

# Wind Power Fundamentals

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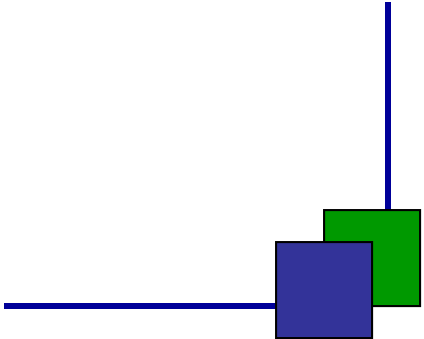
*MIT Wind Energy Group &  
Renewable Energy Projects in Action*

*Email: [wind@mit.edu](mailto:wind@mit.edu)*





# 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

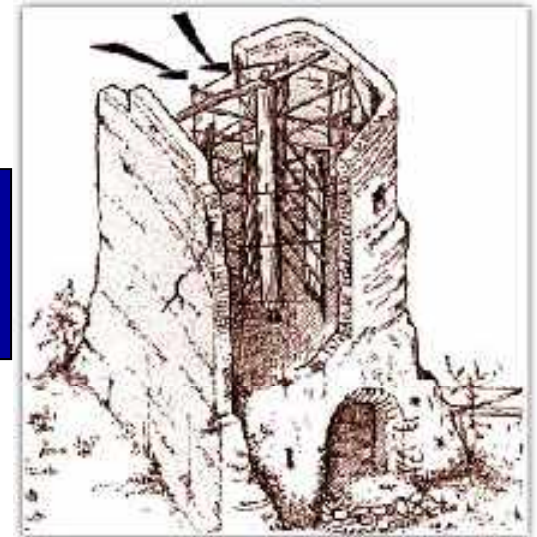
- Ancient Civilization in the Near East / Persia
- Vertical-Axis Wind-Mill: sails connected to a vertical shaft connected to a grinding stone for milling

## 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 19<sup>th</sup> century US

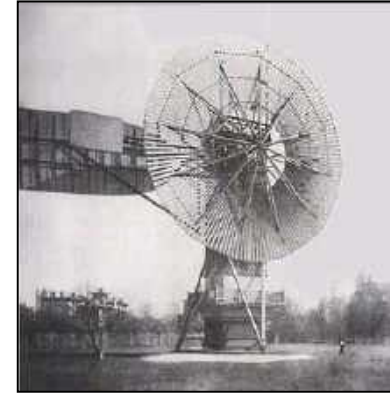
- Wind-rose horizontal-axis water-pumping wind-mills found throughout rural America





# 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

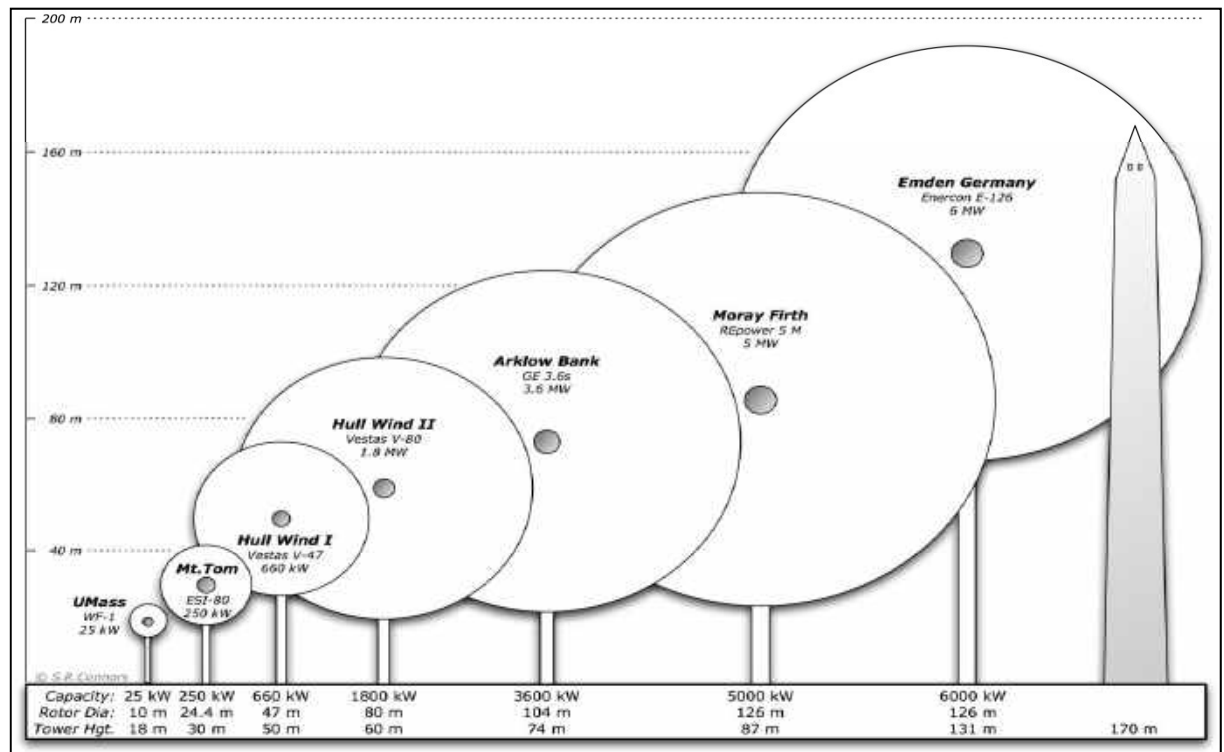
Key attributes of this period:

