Wind Power Fundamentals

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MIT Wind Energy Group &
Renewable Energy Projects in Action

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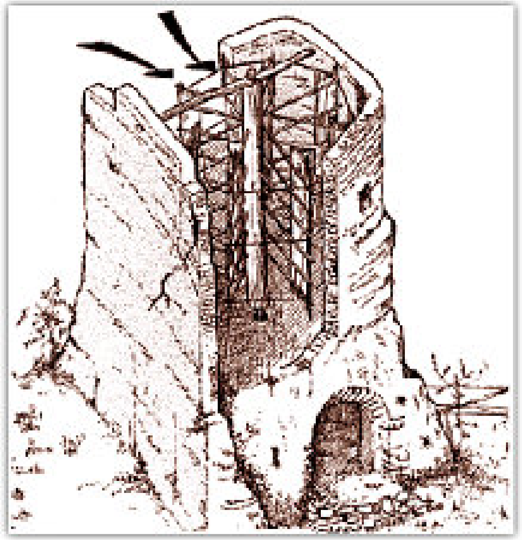
Overview

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

Wind Power in History …

Brief History – Early Systems

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

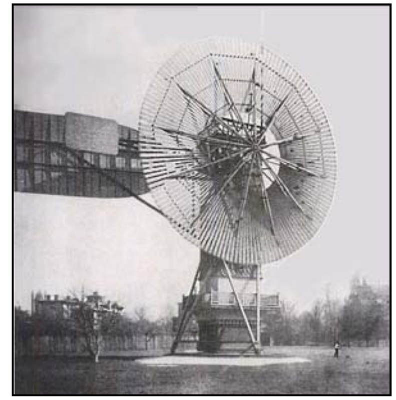
- Post Mill Introduced in Northern Europe
- Horizontal-Axis Wind-Mill: sails connected to a horizontal shaft on a tower encasing gears and axles for translating horizontal into rotational motion

Wind in 19th century US

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

Torrey, Volta (1976) *Wind-Catchers: American Windmills of Yesterday and Tomorrow.* Stephen Green Press, Vermont.
Righter, Robert (1996) *Wind Energy in America.* University of Oklahoma Press, Oklahoma.

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

Torrey, Volta (1976) *Wind-Catchers: American Windmills of Yesterday and Tomorrow*. Stephen Green Press, Vermont.
Righter, Robert (1996) *Wind Energy in America*. University of Oklahoma Press, Oklahoma.

Brief History – Modern Era

Key attributes of this period:

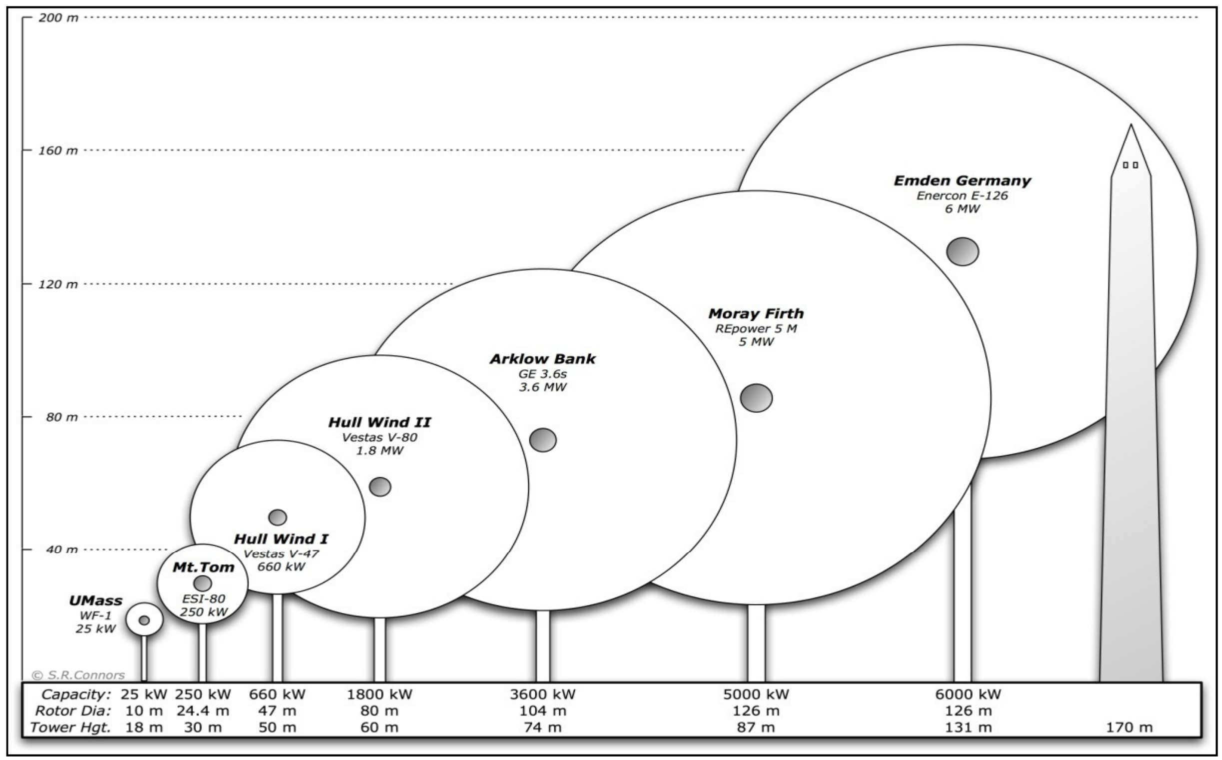
- Scale increase
- Commercialization
- Competitiveness
- Grid integration

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

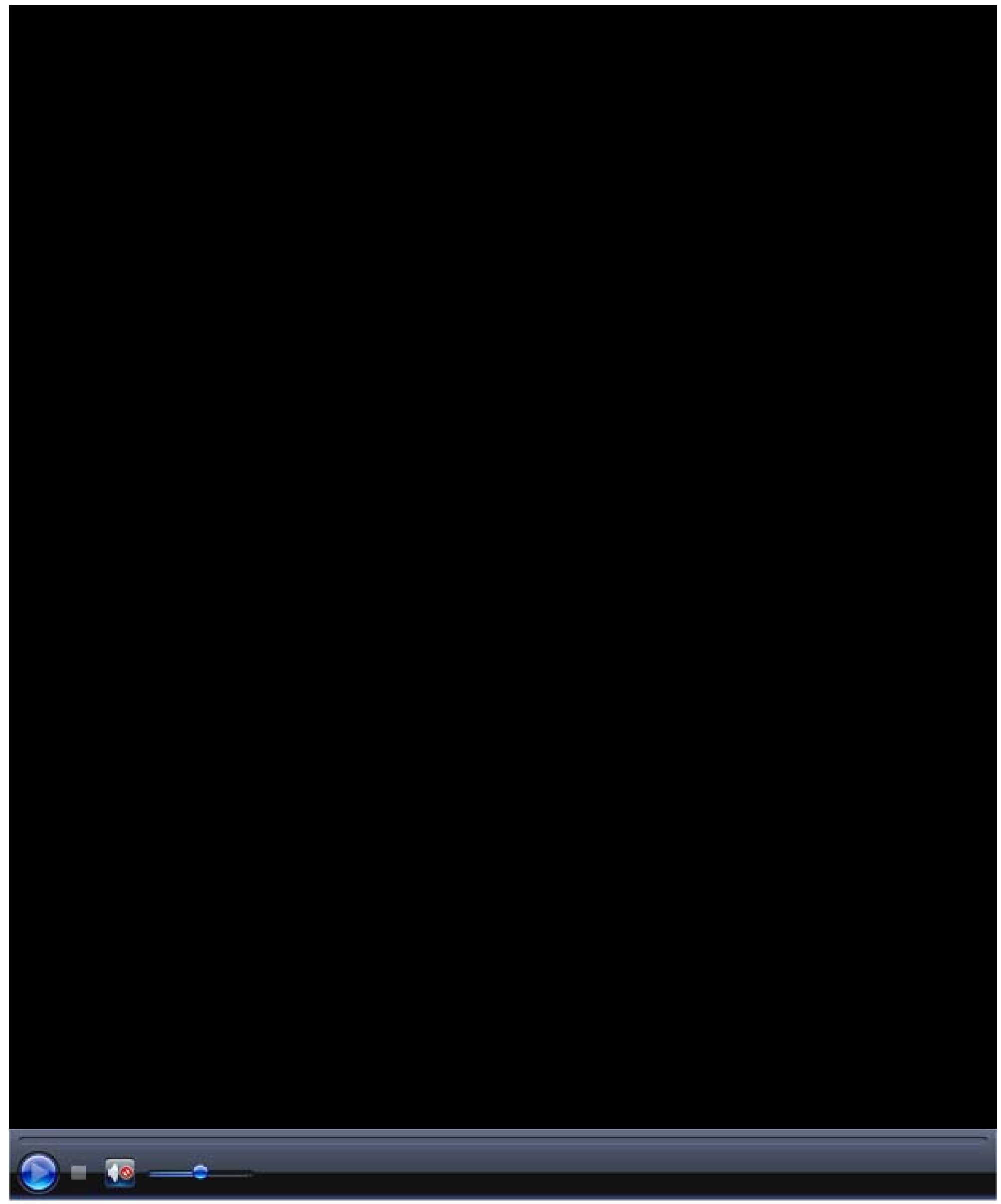
Spatial Scales

Planetary scale: global circulation

Synoptic scale: weather systems

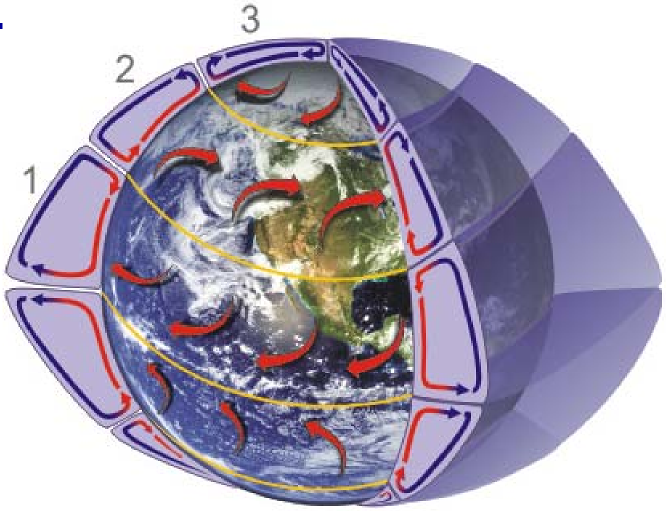
Meso scale: local topographic or thermally induced circulations

