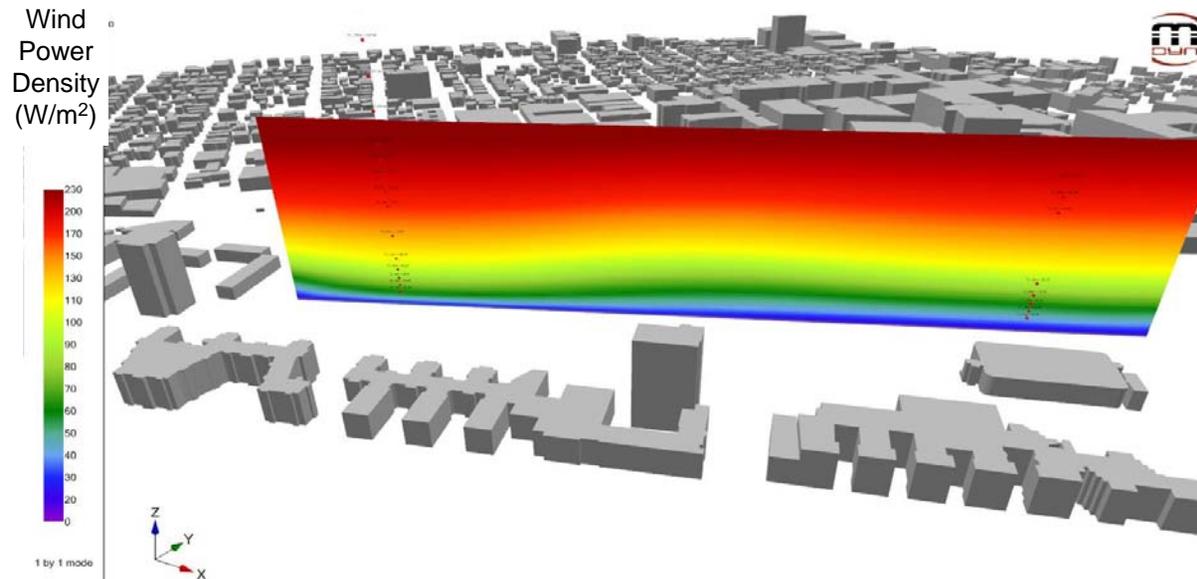
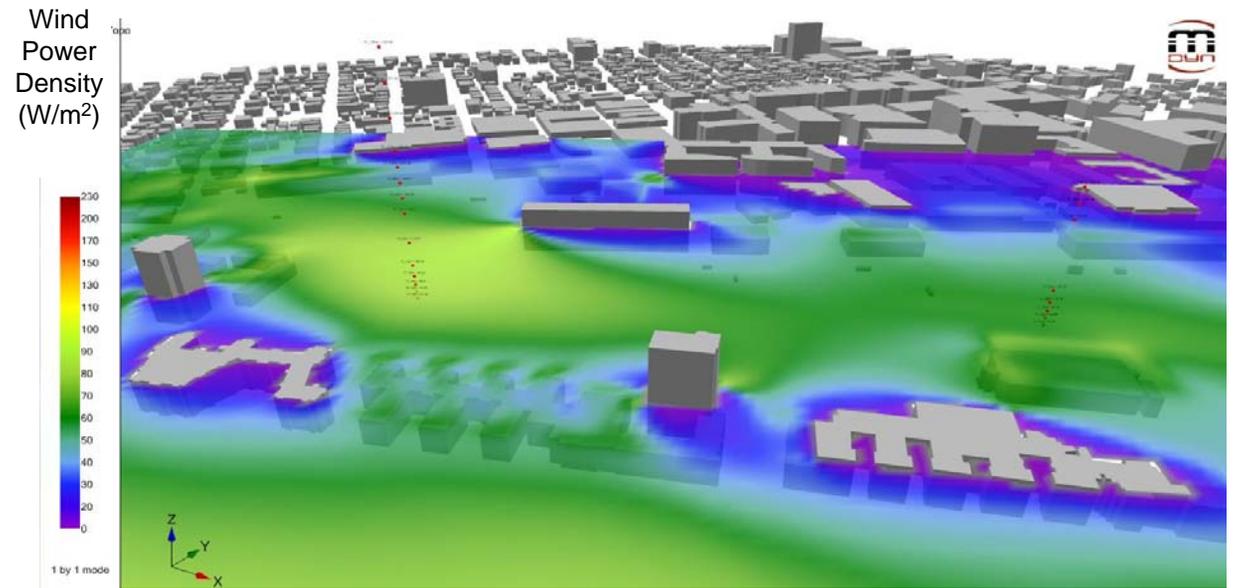
Spatial Analysis of Wind Resource at MIT



3D simulations of wind resource structure at MIT



Wind Power Density at MIT





Q & A

THANK YOU

MIT OpenCourseWare
<http://ocw.mit.edu>

22.081J / 2.650J / 10.291J / 1.818J / 2.65J / 10.391J / 11.371J / 22.811J / ESD.166J
Introduction to Sustainable Energy
Fall 2010

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