- 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



# 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

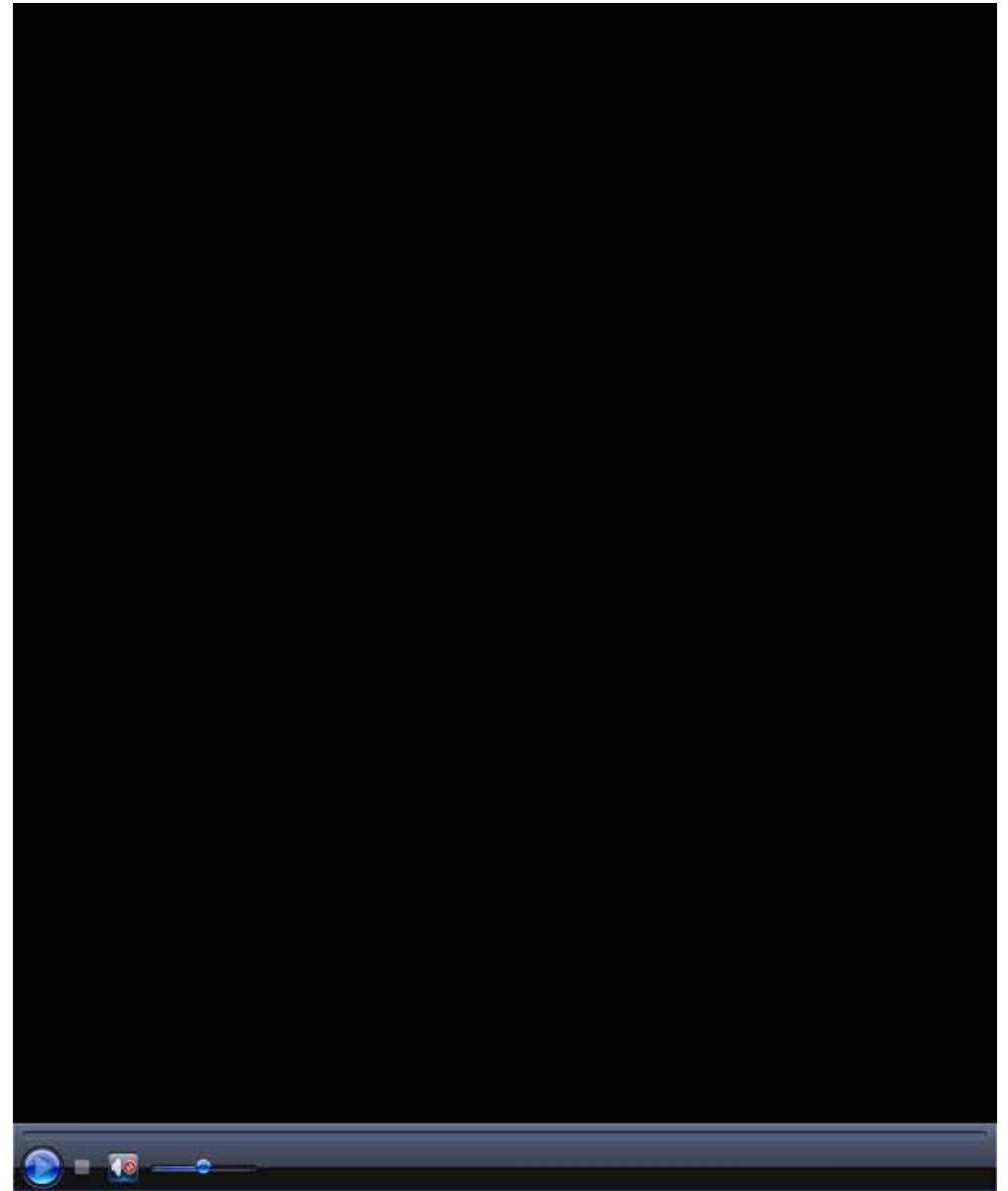
## Spatial Scales

**Planetary scale:** global circulation

**Synoptic scale:** weather systems

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

**Micro scale:** urban topography

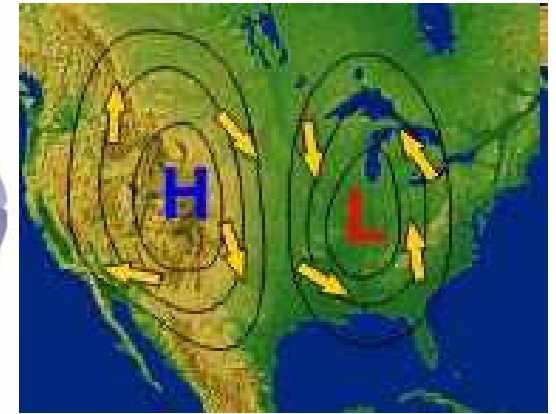
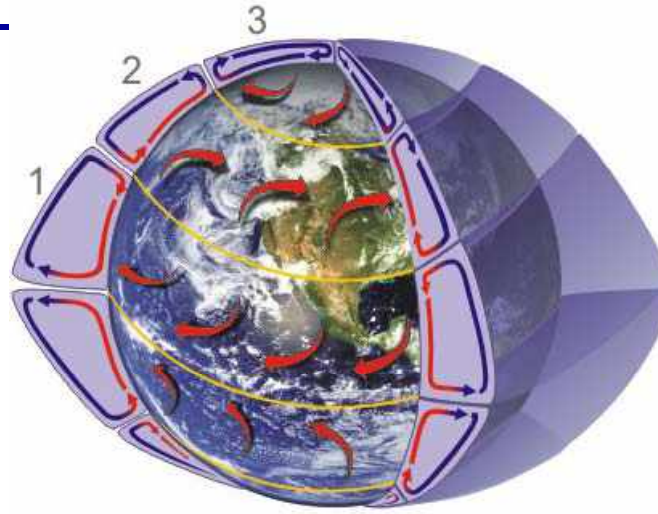


*Source for Graphic: NASA / GSFC*

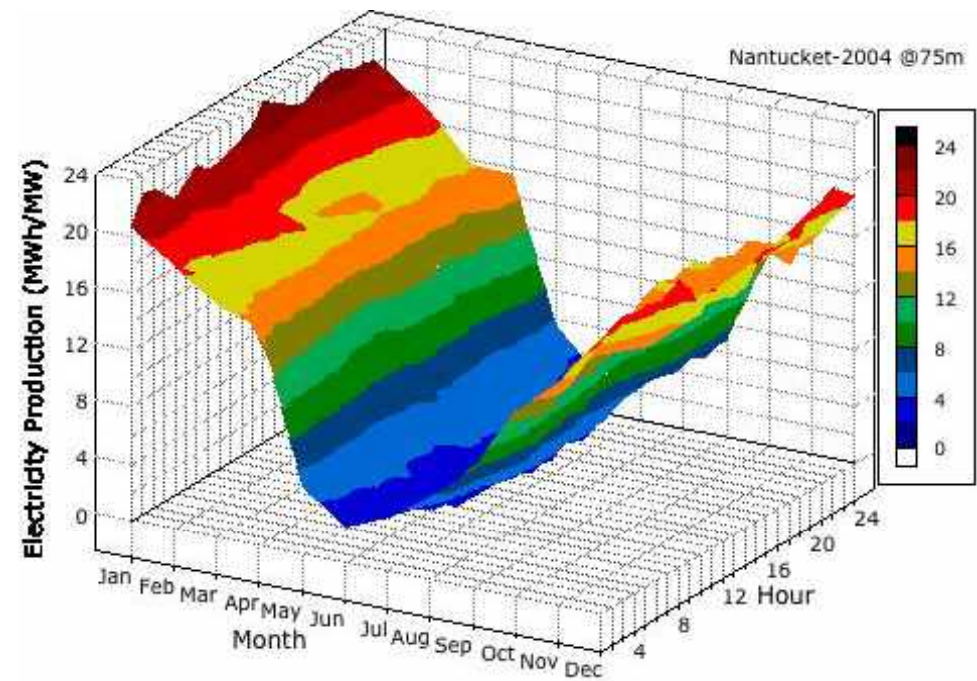
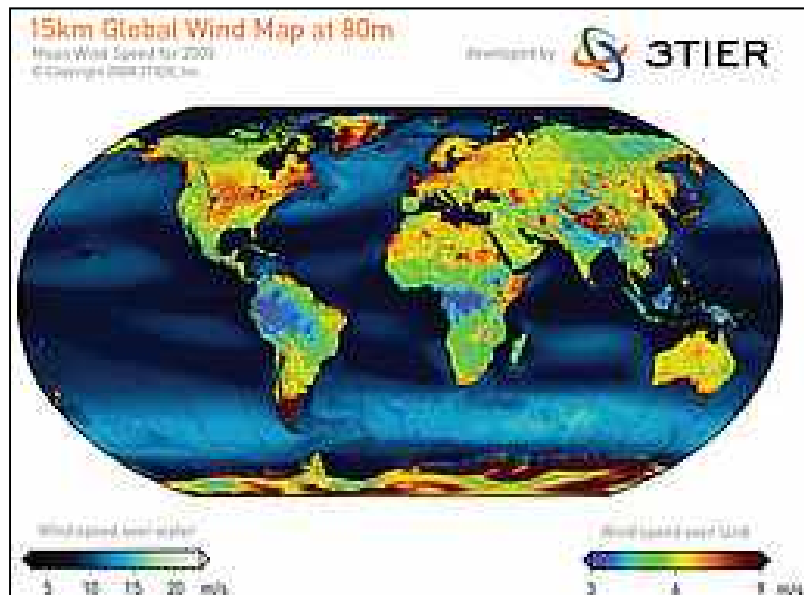
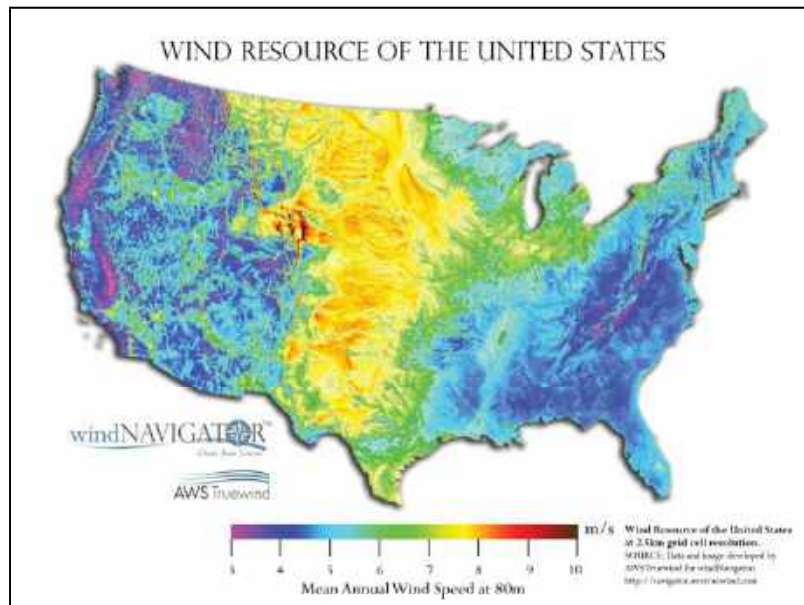


# Wind types

- 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:

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

- Power is KE per unit time:

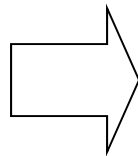
- $P = \frac{1}{2} * \dot{m} * v^2$

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

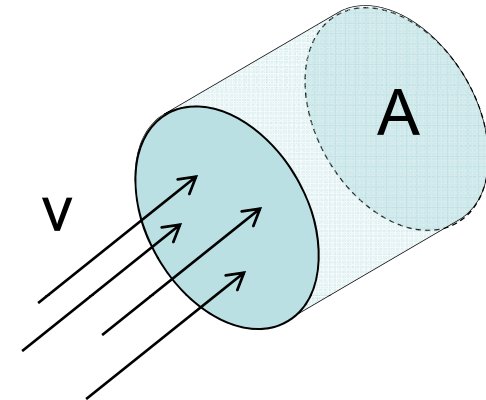
- $\dot{m}/dt = \rho * A * v$

- Thus:

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



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



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

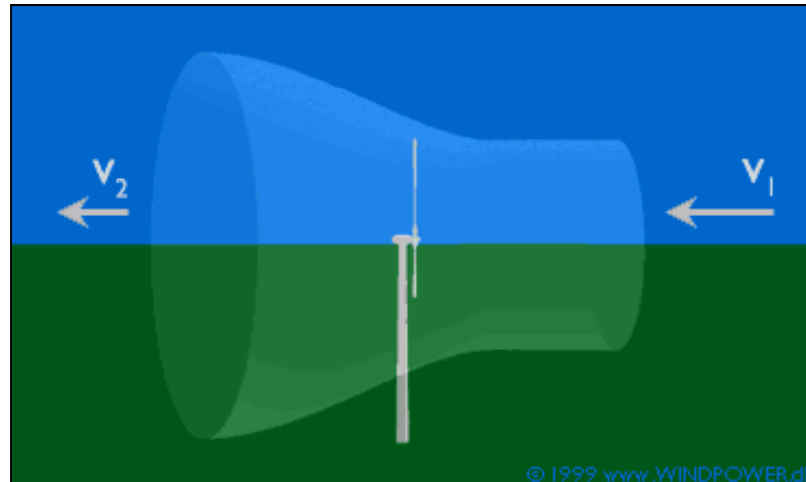
# Efficiency in Extracting Wind Power

## Betz Limit & Power Coefficient:

- Power Coefficient, **C<sub>p</sub>**, 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