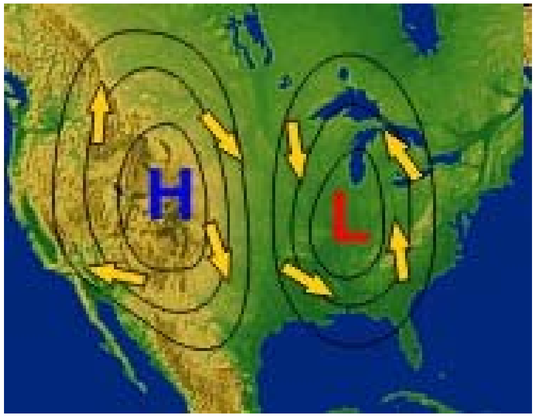
Micro scale: urban topography



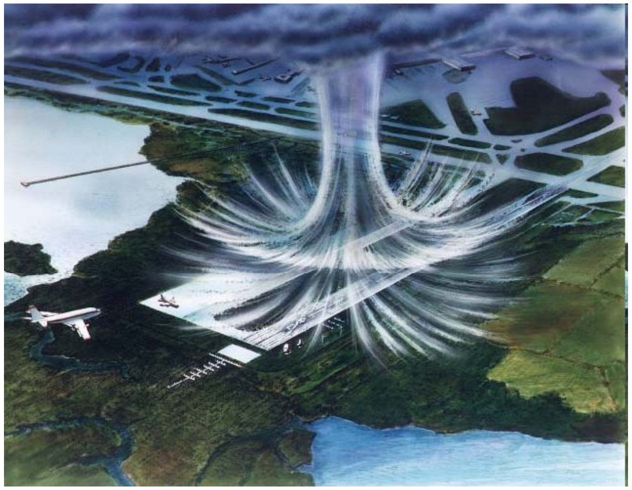
Source for Graphic: NASA / GSFC

Wind types

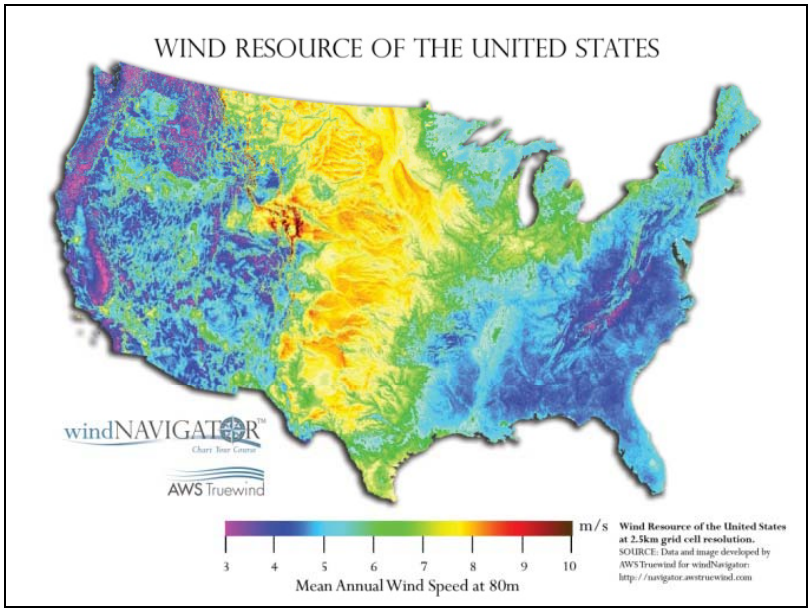


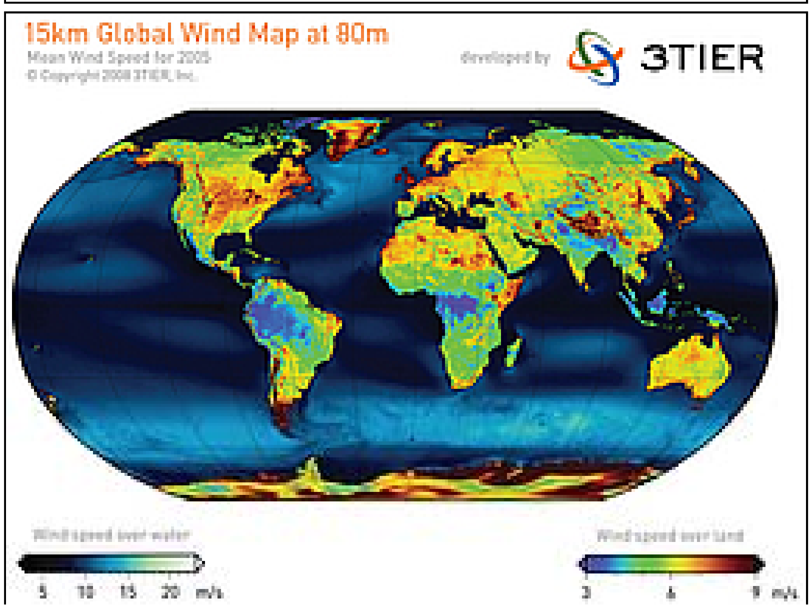


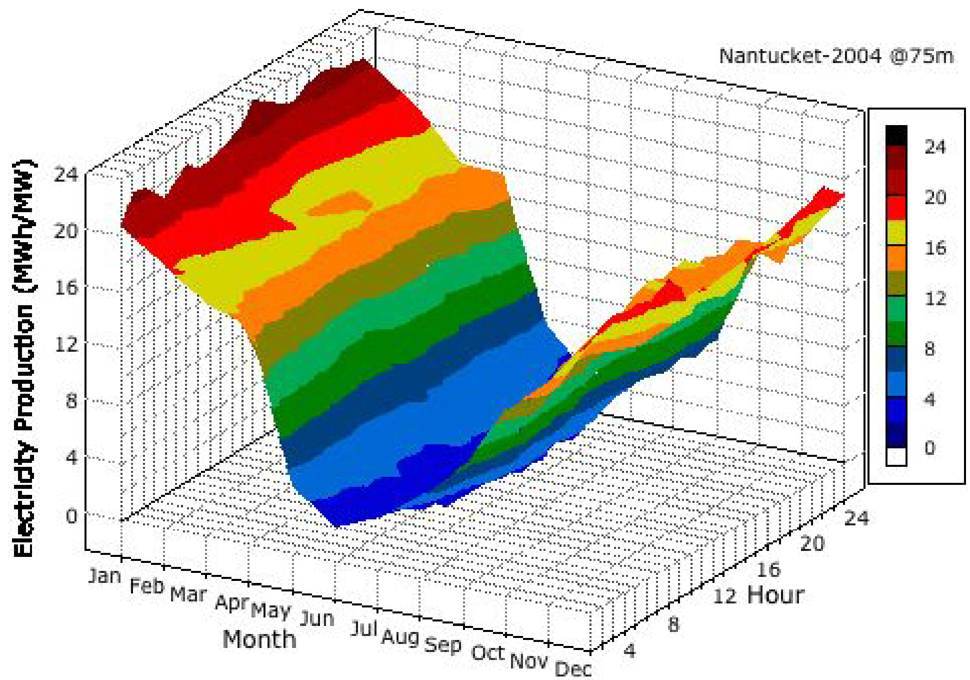
- Planetary circulations:
  - Jet stream
  - Trade winds
  - Polar jets
- Geostrophic winds
- Thermal winds
- Gradient winds
- Katabatic / Anabatic winds – topographic winds
- Bora / Foehn / Chinook – downslope wind storms
- Sea Breeze / Land Breeze
- Convective storms / Downdrafts
- Hurricanes/ Typhoons
- Tornadoes
- Gusts / Dust devils / Microbursts
- Nocturnal Jets
- Atmospheric Waves



Wind Resource Availability and Variability







Source: Steve Connors, MIT Energy Initiative

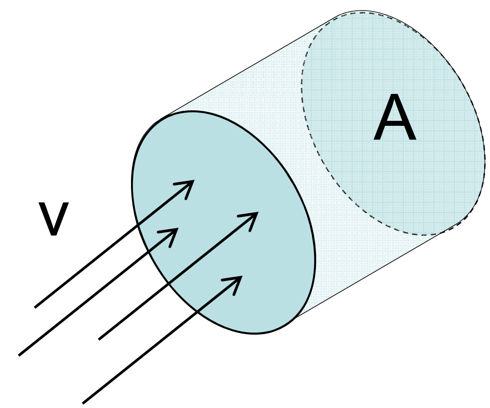
Source for Wind Map Graphics: AWS Truewind and 3Tier

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 = ½ * m * v^2

– Power is KE per unit time:
  - P = ½ * $\dot{m}$ * v^2

$$\dot{m} = \frac{dm}{dt}$$ mass flux

– Fluid mechanics gives **mass flow rate** (density * volume flux):
  - dm/dt = ρ* A * v

– Thus:
  - P = ½ * ρ * A * v^3

- Power ~ cube of velocity
- Power ~ air density
- Power ~ rotor swept area A= **π**r^2

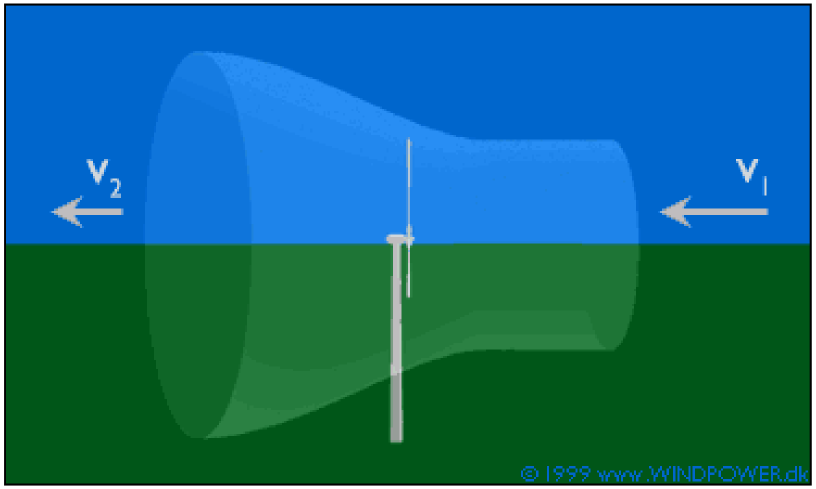
Efficiency in Extracting Wind Power

Betz Limit & Power Coefficient:

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

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

- The **Betz Limit** is the maximal possible Cp = 16/27
- **59%** efficiency is the **BEST** a conventional wind turbine can do in extracting power from the wind



Power Curve of Wind Turbine

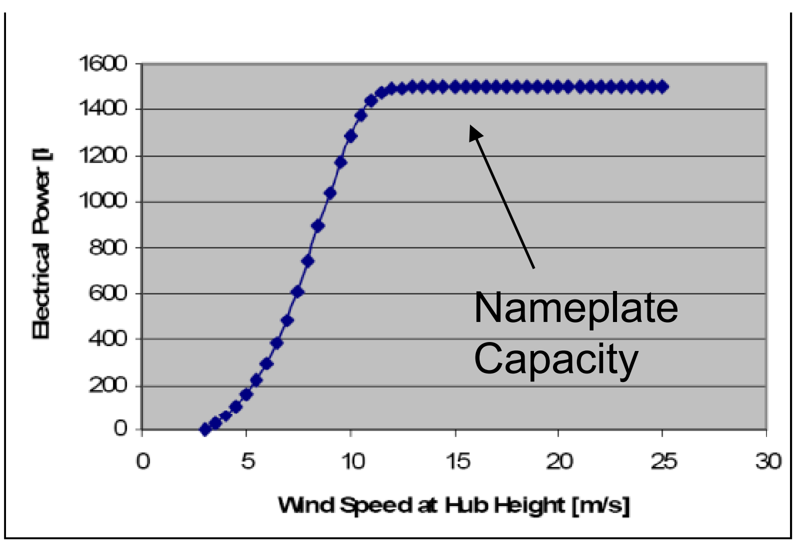
Capacity Factor (CF):

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

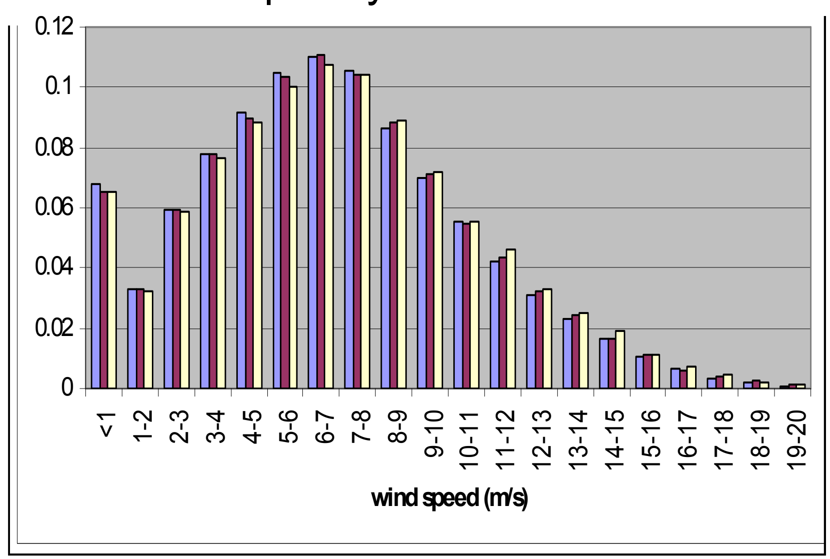
  Capacity Factor = Average Output / Peak Output ≈ 30%

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

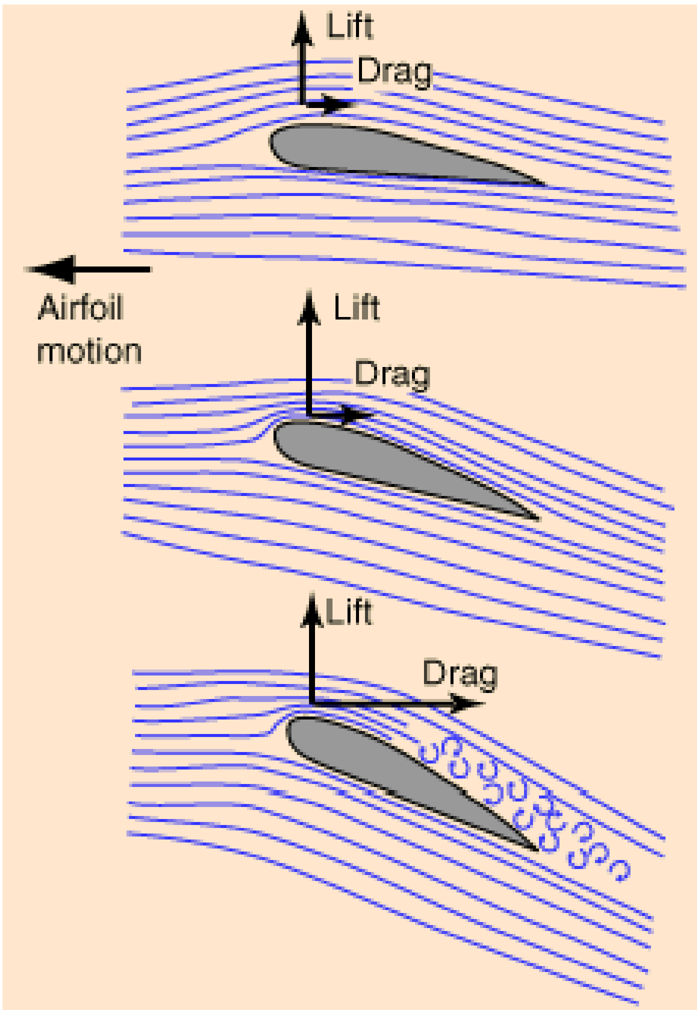
Power Curve of 1500 kW Turbine

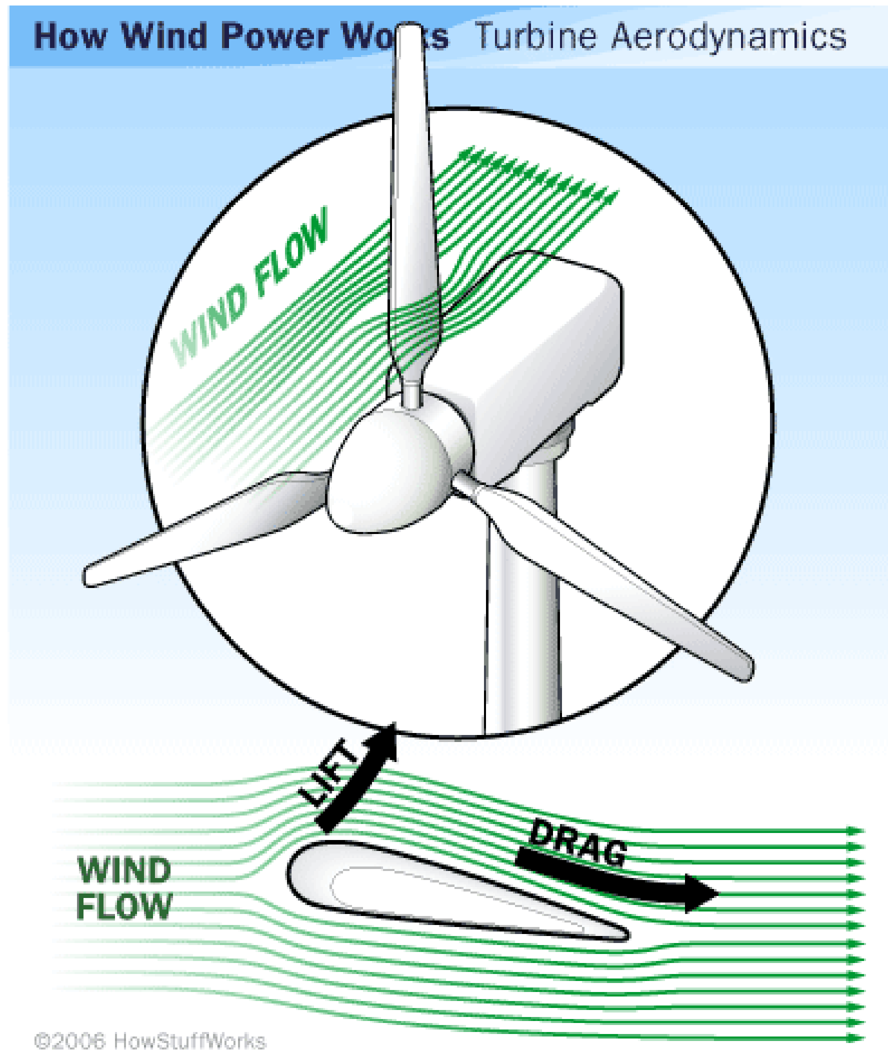


Wind Frequency Distribution



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

	Type of Generation	Combustion Type	Turbine Type Gas	Steam	Water	Aero	Primay Power	Electrical Conversion
3	**Traditional Boiler**	External		•			Shaft	Generator
3	**Fluidized Bed**	External		•			Shaft	Generator
	Combustion						–	–
	Integrated Gasification	Both	•	•			Shaft	Generator
	Combined-Cycle						–	–
	Combustion Turbine	Internal	•				Shaft	Generator
	Combined Cycle	Both	•	•			Shaft	Generator
3	**Nuclear**			•			Shaft	Generator
	Diesel Genset	Internal					Shaft	Generator
	Micro-Turbines	Internal	•				Shaft	Generator
	Fuel Cells						**Direct**	**Inverter**
	Hydropower				•		Shaft	Generator
3	**Biomass & WTE**	External		•			Shaft	Generator
	Windpower					•	Shaft	Generator
	Photovoltaics						**Direct**	**Inverter**
3	**Solar Thermal**			•			Shaft	Generator
3	**Geothermal**			•			Shaft	Generator
	Wave Power		•				Shaft	Generator
	Tidal Power				•		Shaft	Generator
3	**Ocean Thermal**			•			Shaft	Generator

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)