# Power Curve of Wind Turbine

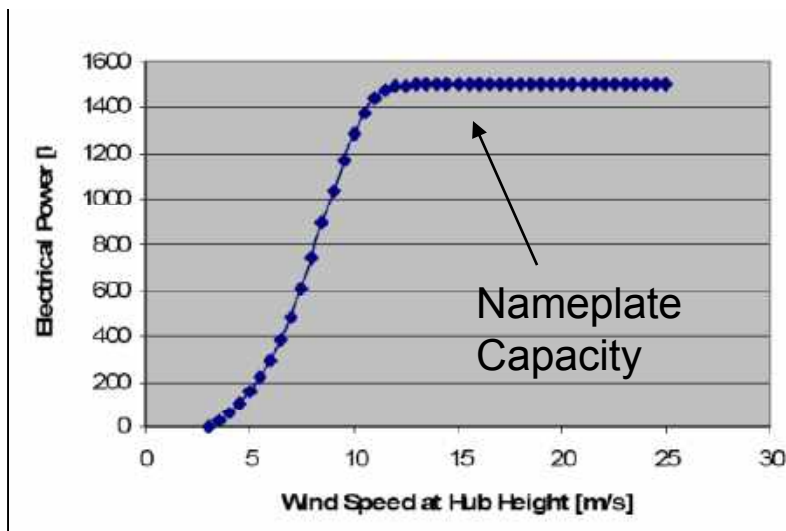
## Capacity Factor (CF):

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

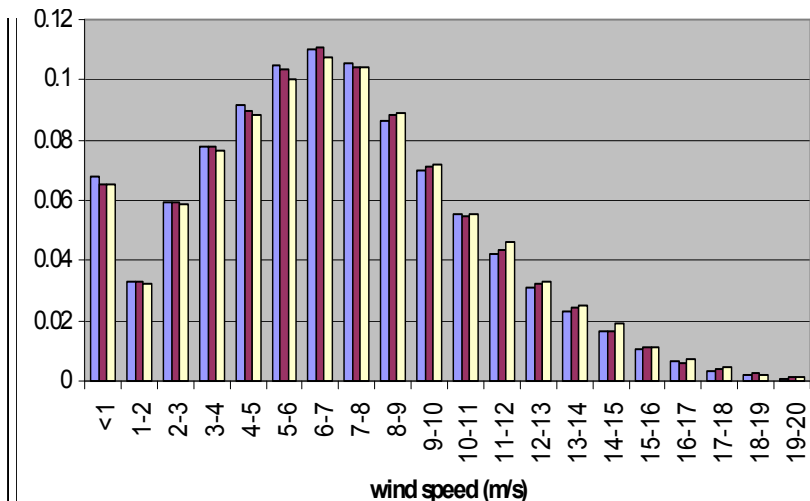
$$\text{Capacity Factor} = \text{Average Output} / \text{Peak Output} \approx 30\%$$

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

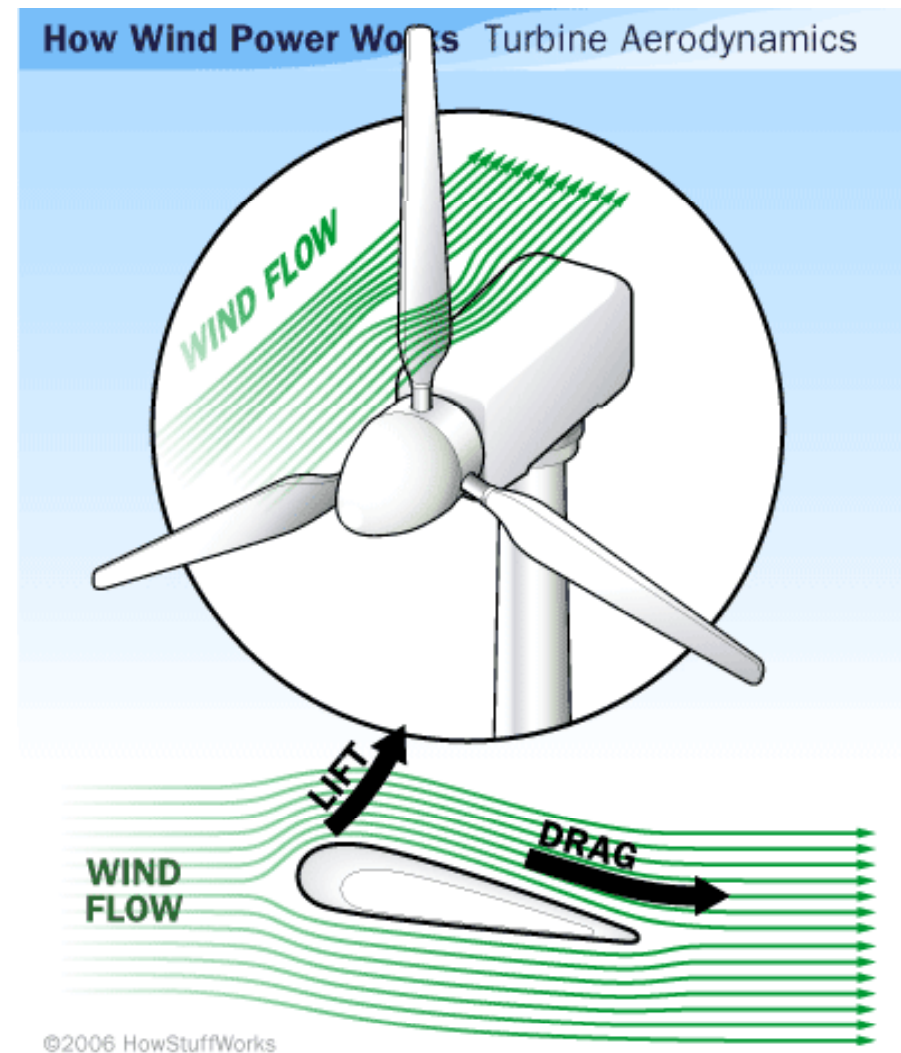
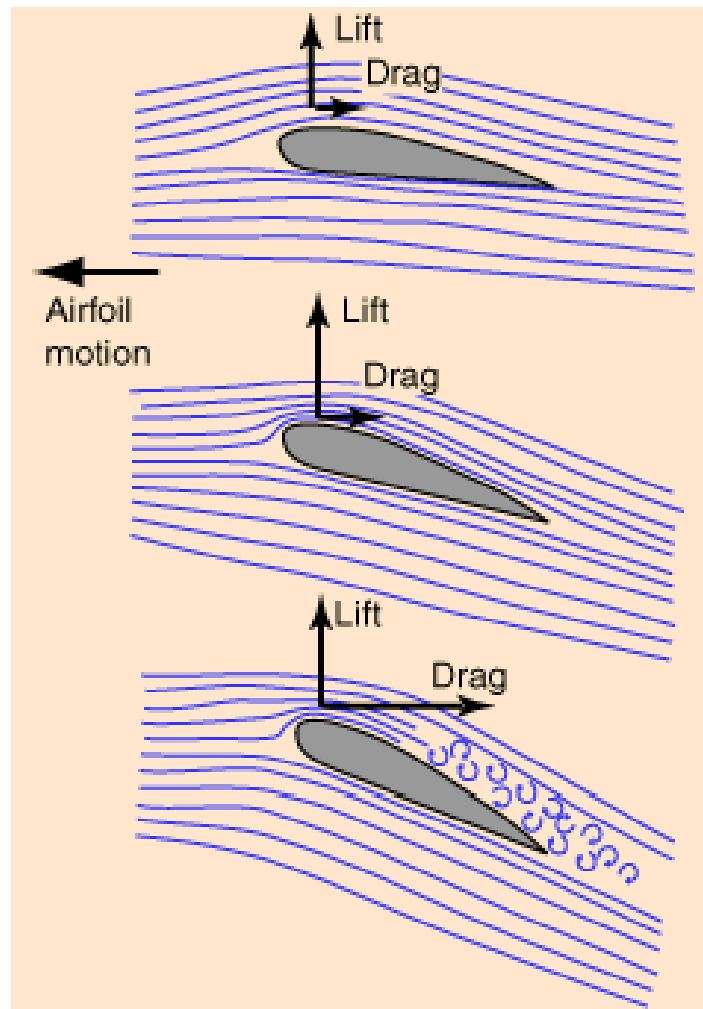
Power Curve of 1500 kW Turbine



Wind Frequency Distribution



# 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				Primary Power	Electrical Conversion
		Gas	Steam	Water	Aero		
<sup>3</sup> Traditional Boiler	External		•			Shaft	Generator
<sup>3</sup> Fluidized Bed Combustion	External		•			Shaft	Generator
Integrated Gasification Combined-Cycle	Both	•	•			Shaft	Generator
Combustion Turbine	Internal	•				Shaft	Generator
Combined Cycle	Both	•	•			Shaft	Generator
<sup>3</sup> Nuclear			•			Shaft	Generator
Diesel Genset	Internal					Shaft	Generator
Micro-Turbines	Internal	•				Shaft	Generator
Fuel Cells						<b>Direct</b>	<b>Inverter</b>
Hydropower				•		Shaft	Generator
<sup>3</sup> Biomass & WTE	External		•			Shaft	Generator
Windpower					•	Shaft	Generator
Photovoltaics						<b>Direct</b>	<b>Inverter</b>
<sup>3</sup> Solar Thermal			•			Shaft	Generator
<sup>3</sup> Geothermal			•			Shaft	Generator
Wave Power		•				Shaft	Generator
Tidal Power				•		Shaft	Generator
<sup>3</sup> 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)

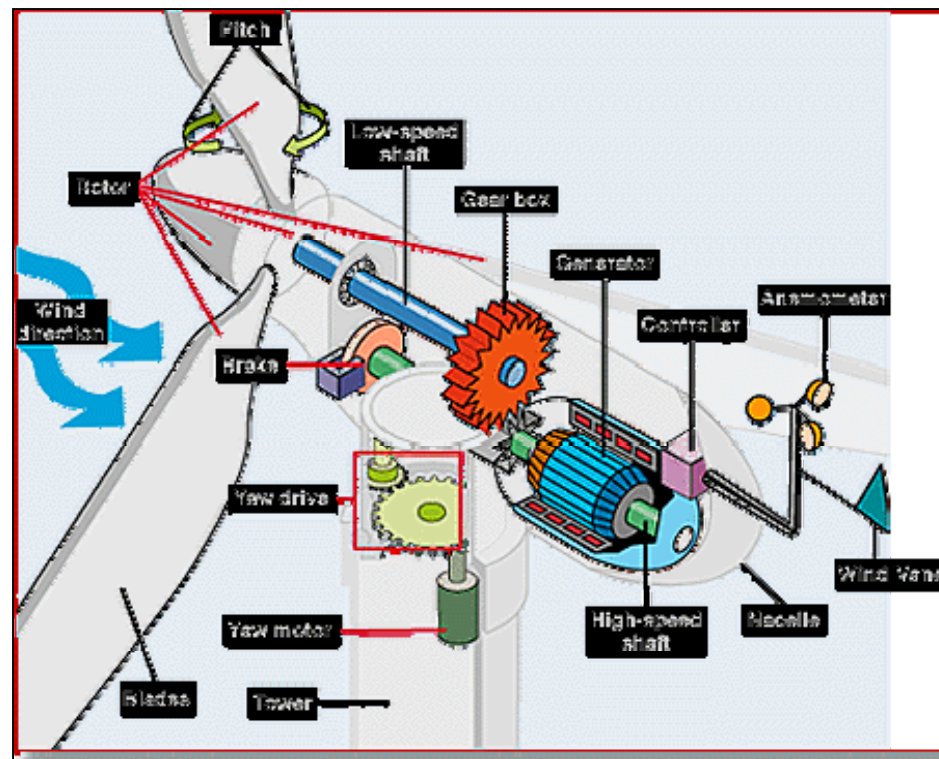
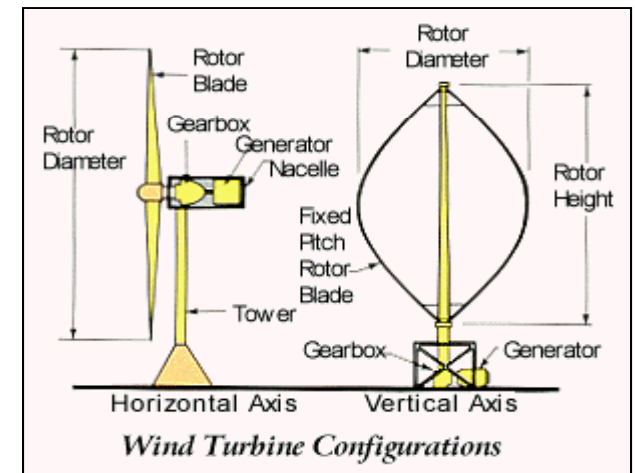


Photos courtesy of Steve Connors, MITEI



# Wind Turbine Subsystems

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



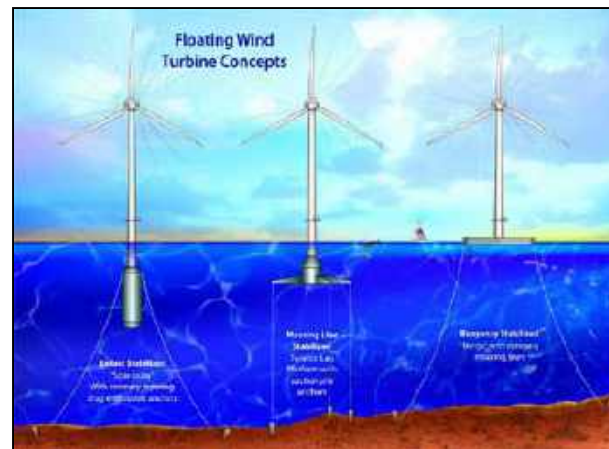
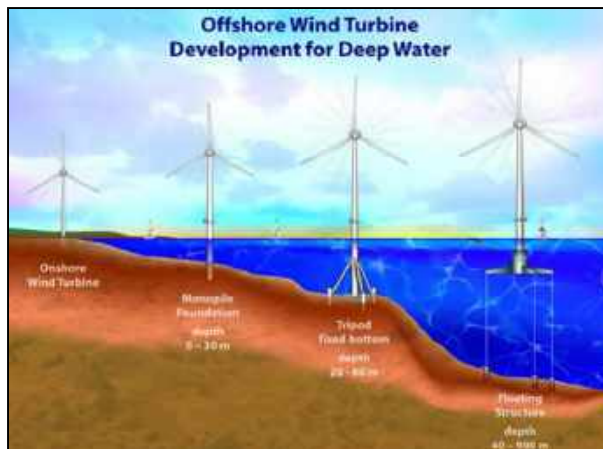
Source for Graphics: AWEA Wind Energy Basics, [http://www.awea.org/faq/wwt\\_basics.html](http://www.awea.org/faq/wwt_basics.html)

# Foundations and Tower

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

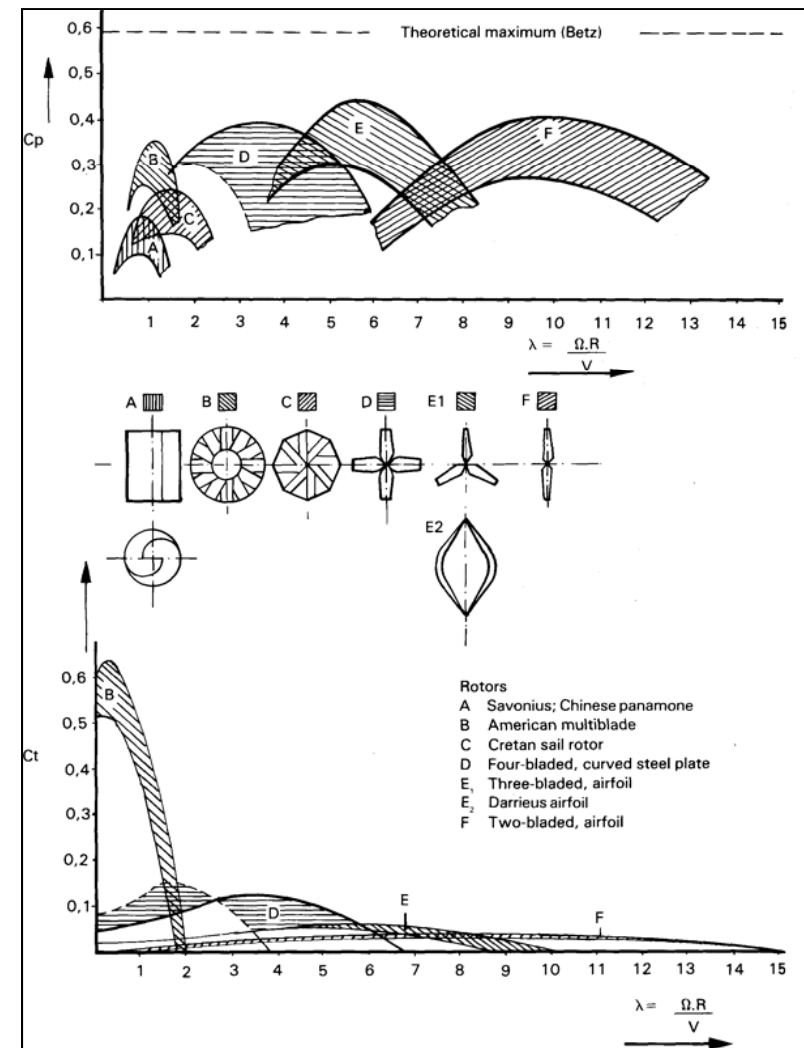


- Many different configurations proposed for offshore



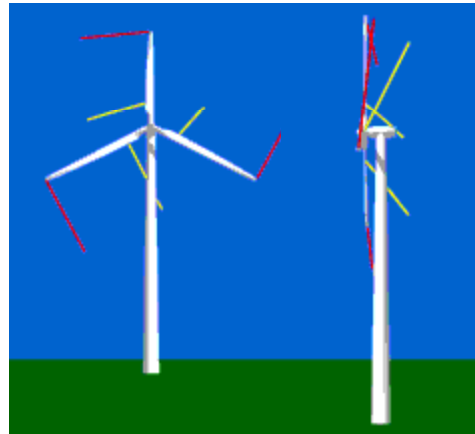
# Nacelle, Rotor & Hub

- 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  $\rightarrow$  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