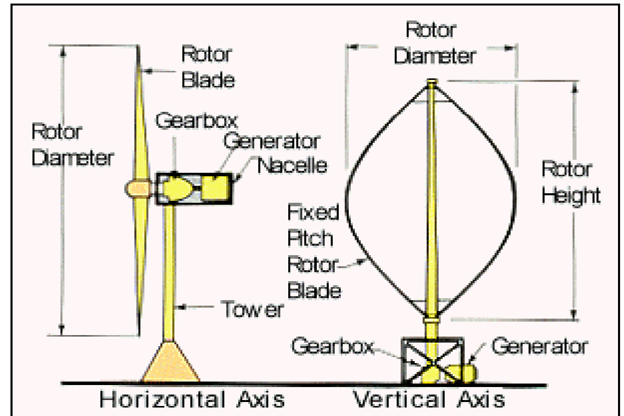
Vertical-Axis – VAWT

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

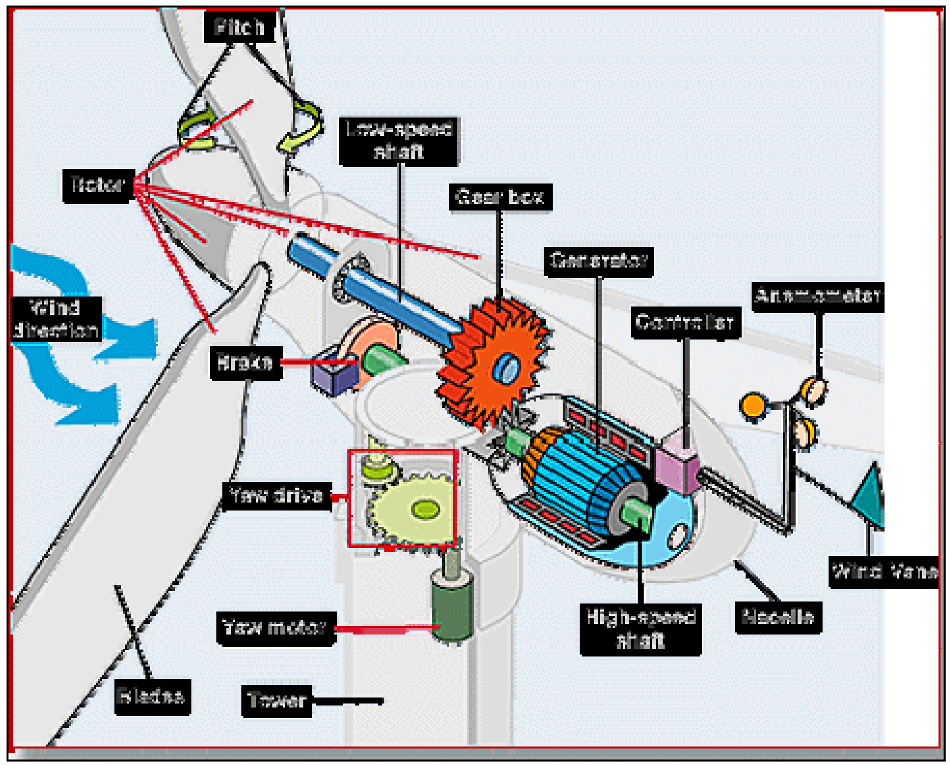
Photos courtesy of Steve Connors, MITEI

Wind Turbine Subsystems

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



Wind Turbine Configurations

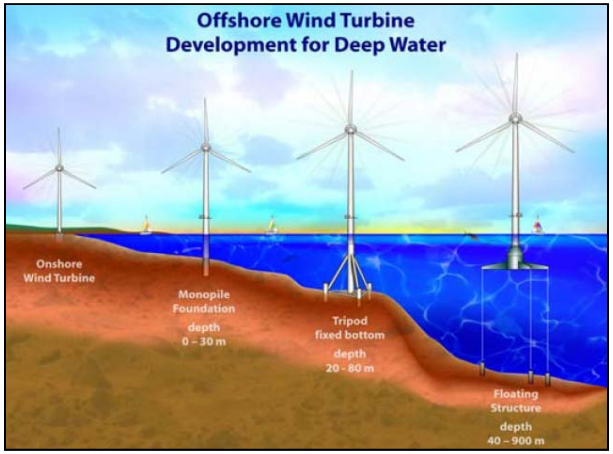


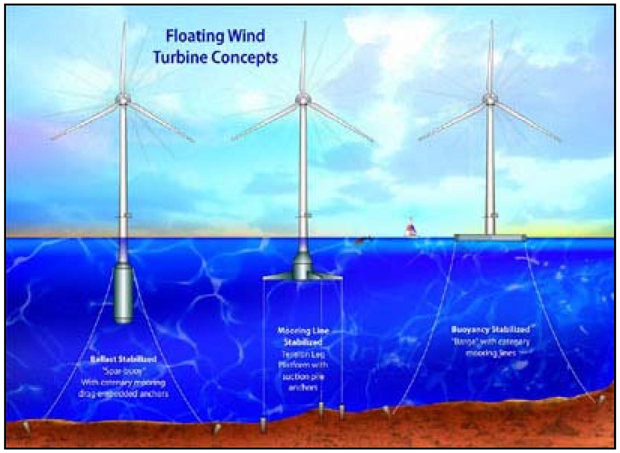
Source for Graphics: AWEA Wind Energy Basics, http://www.awea.org/faq/wwt_basics.html

Foundations and Tower

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

- Many different configurations proposed for offshore

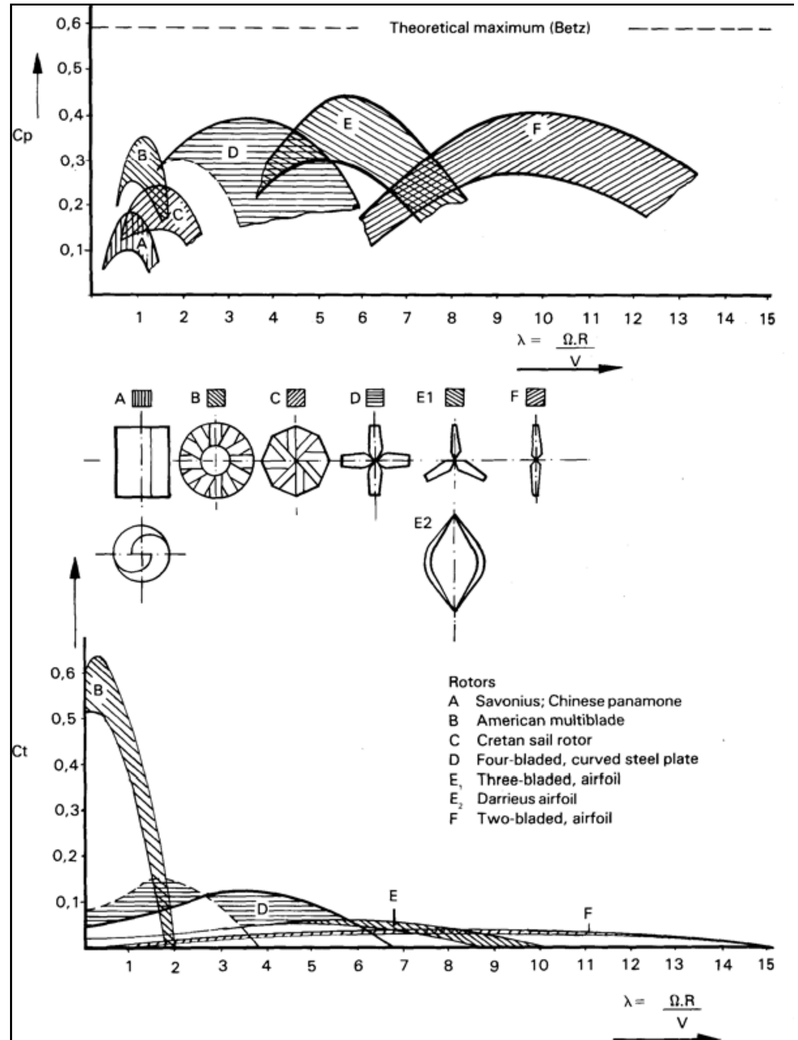




Images from National Renewable Energy Laboratory

Nacelle, Rotor & Hub

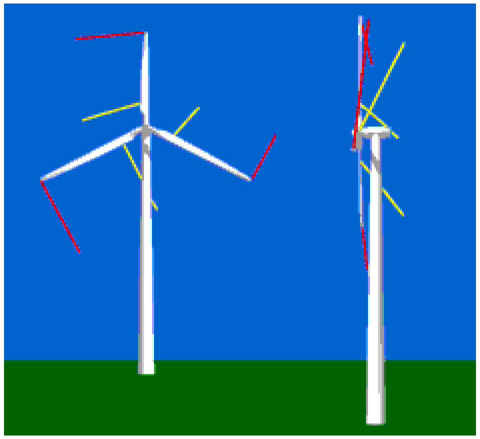
- Main Rotor Design Method (ideal case):
    1. Determine basic configuration: orientation and blade number
    2. take site wind speed and desired power output
    3. Calculate rotor diameter (accounting for efficiency losses)
    4. Select tip-speed ratio (higher → more complex airfoils, noise) and 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



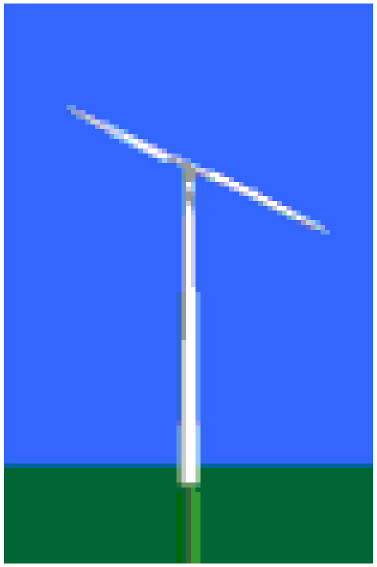
Graphic source Wind power: http://www.fao.org/docrep/010/ah810e/AH810E10.htm