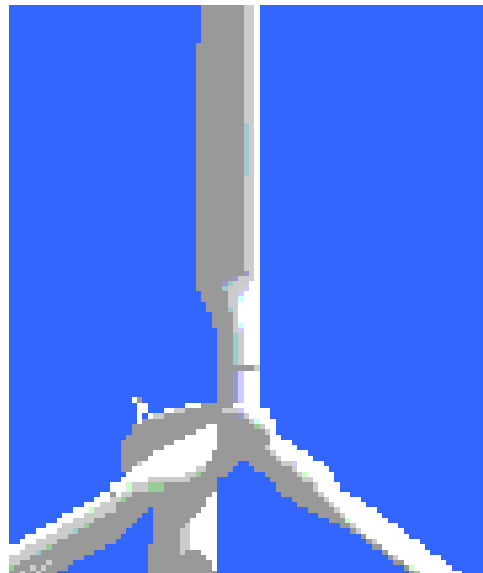


# Wind Turbine Blades

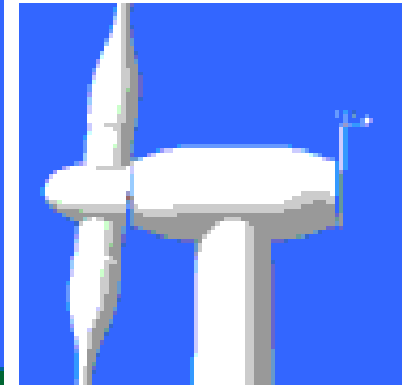
- Blade tip speed:



- Pitch control:

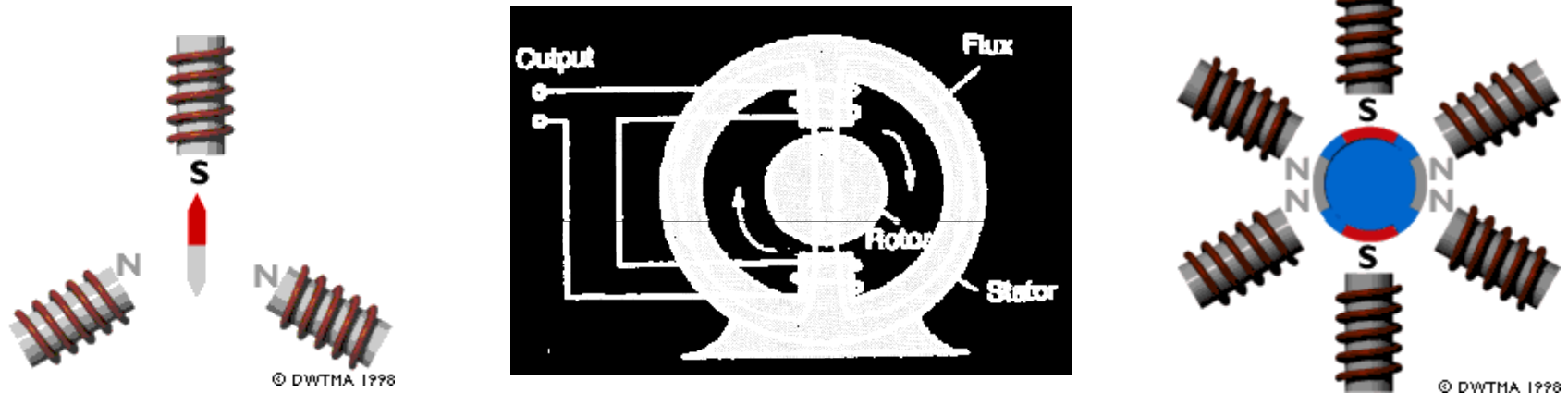


- 2-Blade Systems and Teetered Hubs:



# Electrical Generator

- Generator:
  - Rotating magnetic field induces current

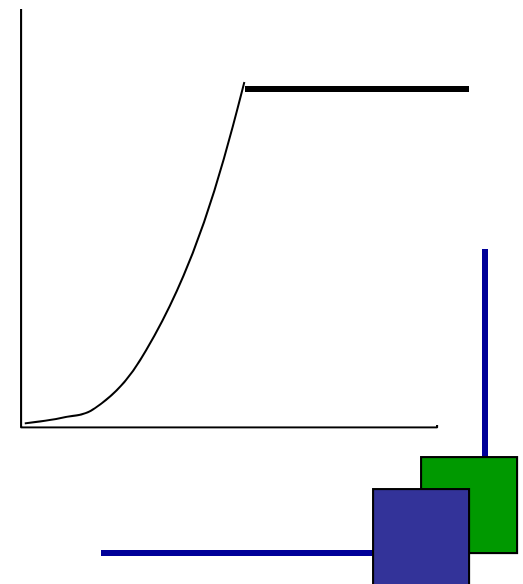
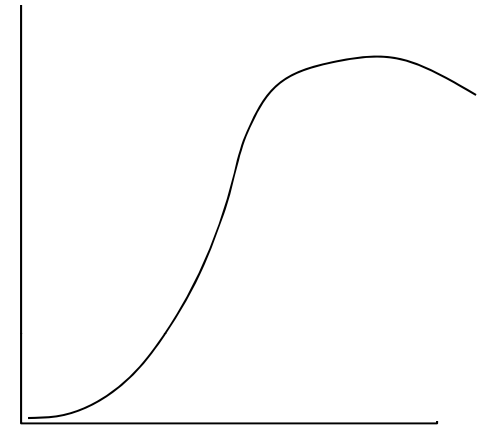


- Synchronous / Permanent Magnet Generator
  - Potential use without gearbox
  - Historically higher cost (use of rare-earth metals)
- Asynchronous / Induction Generator
  - Slip (operation above/below synchronous speed) possible
  - Reduces gearbox wear



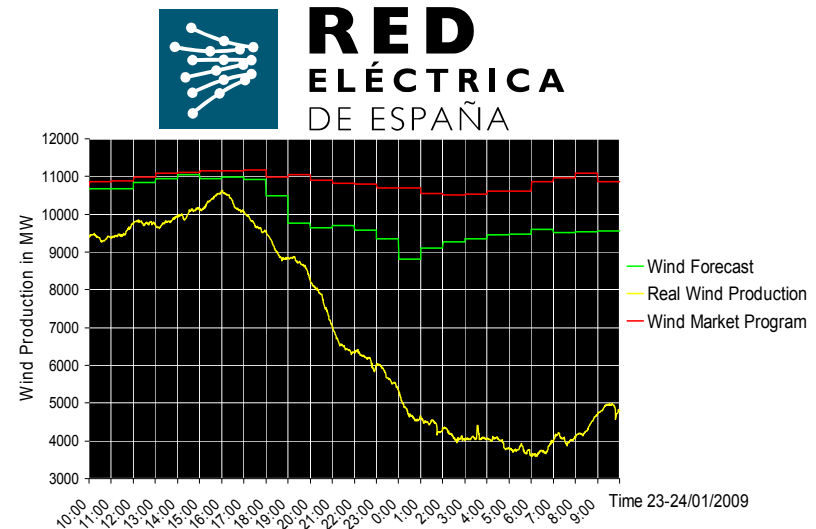
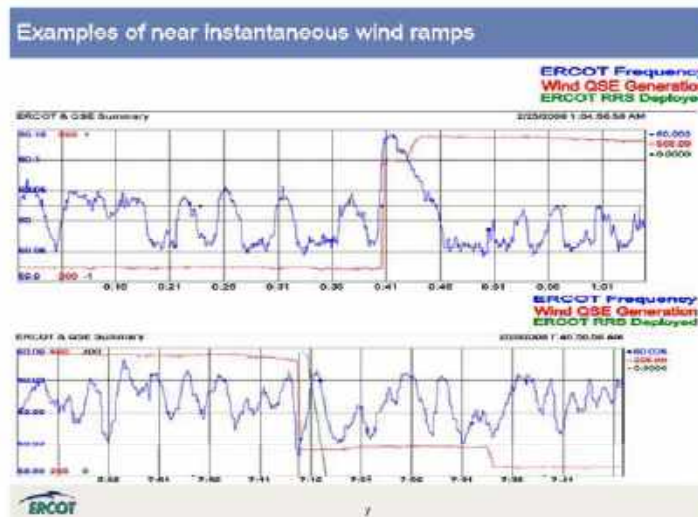
# Control Systems & Electronics