Wind Turbine Blades

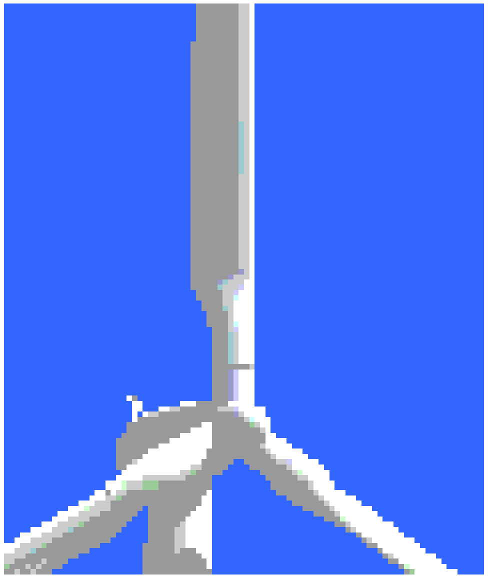
- Blade tip speed:



- 2-Blade Systems and Teetered Hubs:



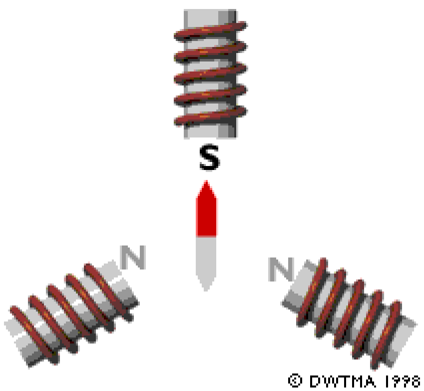
- Pitch control:

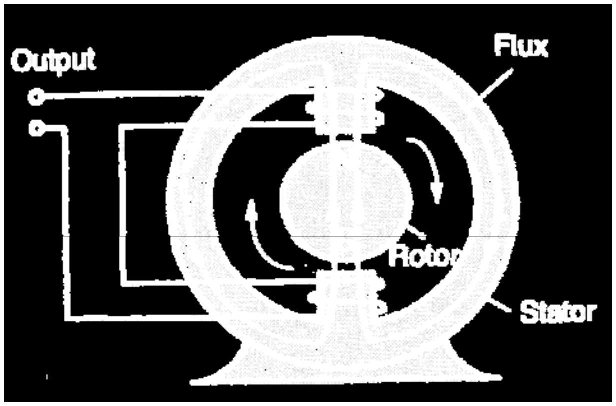


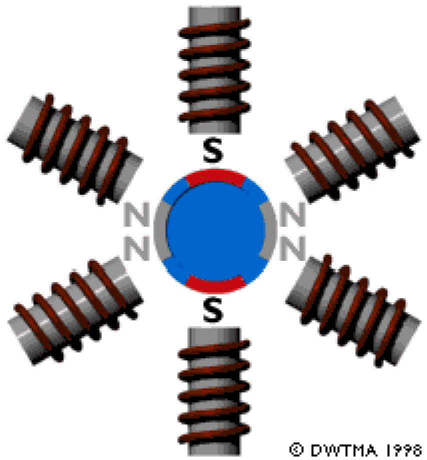
http://guidedtour.windpower.org/en/tour/wres/index.htm

Electrical Generator

- Generator:
  - Rotating magnetic field induces current





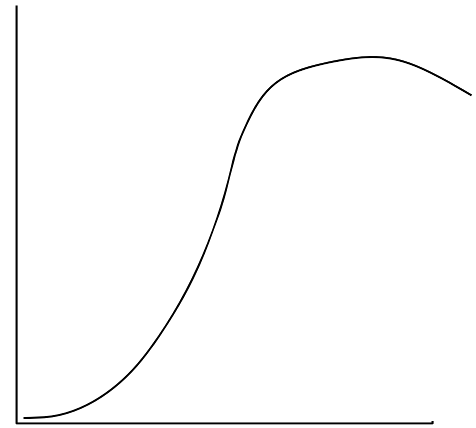


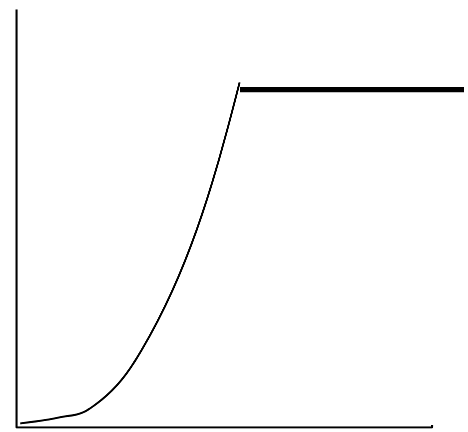
- Synchronous / Permanent Magnet Generator
  - Potential use without gearbox
  - Historically higher cost (use of rare-earth metals)
- Asynchronous / Induction Generator
  - Slip (operation above/below synchronous speed) possible
  - Reduces gearbox wear

Masters, Gilbert, *Renewable and Efficient Electric Power Systems*, Wiley-IEEE Press, 2003
http://guidedtour.windpower.org/en/tour/wtrb/genpoles.htm .

Control Systems & Electronics

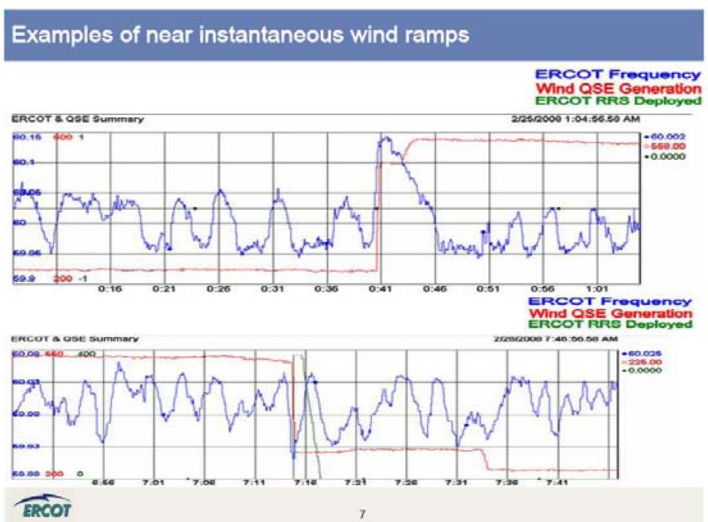
- Control methods
  - Drivetrain Speed
    - Fixed (direct grid connection) and Variable (power electronics for indirect grid connection)
  - Blade Regulation
    - Stall – blade position fixed, angle of attack increases with wind speed until stall occurs behind blade
    - Pitch – blade position changes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



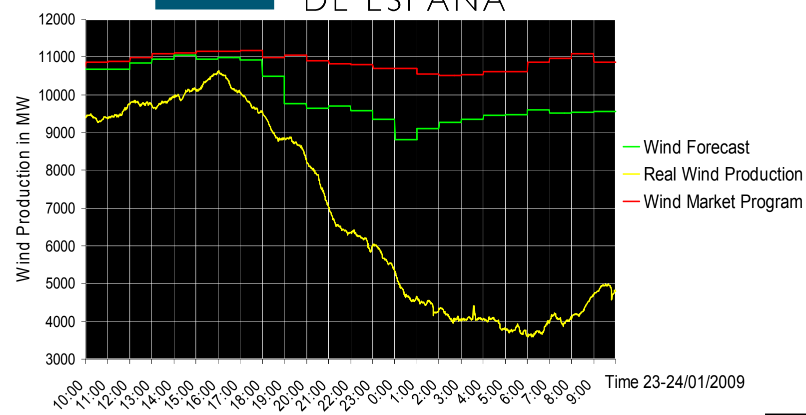


Wind Grid Integration

- 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)



RED ELÉCTRICA DE ESPAÑA



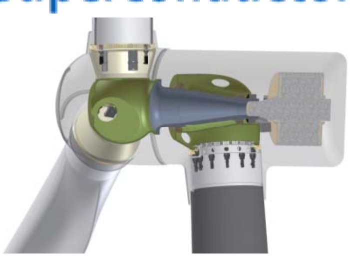
Left graphic courtesy of ERCOT

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

American Superconductor®



VERGNET GROUPE

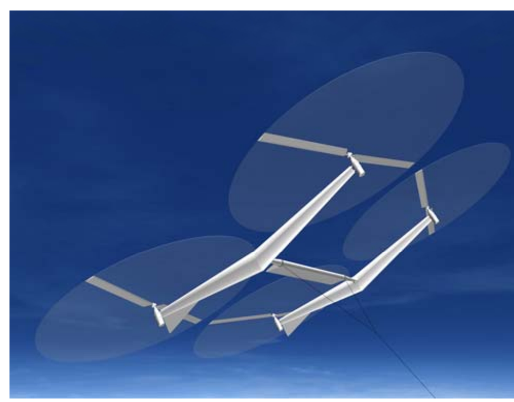
Northern POWER SYSTEMS

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

FloDesign Wind Turbine
there's change in the wind

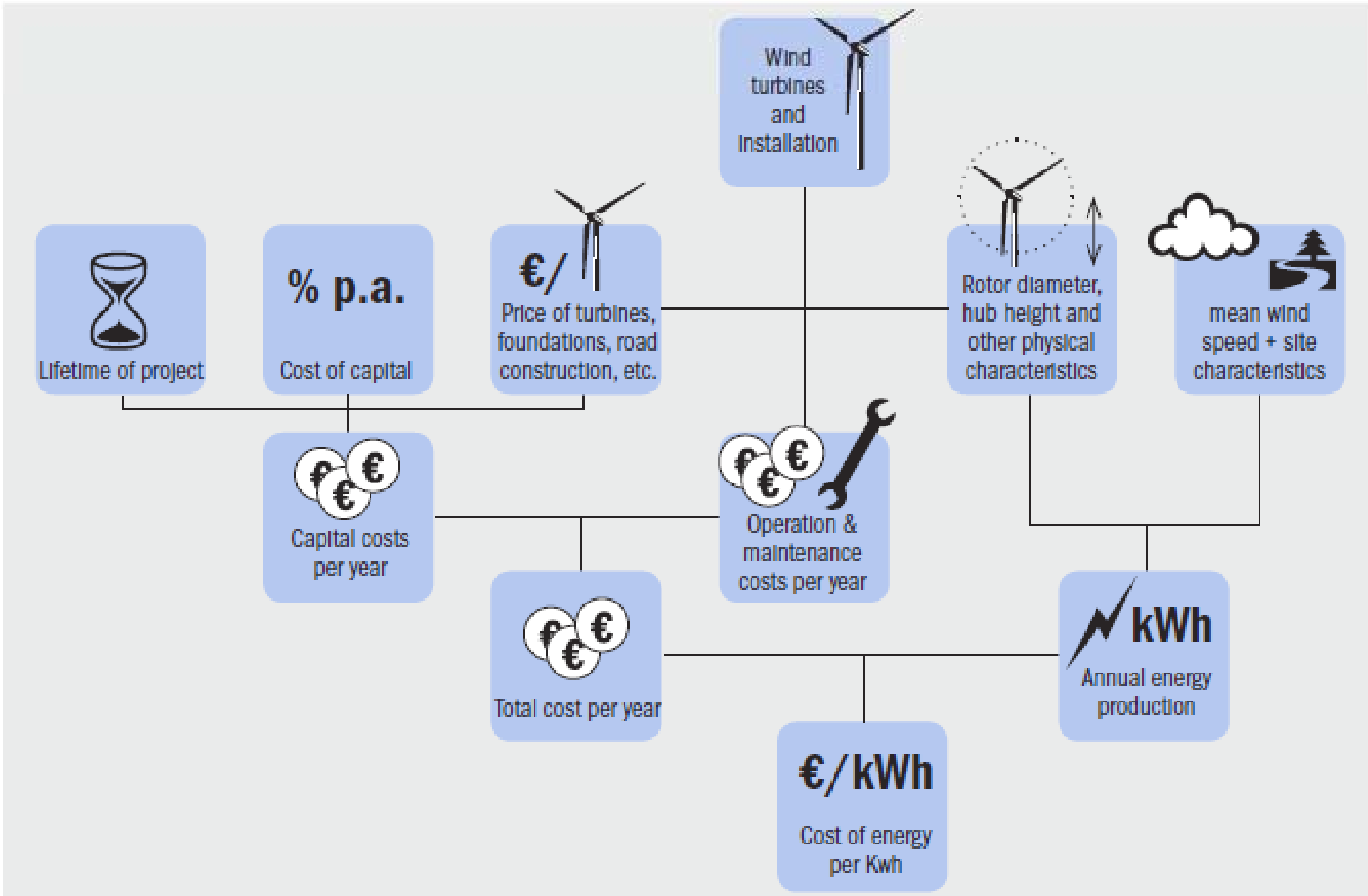
Sky Windpower



Going Beyond the Science & Technology of Wind…

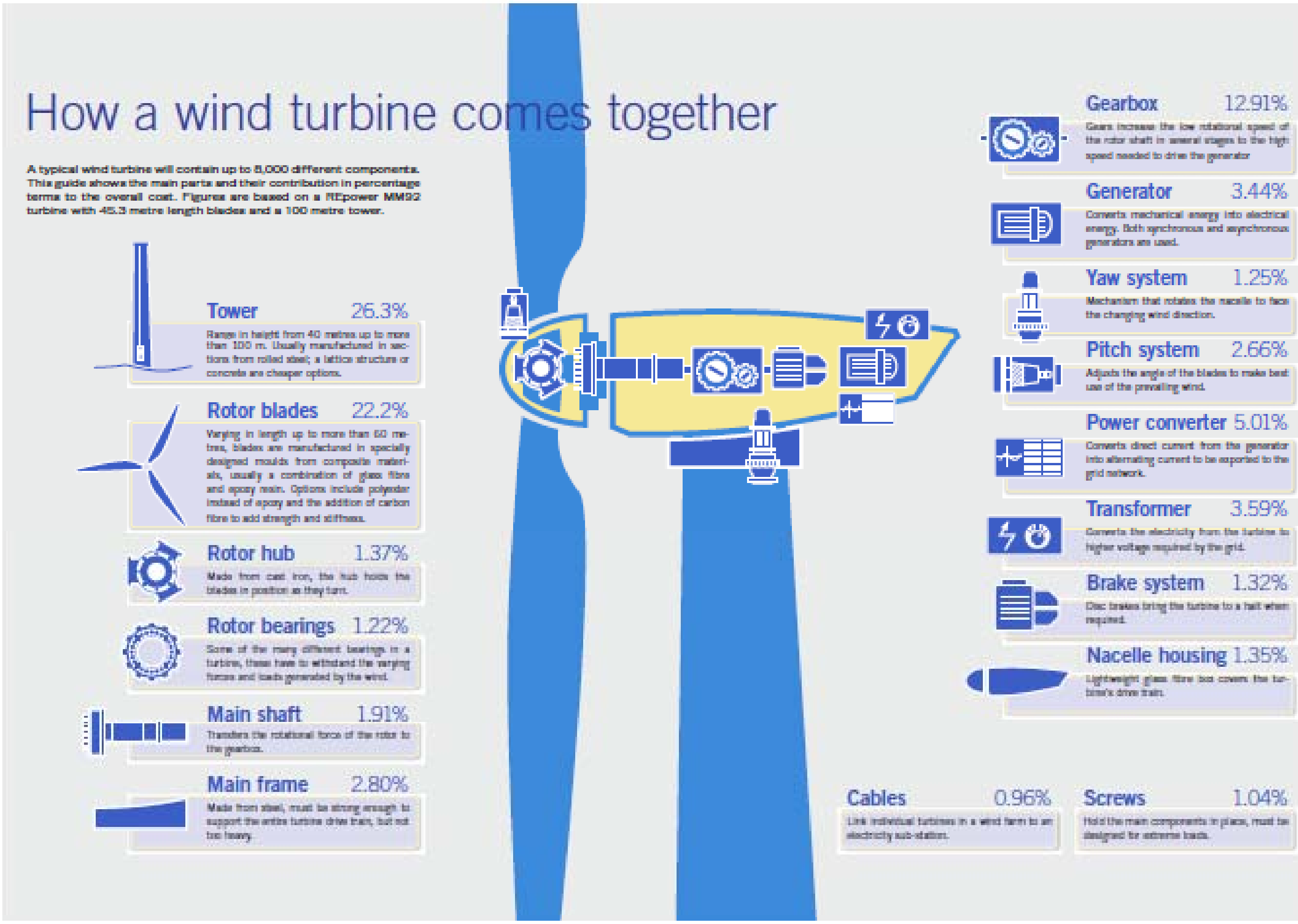
Source: EWEA, 2009

Wind Energy Costs



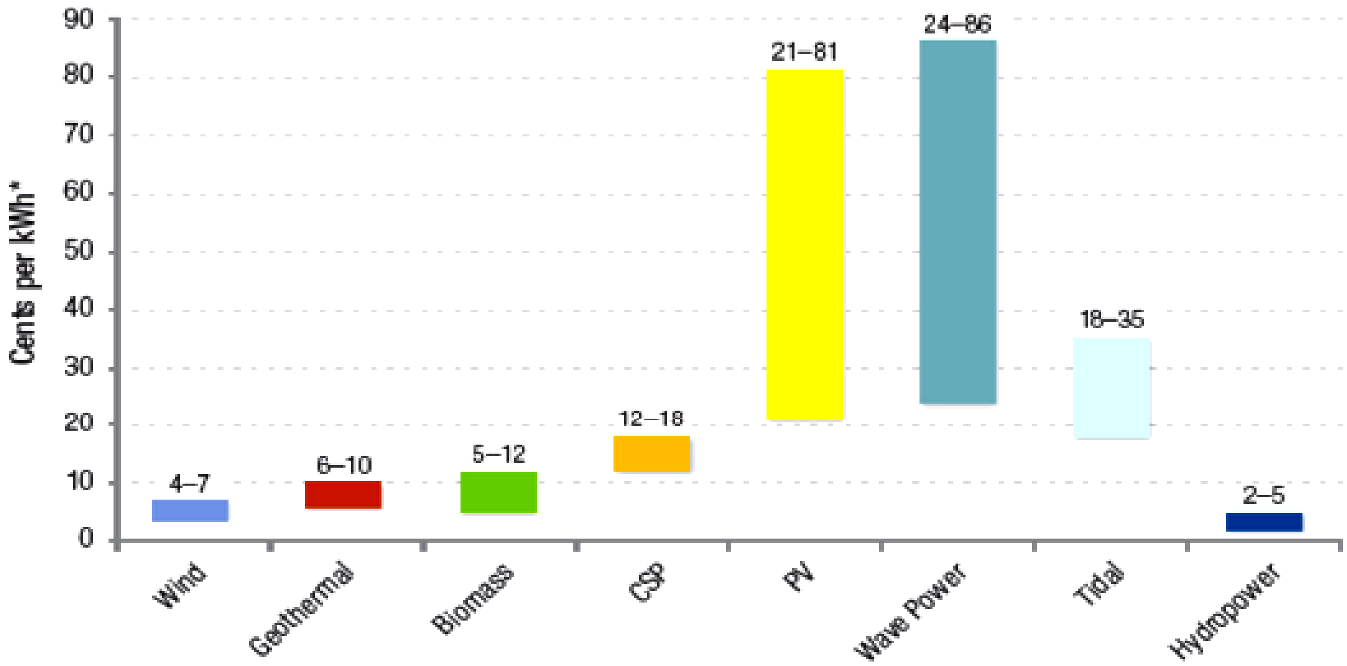
Source: EWEA, 2009

% Cost Share of 5 MW Turbine Components



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

Costs -- Levelized Comparison



* 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

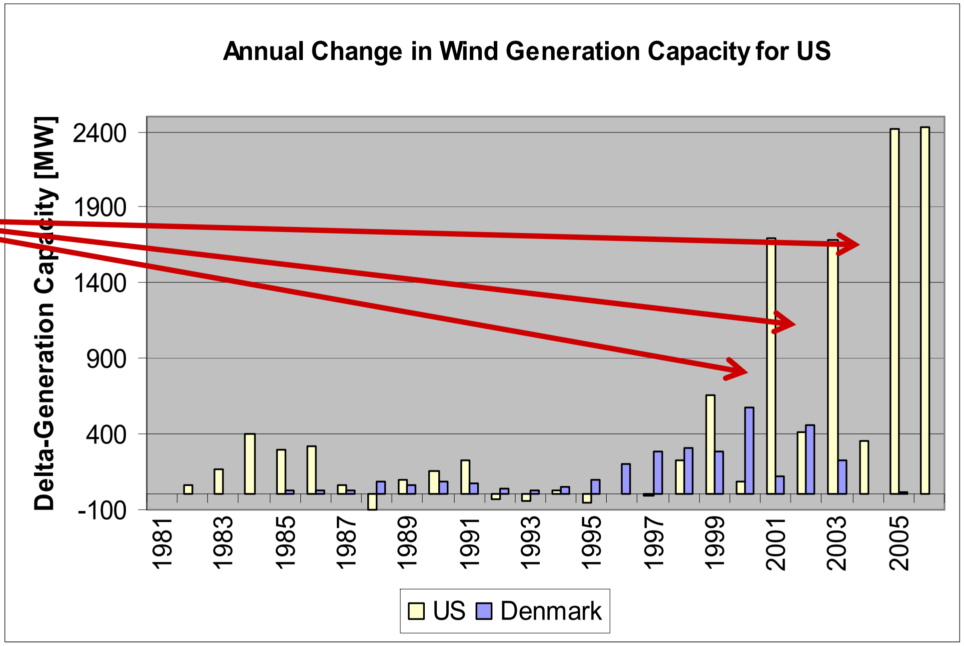
Reported in US DOE. 2008 Renewable Energy Data Book