- 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

 American  
Superconductor®



 **VERGNET**  
GROUPE

  
**Northern**  
POWER SYSTEMS

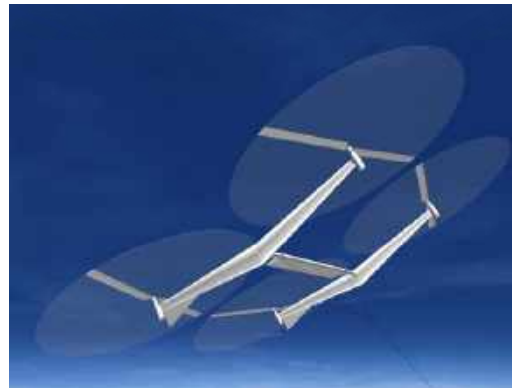


# Future Technology Development

- 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



## Sky Windpower



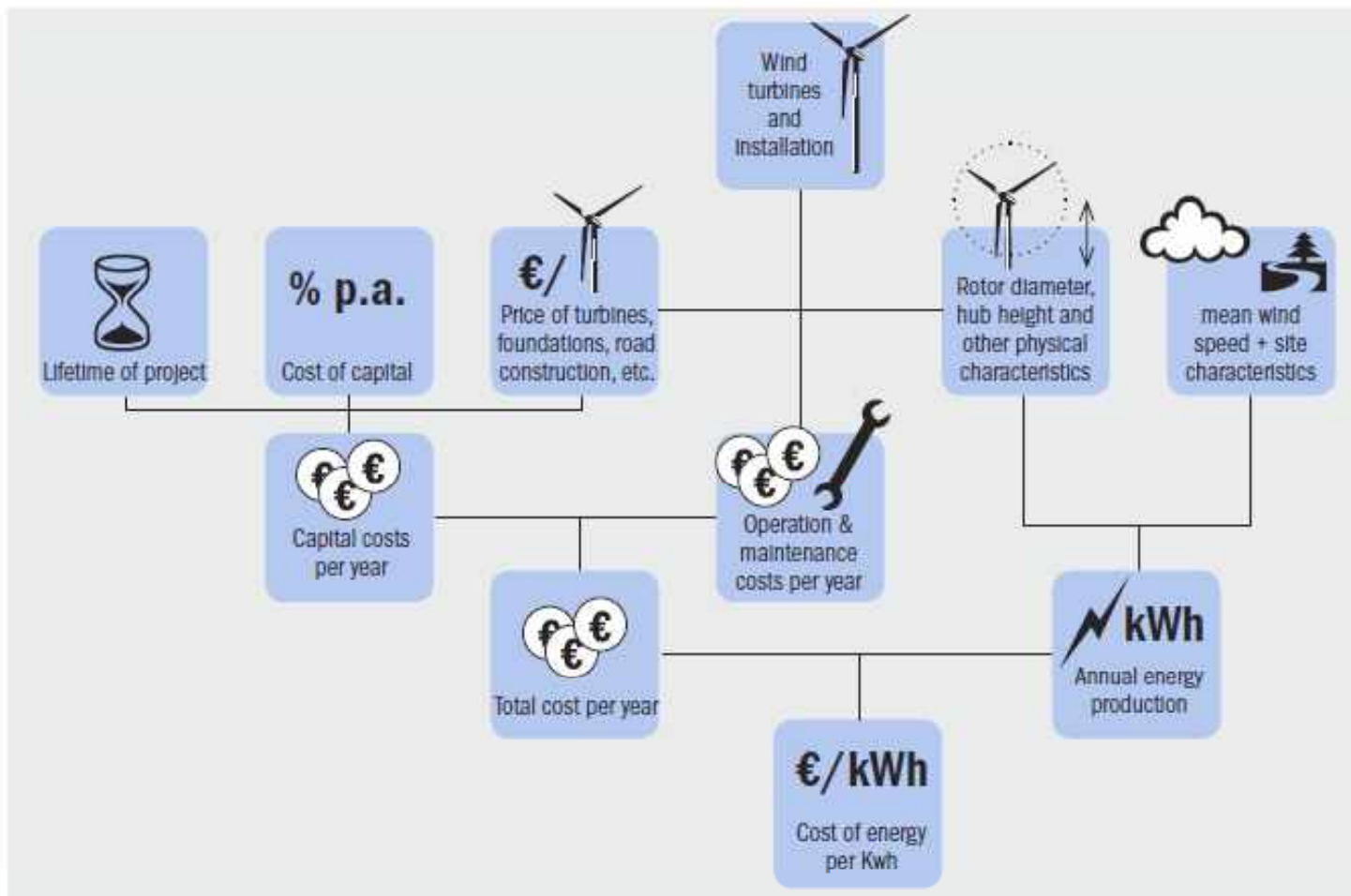
# Going Beyond the Science & Technology of Wind...