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



[1]Wiser, 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;

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

Cambridge, MA

The Environment

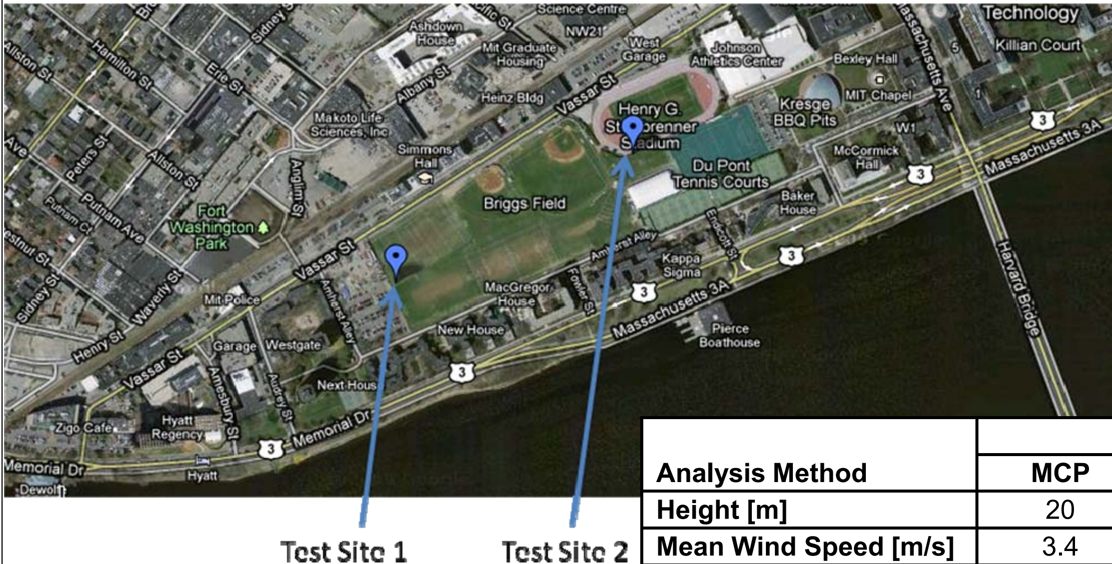
- Cleaner air -- reduced GHGs, particulates/pollutants, waste; minimized opportunity for oil spills, natural gas/nuclear plant leakage; more sustainable effects
- Planning related to wildlife migration and habitats
- Life cycle impacts of wind power relative to other energy sources
- Some of the most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

Turbine Photo Source: http://www.skystreamenergy.com/skystream-info/productphotos.php

MIT Project Full Breeze



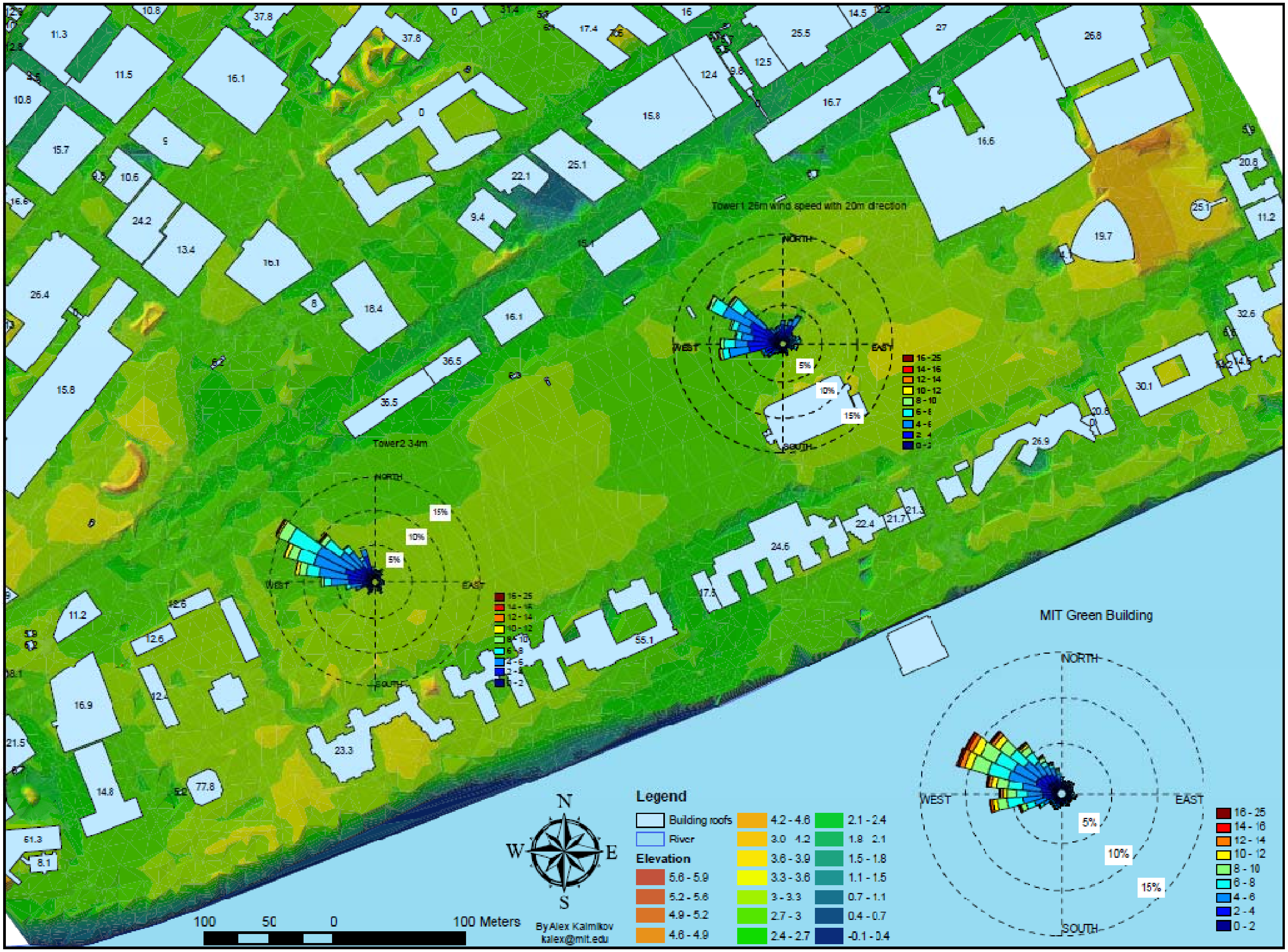
- 3 and 6+ months of data at two sites on MIT's Briggs Field
- Complemented with statistical analysis using Measure-Correlate-Predict method

	Met station 2					
Analysis Method	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%

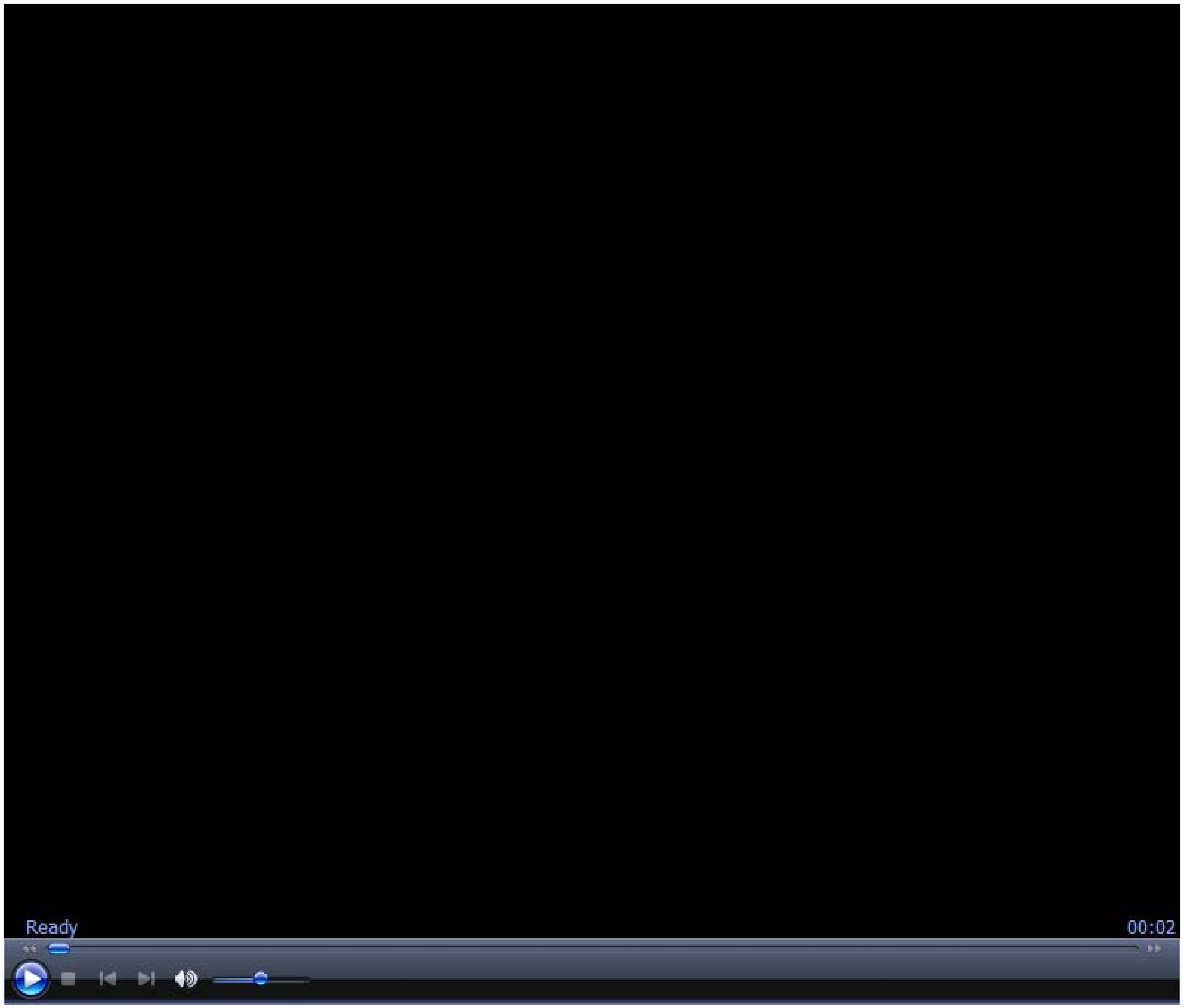
	Met station 1					
Analysis Method	MCP	CFD	MCP	CFD	MCP	CFD
Height [m]	20	20	26	26	34	34
Mean Wind Speed [m/s]	3.3	2.7	3.7	2.9	n/a	3.1
Power Density [W/m^2]	39.4	41.9	55.6	50.2	n/a	60.5
Annual Energy Output [kW-hr]	817	974	1,259	1,193	n/a	1,430
Annual Production CFD [kW-hr]	n/a	931	n/a	1,135	n/a	1,377
Capacity Factor	4%	5%	6%	6%	n/a	7%
Operational Time	35%	26%	45%	29%	n/a	32%