*Source: EWEA, 2009*

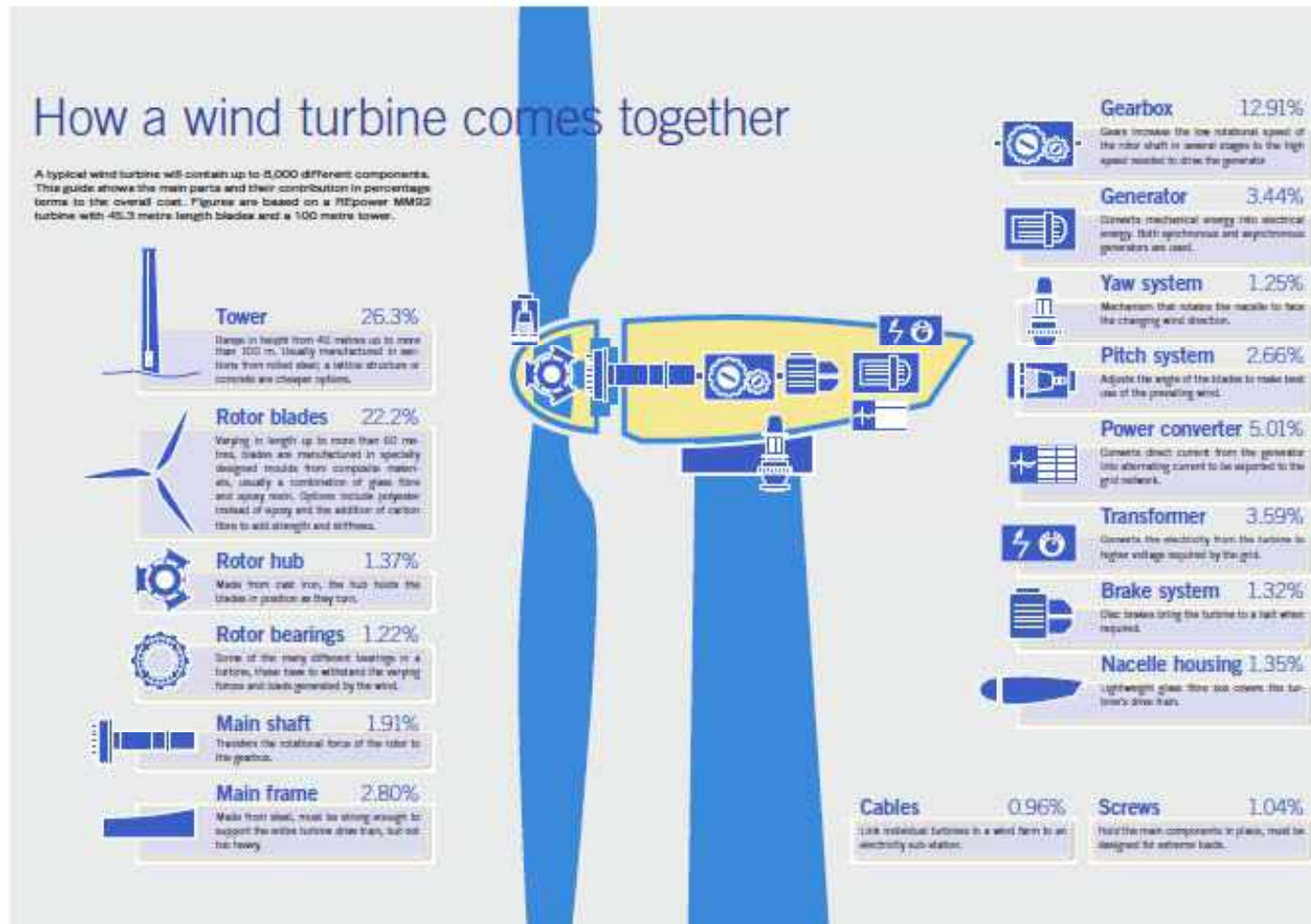


# Wind Energy Costs



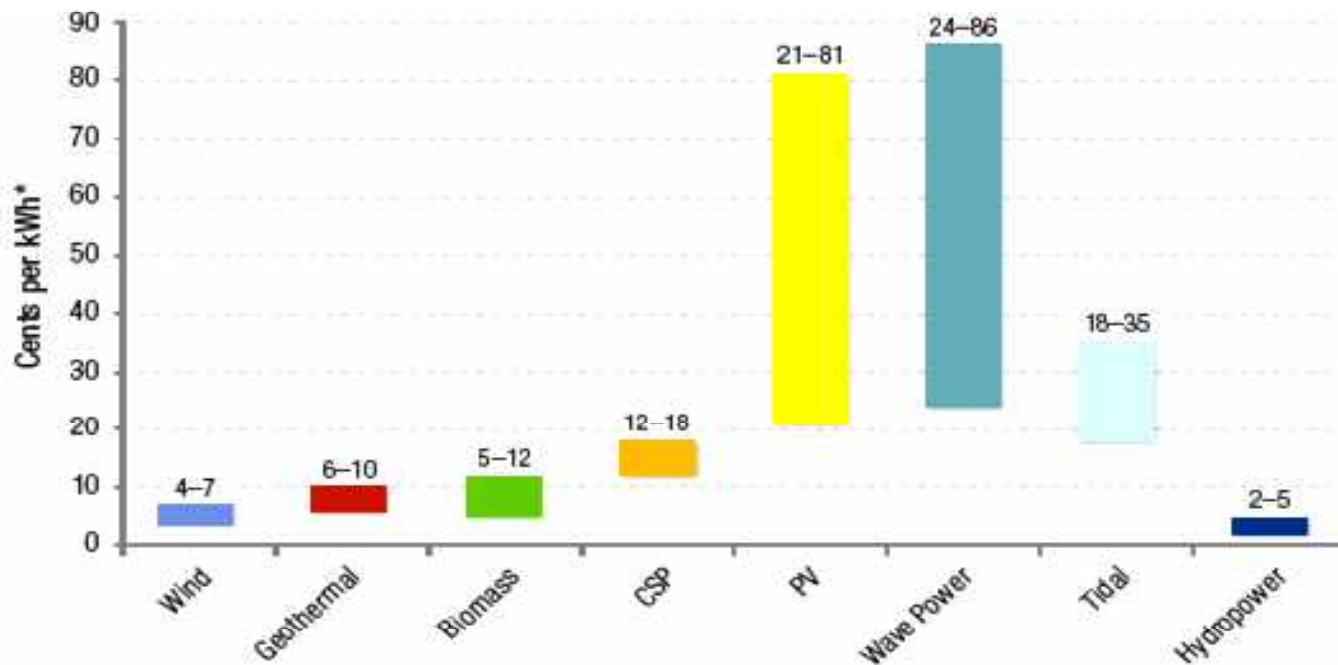
Source: EWEA, 2009

# % 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

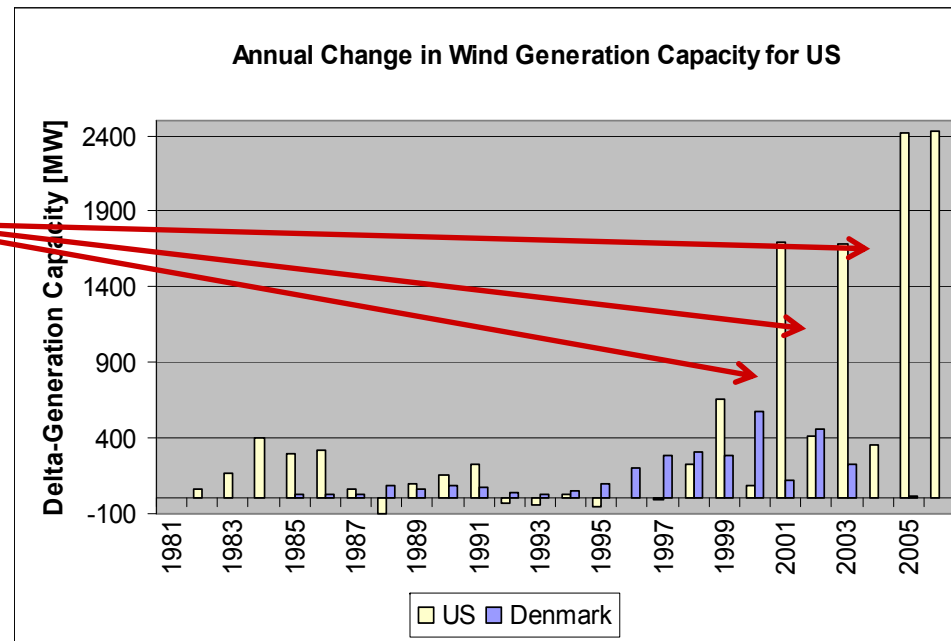
*Reported in US DOE. 2008 Renewable Energy Data Book*

# 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



<sup>1</sup>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].

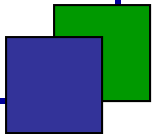


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## Policy Options Available

- 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

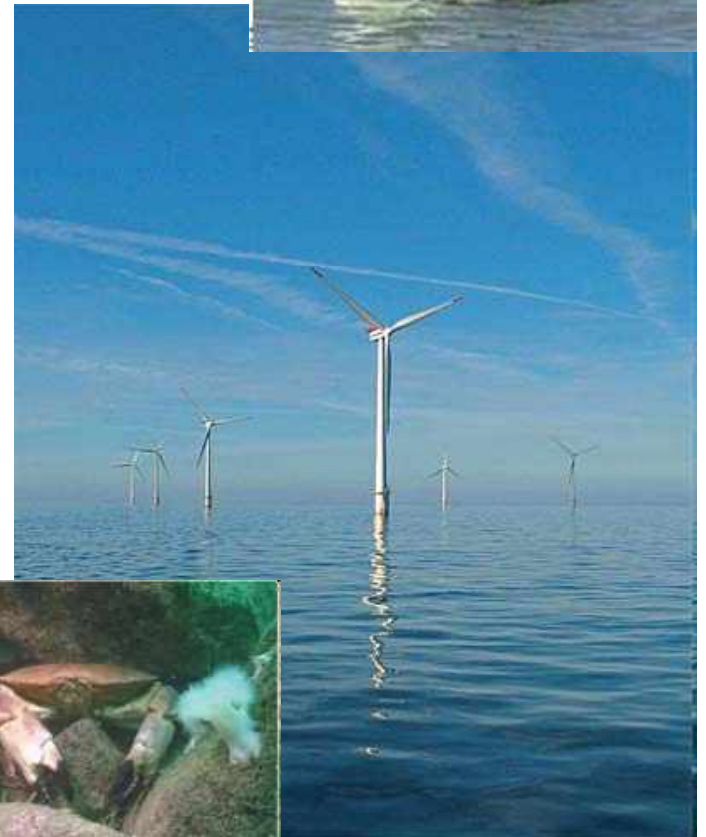
The view from the southwest shows (left to right) the vertical-axis Mariah Windspire, Southwest Skystream, Swift, five AeroVironment AVX1000s, and Proven 6.

*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...



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

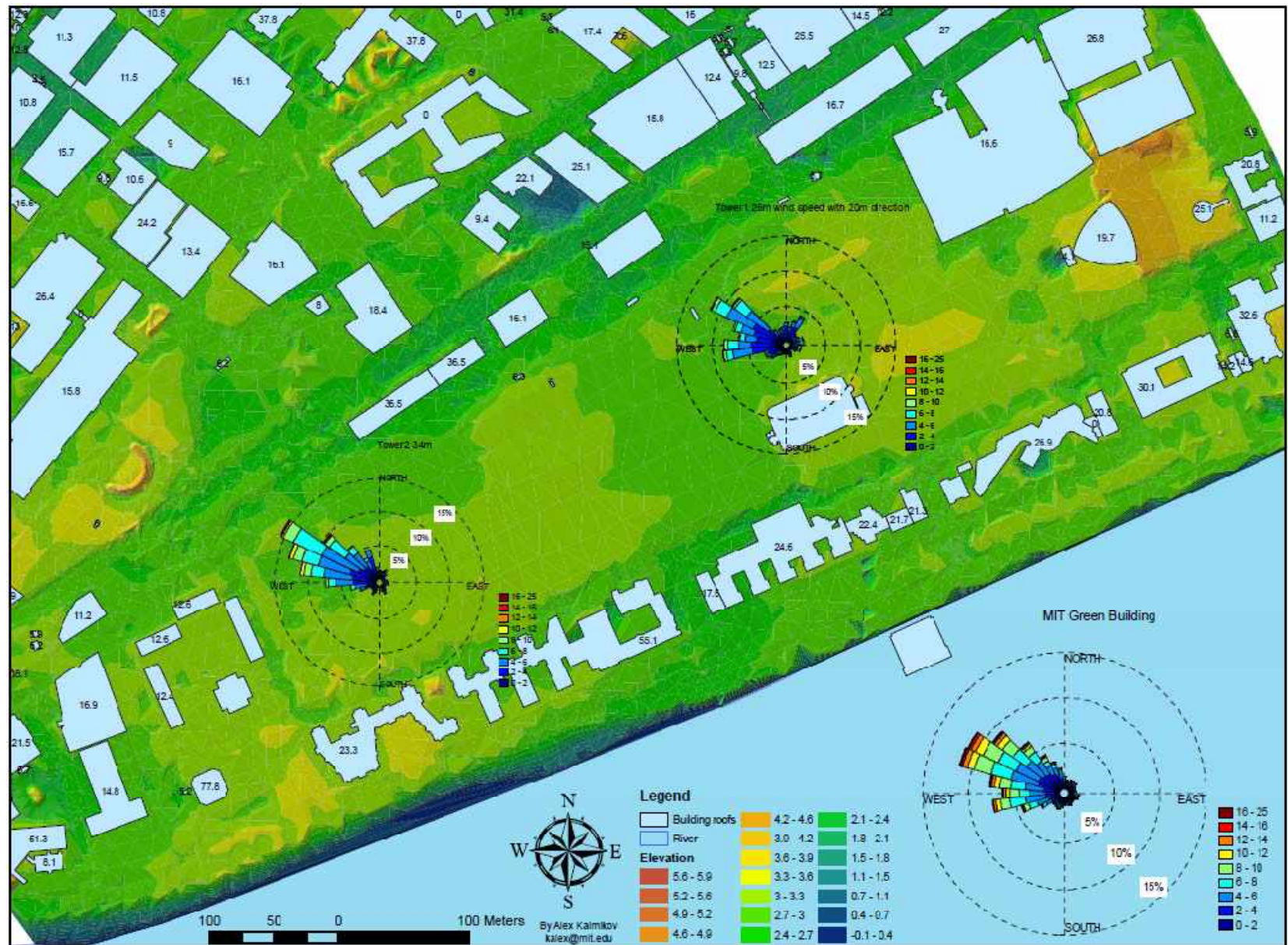
Analysis Method	MCP
-----------------	-----

- | Test Site 1 | Test Site 2 |
|-------------|-------------|
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| 2           | 2           |
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| 99          | 99          |
| 100         | 100         |