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

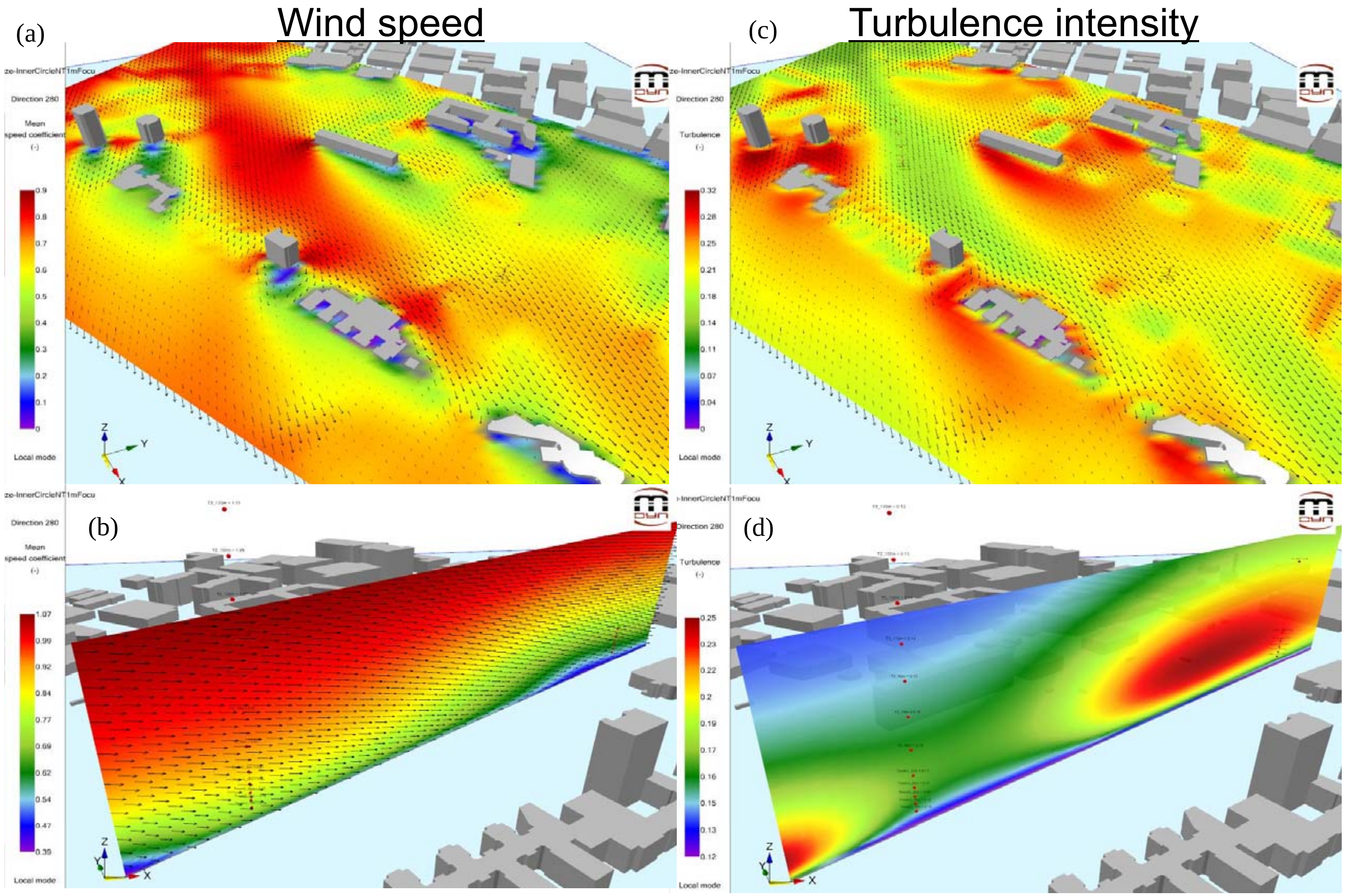
Spatial Analysis of Wind Resource at MIT



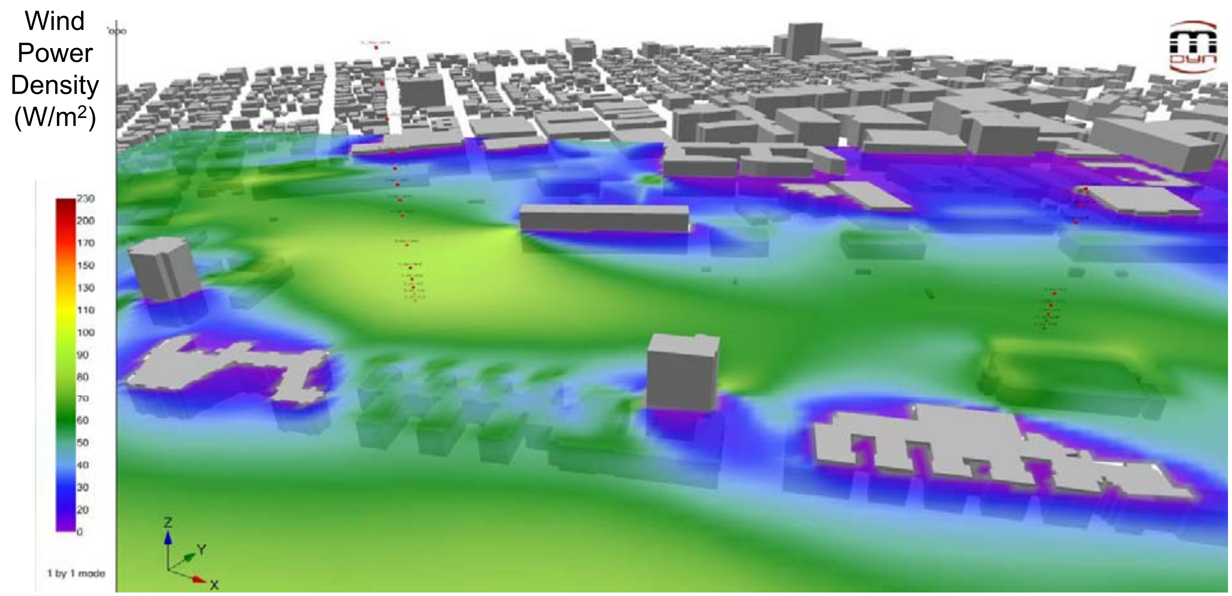
3D model of MIT campus

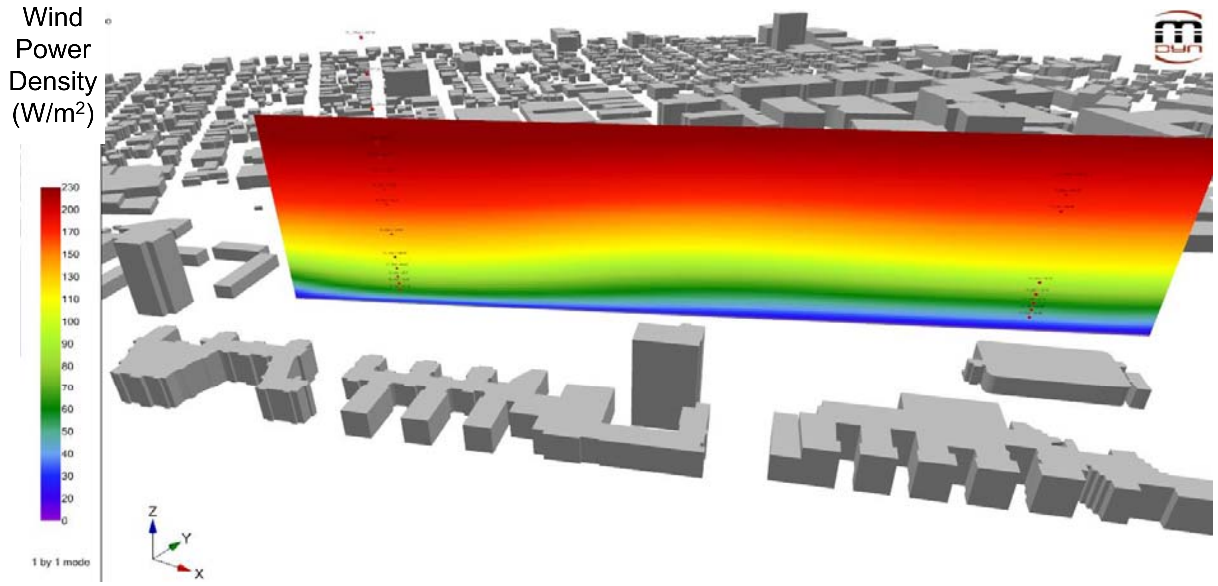


3D simulations of wind resource structure at MIT



Wind Power Density at MIT





Q & A

THANK YOU