- | 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





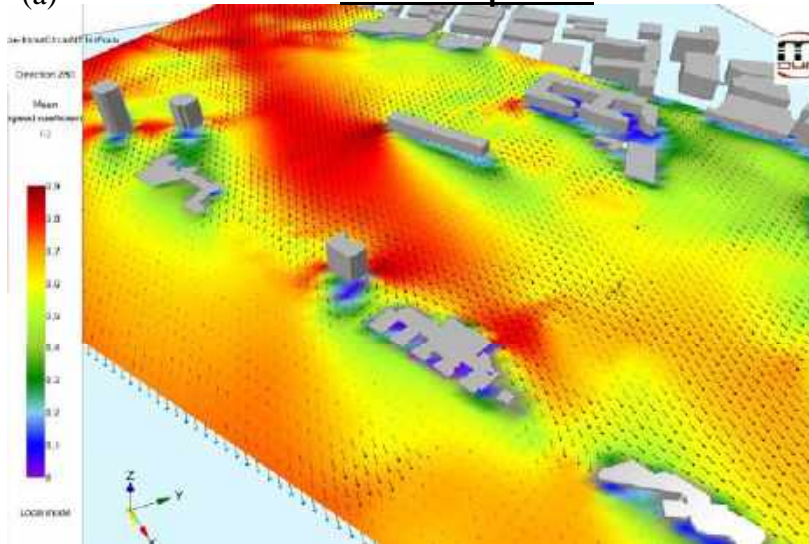
# 3D model of MIT campus



# 3D simulations of wind resource structure at MIT

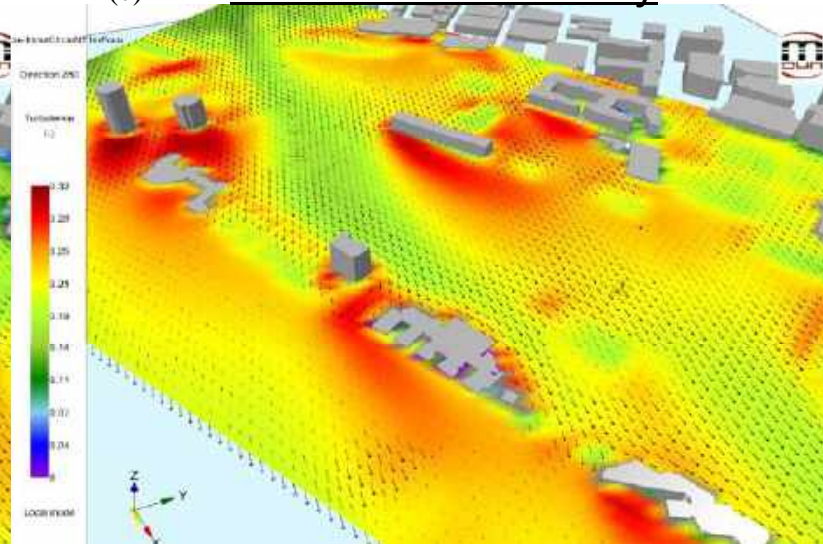
Wind speed

(a)

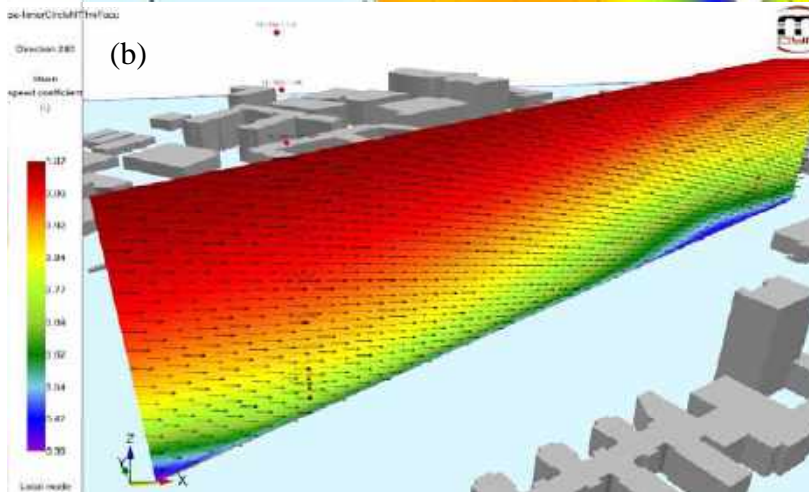


Turbulence intensity

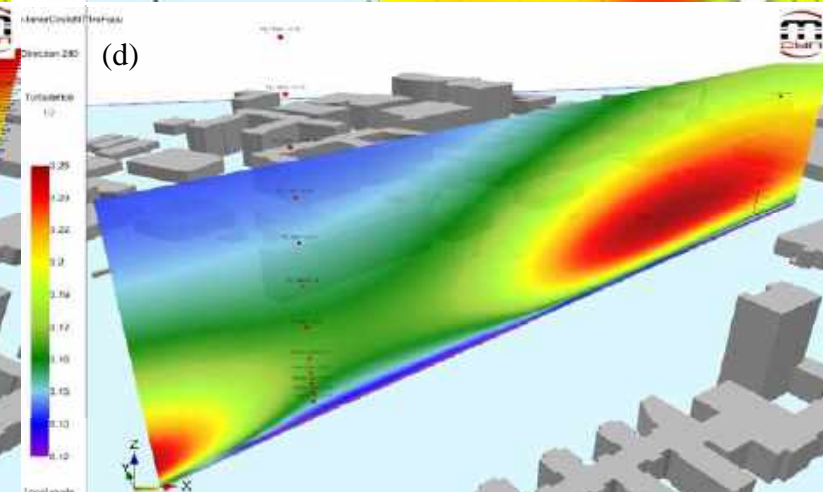
(c)



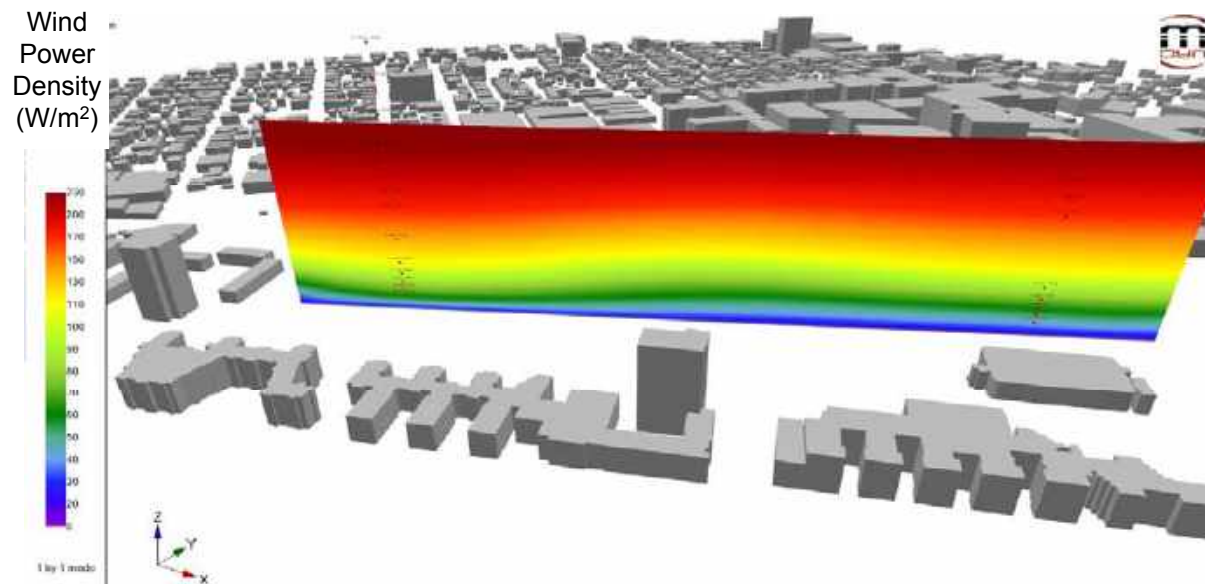
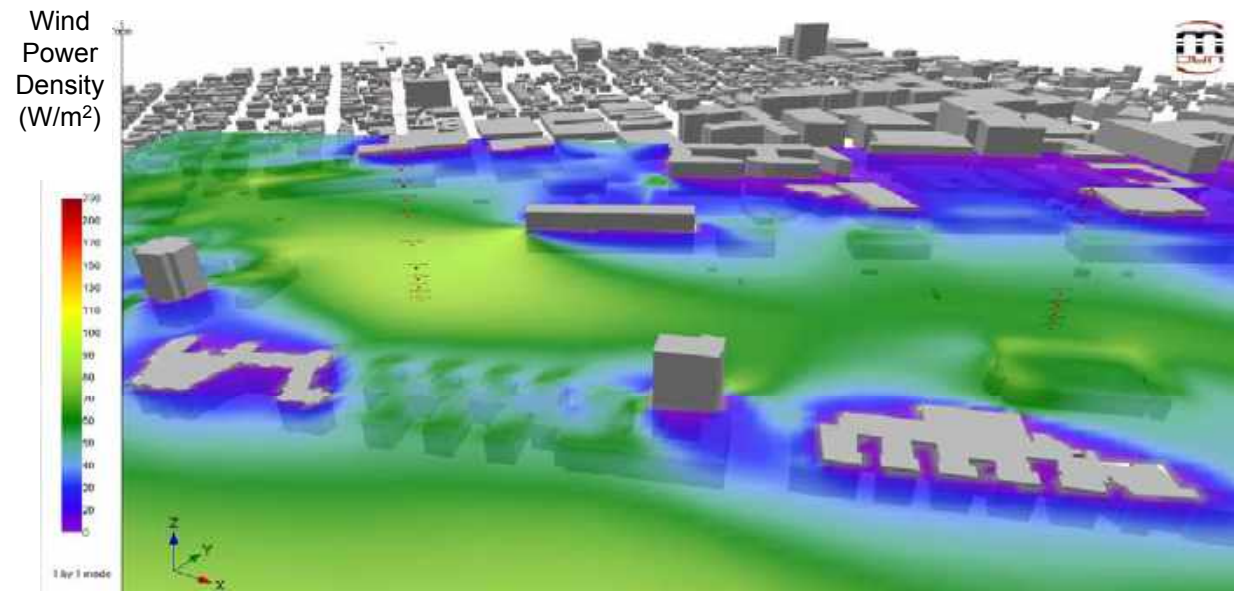
(b)



(d)



# Wind Power Density at MIT



**Q & A**

**THANK YOU**

